

Proceedings of the 4th WTA International PhD Symposium

13-16 September 2017
Delft, The Netherlands

W.J. Quist, S.J.C. Granneman & R.P.J. van Hees (eds.)

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Edited by W.J. Quist, S.J.C. Granneman & R.P.J. van Hees

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INTRODUCTION

After successful events in Leuven (2009), Brno (2011) and Stuttgart (2014), WTA Nederland-Vlaanderen and the chair of Heritage & Technology at Delft University of Technology, Faculty of Architecture and the Built Environment host the 4th WTA International PhD Symposium from 13-16 September 2017 in Delft, the Netherlands.

WTA Nederland-Vlaanderen is one of the regional groups within the WTA International Association. The aim of WTA is fostering of building preservation, building repair and monument maintenance related research, as well as the practical application and proliferation of such research. An important task here is to transfer the scientific achievements towards practice and to utilize and apply new knowledge and advanced technologies. The co-organising chair of Heritage & Technology at TU Delft is active in research and education on the technical and construction-historical aspects of Architectural Heritage.

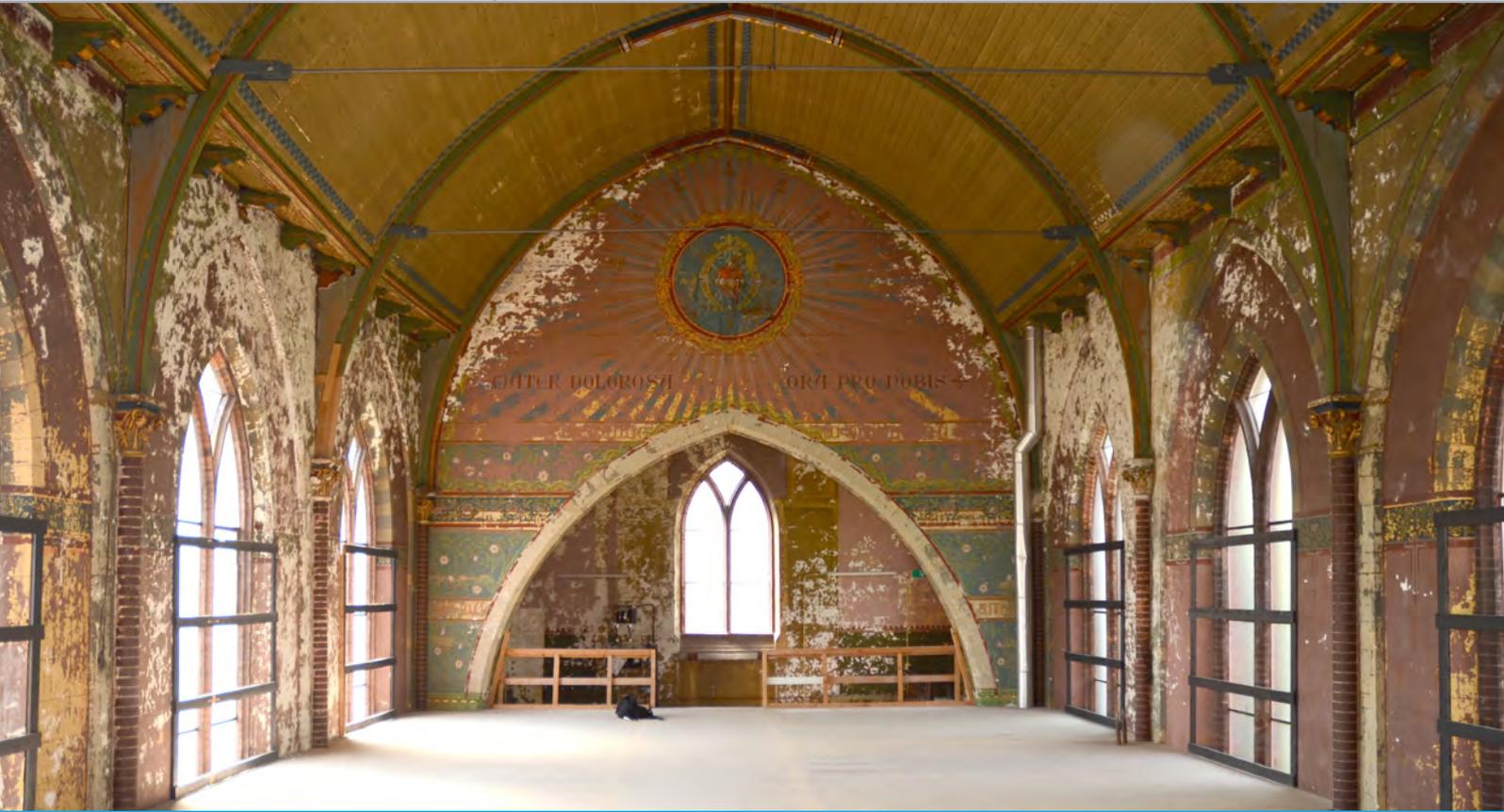
The aim of the WTA International PhD symposiums is to unite PhD candidates, post-docs and other junior researchers conducting research in the field of building conservation. It provides a forum for PhD candidates to present their research, discuss ongoing PhD studies to support future work and gives PhD candidates the opportunity to establish contacts within the international scientific community.

From the approximately 40 abstracts, 23 papers have been positively reviewed by members of the scientific committee and have been selected for presentation during the symposium and publication in these proceedings. The papers have been arranged in these proceedings according to the presentation schedule. Wido Quist and Sanne Granneman should be acknowledged for their great efforts to make this symposium possible.

The symposium will take place in the building of the Faculty of Architecture and the Built Environment of Delft University of Technology. This building offers an outstanding example of adapted re-use of a historical building. We are confident that the informal setting and the broad and interesting range of covered topics of the symposium will be a fruitful environment for discussion amongst junior and senior researchers.

August 2017
Prof.ir. Rob van Hees

On behalf of the organising team, consisting of:
Dr. W.J. Quist
S.J.C. Granneman MSc
Prof. R.P.J. van Hees



**THURSDAY
14 SEPTEMBER**

DESIGN AND DEVELOPMENT OF SPECIAL CONCRETES - ADAPTION OF MATERIALS FOR SPECIAL REHABILITATION TASKS

A. Flohr, A. Gypser and A. Osburg¹

KEYWORDS

Concrete Rehabilitation, PSCC, Tamped Concrete, Super-Sulphated Cement Concrete

ABSTRACT

Today the requirements for concrete restoration are not only aspects of retrofitting or restoration of bearing capacity but increasingly aspects of preservation of historic structures, such as industrial monuments, civil engineering structures and buildings of the 1960s. Thereby the facsimile replication of the concrete surface is a particular challenge.

For the manufacture of delicate and complex structures with restricted accessibility self-compacting concrete (SCC) is well suited. A modification with polymers normally ensures the durability of repair mortars or concretes (PCC). The combination of PCC and SCC to the Polymer-modified Self-compacting Concrete (PSCC) for the restoration of historic concrete constructions is the logical consequence, to combine the advantages of both materials. The PSCC not only has excellent mechanical properties, but it is also possible to imitate the original surfaces. PSCC is therefore an interesting alternative to well established materials and methods.

Historic concrete constructions are often manufactured of concretes with very stiff consistencies, the so called tamped concretes. There is a need therefore to develop materials and methods for the rehabilitation of structures made of tamped concrete. For this reason first investigations have been performed to the recipe development and optimization of its composition but also properties, furthermore to the design possibilities and how polymers influence the concrete properties.

In Germany between 1920 and 1970 industrial buildings and hydraulic structures have been built with concretes, where the content of Portland cement clinker was nearly complete substituted by latent hydraulic materials. The binders of those concretes contain large quantities of blast furnace slag and calcium sulphate and are called super-sulphated cement (SSC). Because of the high sulphate content, the compatibility of concrete structure with SSC is not given to concretes or mortars with other cements. If there is an adequate range of moisture, harmful new formations of phases will occur in the contact zone between SSC-concrete and the other concrete. In the field of rehabilitation PCC are well established. These are polymer-modified mortars or concretes with Portland cement, which are not suitable for the rehabilitation of structures of SSC-concrete. An alternative is the polymer-modification of SSC-concretes with polymers.

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INTRODUCTION

Within the scope of the research project nuBau-Transfer “Methods for the development and application of innovative, functional materials for the restoration of buildings” different materials for repair and restoration of buildings have been developed and optimized. Presented in this paper are selected results of the development of Polymer-modified Self-compacting Concrete, of tamped concrete and of polymer-modified super-sulfated cement concrete.

POLYMER-MODIFIED SELF-COMPACTING CONCRETE (PSCC)

At first the studies focused in the development and application of a filler type PSCC with a polymer content of 10 % of the cement weight. The PSCC mixture was projected and modified to achieve optimal material properties. To characterize the concrete as well as for comparative studies, fresh and hardened concrete properties were determined and compared to the properties of a not modified reference. The polymers in the structure of the hardened concrete reduced the elastic modulus and the compressive strength. A low elastic modulus and a moderate compressive strength are important for the functional efficiency of repair systems. The measured values for bonding strength were always higher than 2 N/mm² and the failure occurred in all cases in the substrate. Furthermore, the PSCC could be categorized as freeze-thaw resistant and resistant to freeze-thaw and deicing salt. In contrast, the reference concrete is not resistant to freeze-thaw and deicing salt. So it can be stated, that a polymermodification is necessary to guarantee the durability of this concrete. [1][2]

On the basis of these results further concrete formulations have been developed, which meet the current requirements from practice. The methodological approach was based on successive investigations on paste, mortar and concrete. These tests formed the basis for a purposeful concrete design, also if there are variations of the precursors, which are necessary because of certain concrete technological boundary conditions. The rheological properties of the pastes, the base mortars and concretes have been determined using selected methods und compared to the results of the already established concrete compositions. Figures 1 to 6 exemplify the investigations on fresh mortar and fresh concrete. The desired characteristics have been unerringly achieved.



Figure 1: Pneumatic lifting device for determine the slump flow of the pastes



Figure 2: Determination of the slump flow of a cement paste sample



Figure 3: Determination of the V-funnel flow time of the mortars

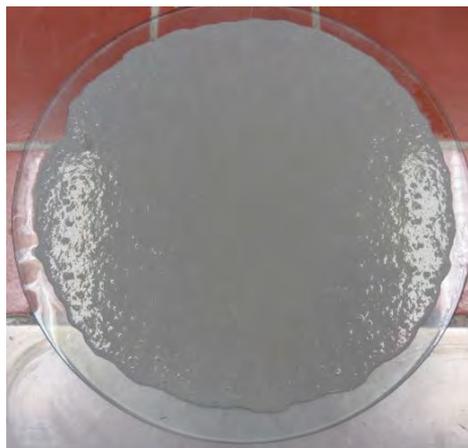


Figure 4: Determination of the slump flow of the mortars

In the concrete investigations it was obviously, that the unmodified references showed significant appearances of segregation and separation (figure 5) in part. The stabilizing effect of the polymers is well illustrated in figure 6.



Figure 5: Unmodified reference (SCC) with appearance of separation



Figure 6: PSCC with no appearance of separation

Another aspect of the investigations was the influences of the design concept or rather type of SCC (filler-type, viscosity agent-type and combined-type) on the rheological behavior of the fresh concrete, the hardened concrete properties and the appearance of the concrete surface. It was determined that it is possible to produce functioning self-compacting concretes independent of the type of SCC. The composition of the concretes is shown in Table 1. In every case the fresh concrete properties were improved due to the polymer modification (table 2). The hardened concrete properties are shown in table 3.

For the assessment of the concrete surfaces, samples were produced in special ashlar-formed formworks with a height of 50 cm, a width of 25 cm and a depth of 3 cm. The surfaces of the formworks have been prepared on the one side with a PE-foil and on the other side with a suitable release agent. Table 4 summarizes the qualities of the surfaces of the different SCC-types. With all variants the polymer-modified SCC revealed a better surface quality. Especially the amount of near-surface air voids is significantly reduced.

	Cem. [kg/m ³]	Limest. [kg/m ³]	Water [kg/m ³]	Polym. [kg/m ³]	Superpla st. [kg/m ³]	VA [kg/m ³]	Aggr. [kg/m ³]
Filler-SCC	390	260	197	-	8,8	-	1470
Filler-PSCC	368	245	209	36,8	4,0	-	1410
VA-SCC	255	170	186	-	12,4	3,0	1680
VA-PSCC	255	170	208	25,5	3,3	1,8	1620
Comb.-SCC	330	220	202	-	6,0	1,8	1540
Comb.-PSCC	330	220	214	33	6,0	1,5	1490

Table 1: Composition of the different SCC-Types

	Slumpflow [cm]	V-funnel flow time [s]	Air void content [%]	Bulk density [g/cm ³]	Fresh concrete temperature [°C]
Filler-SCC	71,0	12,9	2,2	2,34	23,0
Filler-PSCC	67,5	6,9	6,0	2,21	23,0
VA-SCC	67,5	15,3	1,4	2,29	21,5
VA-PSCC	69,5	8,1	1,9	2,24	21,5
Comb.-SCC	72,5	6,7	0,9	2,31	21,5
Comb.-PSCC	69,5	13,2	3,1	2,27	21,5

Table 2: Fresh concrete properties of the different SCC-Types

	Compressive strength [N/mm ²]	Bulk density [g/cm ³]
Filler-SCC	53,2	2,34
Filler-PSCC	44,4	2,28
VA-SCC	33,4	2,30
VA-PSCC	27,7	2,22
Comb.-SCC	42,9	2,33
Comb.-PSCC	39,5	2,24

Table 3: Hardened concrete properties of the different SCC-Types

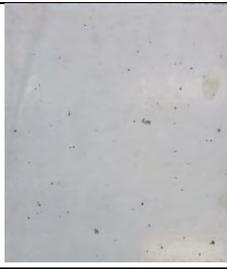
SCC-Type		SCC	PSCC
Filler-type	release agent		
	PE-foil		
viscosity agent-type	release agent		
	PE-foil		

Table 4: Surfaces of the different SCC-Types

TAMPED CONCRETE

Motivated by cooperation partners from practice, a further special concrete with certain properties was included in the investigations. It has been regarded as necessary to introduce the tamped concrete with its particular look and surface structure, because this material was used for many historical and in part heritage concrete buildings of the late 19th and early 20th century. Therefore it was necessary to develop and customize material, methods and technologies for the restoration of structures made of tamped concrete.

First experiments have been done for the determination of compositions, adjustment and optimization of properties, to the design possibilities and how the properties of the concrete can be influenced by using polymers.

At the moment the investigations are limited to the determination and adjustment of the concrete composition for a purposeful achievement of the required fresh concrete behavior and adaption of certain optical properties of the hardened concrete. Beside the adjustment of the composition to reach the optical properties, different manufacturing techniques were tested. In principle, tamped concretes could be produced which correspond in structure as well as in color

to historical tamped concretes (figure 7). The investigations of the durability and the influence of polymers in the structure of the tamped concrete are still in progress.



Figure 7: Structural and color design options of tamped concrete

POLY-MERMODIFIED SUPER-SULPHATED CEMENT CONCRETE (PSSCC)

Also motivated by cooperation partners from practice, a second special concrete with certain properties the super-sulphated cement concrete (SSCC) was included in the investigations. Goal of the investigation was to clarify if the polymer-modification of SSCC leads to similar benefits as known from polymer-modified Portland cement concrete (PCC). It became apparent that important properties which are relevant for the durability of the concrete could be improved due to the polymer-modification, but there are also differences to the characteristics of PCC. The Compositions of the SSCC and the PSSCC is specified in table 5.

	SSCC [kg/m ³]	PSSCC [kg/m ³]
Super-sulphated cement	340	340
Water	187	187
Polymer	-	34
Aggregates	1800	1720

Table 5: Compositions of the super-sulphated cement concretes

The processability of the fresh SSCC (table 6) could be improved through the addition of the polymers. A superplasticizing effect and simultaneous no separation, no sedimentation and no segregation were observable.

	Flow spread [mm]	Air void content [V.-%]	Bulk density [g/cm ³]	Fresh concrete temperature [°C]
SSCC	420	1,9	2,31	20,6
PSSCC	< 630	1,6	2,29	19,6

Table 6: Fresh concrete properties of the different SCC-Types

The properties of the hardened concrete displayed some variations from the known properties of PCC. The increased bending tensile strength and the decreased Young's-modulus are important benefits for reconstruction materials and known from conventional PCC. The increased compressive strength of the polymer-modified SSCC was not expectable (figure 8, 9 and 10). The reasons for this increase in compressive strength are investigated in further analyses.

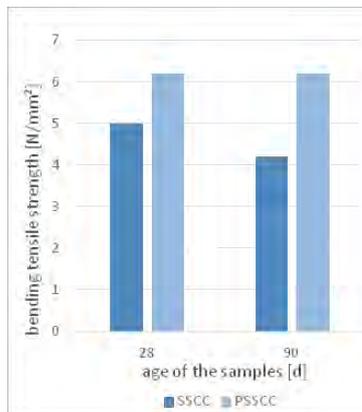


Figure 8: Bending tensile strength of the samples

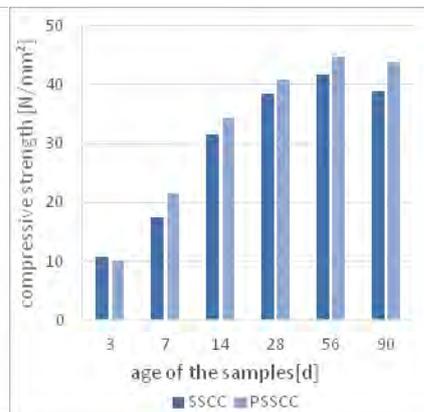


Figure 9: Compressive strength of the samples

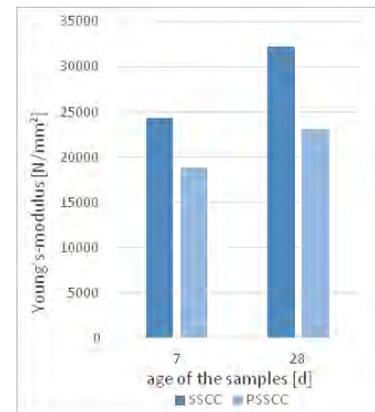


Figure 10: Young's-modulus of the samples

Considering the microstructure of the concretes, it is observable that the pore radius distribution of the PSSCC shifts towards smaller pore radii. A significant decrease of pores with capillary effect was visible (figure 11). The decreased part of capillary pores has a positive effect on the durability of the material. Furthermore a significant decrease of depth of carbonation was determined. That is evidence for a denser structure and therewith for a higher resistance against media which cause corrosion. Further investigations to the influence of the water-cement-ratio and the polymer-cement-ratio are still in progress.

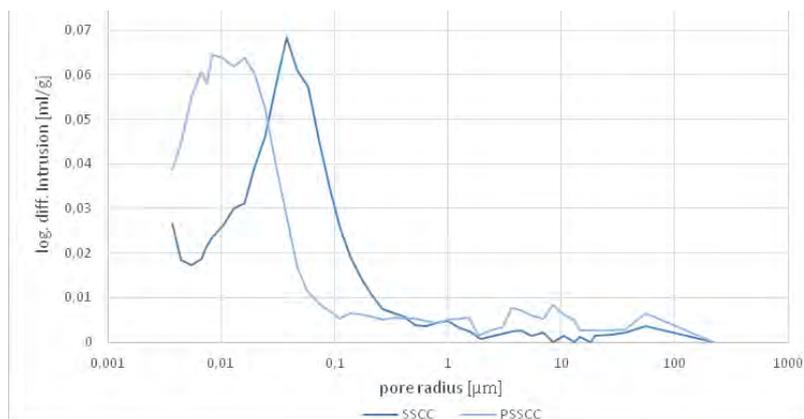


Figure 11: Pore radius distribution of the polymer-modified concrete and the reference concretes determined with mercury intrusion porosimetry

Based on scanning electron microscope images of the binder of the concretes, considerable morphologic differences of the crystalline structures of the PSSCC and the reference were visible (figure 12). The hypothesis is that the formation of ettringite is restrained due to the polymer-modification and the prismatic crystals formed are smaller in shape.

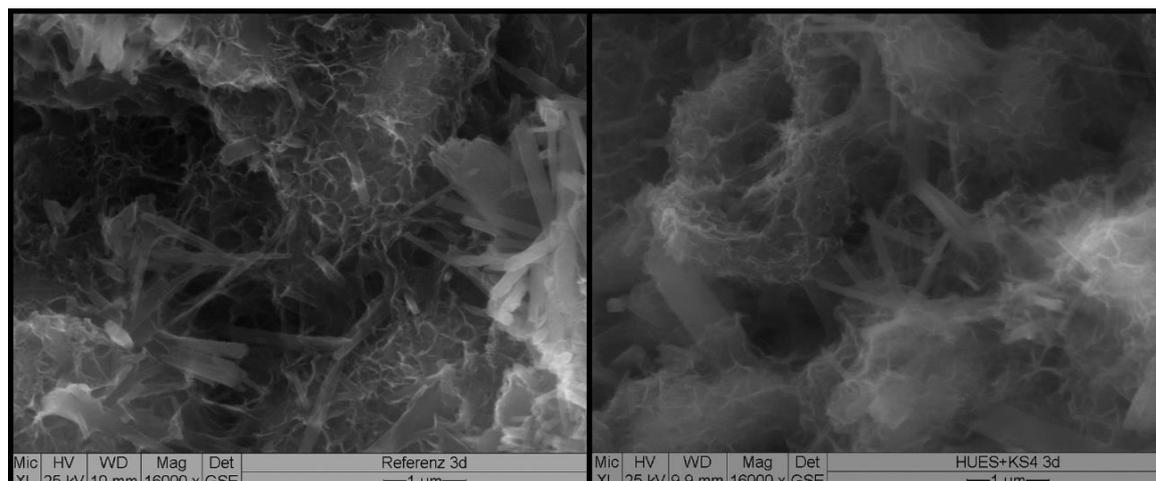


Figure 12: SEM-images of SSCC (left side) and PSSCC (right side) after 72 h of hydration

Furthermore was observable, that the adsorption process and the film formation of the polymers are completed after 48 h. The polymers are homogeneous distributed in the cement phase of the concretes.

CONCLUSIONS

Finally, it can be stated that every single rehabilitation task of historical concrete structures needs a specific analysis of the state of construction and therewith a certain selection of the reconstruction material. For a purposeful adjustment of the reconstruction material on the original substance usually specific investigations or even innovative material developments are necessary. In many cases the modification of the cementitious reconstruction material with polymers is useful to ensure its durability and to adapt mechanical properties.

ACKNOWLEDGEMENTS

The presented studies are part of the research project "Methods for the development and application of innovative, functional materials for the restoration of buildings". It is funded by the Federal Ministry of Education and Research, Germany and belongs to the initiative "Innoprofile".

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MITIGATING SALT DAMAGE IN LIME-BASED MORTARS WITH MIXED-IN CRYSTALLIZATION MODIFIERS

Sanne J.C. Granneman¹, Barbara Lubelli¹, and Rob P. J. van Hees^{1,2}

KEYWORDS

Crystallization Modifiers, Self-Healing, Lime Mortar

ABSTRACT

This paper describes some of the most important results of a four year PhD research on the use of crystallization modifiers mixed in lime mortar to mitigate salt crystallization damage. The research focused on two of the most damaging salts, sodium chloride and sodium sulfate, and suitable crystallization modifiers (sodium ferrocyanide and borax). We report the major findings related to the effectiveness of the modifiers when mixed in the mortar, and the results of characterization of the additivated mortars in comparison with reference mortars. Moreover, the durability of the developed mortars to salt decay is discussed, based on the results of an accelerated salt weathering test carried out in laboratory. No major effects of the modifiers on the fresh and hardened mortar properties were observed which might restrain the application of crystallization modifiers in restoration mortars. Additionally, the mortars with mixed-in modifiers showed a considerable improvement of the salt resistance when compared to reference mortars. Considering these results an outlook for future research pathways is given.

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INTRODUCTION

Salt crystallization damage in porous building materials is a ubiquitous threat to our built cultural heritage. Low mechanical strength makes lime-based mortars especially susceptible to salt damage. In restoration or renovation works, replacement of renders and plasters often constitutes a large part of the total costs of the project. Current solutions, such as using a stronger binder or changing the moisture transport properties of the mortar, usually have a limited resistance to salt decay and low compatibility with the existing materials [1, 2].

Alternatively, the use of crystallization modifiers has been proposed [3]. Crystallization modifiers do not aim to alter the material properties, but the damaging mechanism itself. Using crystallization modifiers in porous building materials has gained wide research interest in the last years (see e.g., [3-5]). However, the use of modifiers in a fresh mortar, thereby giving the mortar “self-healing properties”, is relatively new. By mixing modifiers in during mortar production, they can become active as soon as the damaging salts enter the porous material. Promising results have already been obtained in a pilot study [6].

To further study the feasibility of the use of crystallization modifiers to mitigate salt crystallization damage, a PhD research was started. This research had the following aims: i) Identify suitable modifiers for two of the most abundant and damaging salts: sodium chloride and sodium sulfate, ii) Study the modifier-salt interaction in bulk solution to elucidate the working mechanism and find a suitable concentration, iii) Test the effect of modifier addition on mortar properties (which might limit their application), and iv) Test the durability of additivated mortars in an accelerated salt weathering test.

From literature research, sodium ferrocyanide and borax (sodium tetraborate decahydrate) were identified as potential modifiers for sodium chloride and sodium sulfate, respectively [7]. Ferrocyanide is a well-known modifier for sodium chloride. Therefore, this research focused on the study of its effect on fresh and hardened mortar properties and on its capability of mitigating salt decay in mortar. Borax on the other hand is less well-known and was therefore first studied in bulk solution experiments. In this research, the effect of borax addition on solution properties and its effect on crystallization of sodium sulfate were studied. As has been reported in Ref. [8], depending on the starting concentration of the solution, two different phases of borax precipitate, each having a different effect on sodium sulfate crystallization.

In this paper the major findings relating to the effect of modifier addition on mortar properties and to the durability of additivated mortars are reported. First, an experiment to test whether borax’ effectiveness is affected by the carbonation process is described. Then, the effect of modifiers on mortar properties such as workability, water absorption and drying and flexural and compressive strength are reported. Finally, the durability of the additivated mortars with respect to salt crystallization damage is discussed based on the results of an accelerated salt weathering test.

MATERIALS AND METHODS

Mortar characterization

Two types of specimens were prepared: lime only specimens and mortar (lime + sand) specimens. The first, used to study the effect of borax on sodium sulfate crystallization, were prepared by mixing calcium hydroxide powder (Sigma-Aldrich, $\geq 96\%$ purity) with distilled water only or with water additivated with the modifier. After carbonation, a blank specimen was treated with borax solution. Then, the blank and the two borax specimens

were contaminated with sodium sulfate solution. After drying, the specimens were broken and the cross section was studied using SEM. By comparing specimens additivated with borax prior to carbonation and those to which borax was added later on, the effect of carbonation on the effectiveness of borax as modifier of sodium sulfate crystallization was assessed. Full details of this experiment can be found in Ref. [9].

Mortar specimens were prepared (according to EN1015-2) to test fresh and hardened mortar properties and assess the durability towards salt decay of the additivated mortars. Commercial air lime (Supercalco90) and standard sand (EN 196-1) were used. The modifier was added to the water used to prepare the specimens: 0.94 wt% sodium ferrocyanide and 3.2 wt% borax were added with respect to the lime. Several fresh and hardened mortar properties were tested according to standard procedures or techniques: workability (EN1015-3), water absorption and drying (EN1015-18), porosity and pore size distribution (Mercury Intrusion Porosimetry) and flexural and compressive strength (EN1015-11). Full details on the preparation of the mortars and the testing methods can be found in Ref. [9].

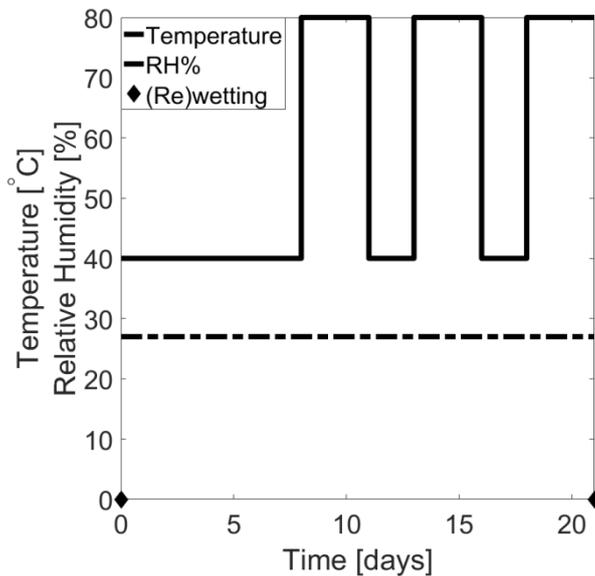


Figure 1: Temperature and RH cycles used in the accelerated salt weathering test. This entire cycle was repeated 5 times.

Accelerated salt weathering test

The salt crystallization resistance of the reference and additivated mortar specimens was tested with a custom designed salt weathering test, shown in Figure 1, simulating circumstances found in practice. 80 RH% is above the equilibrium relative humidity of sodium chloride ($RH_{eq} = 75\%$), but below that of the sodium sulfate phases. Consequently, the sodium chloride crystals will deliquesce when the humidity goes up and recrystallize when the humidity goes down again. This ensures multiple crystallization cycles for sodium chloride, a requirement for this specific salt for damage development. Recrystallization of sodium sulfate was obtained only by rewetting with liquid water at the end of a cycle.

Before the test, the specimens were contaminated with salt solution via capillary absorption. A precise amount of solution was used to ensure contamination with 1 wt% sodium sulfate or 2 wt% sodium chloride with respect to the mortar. In total 3.46 (reference NaCl), 3.91 (ferrocyanide), 1.77 (reference Na_2SO_4) or 1.91 (borax) gram salt was added to the specimens during the complete test. For each mortar type, 3 replicas were tested.

After each complete cycle, all specimens were rewetted with water equal to the initial amount used to contaminate the specimens. After 3 cycles, salt solution (exact amount to obtain again 1 wt% sodium sulfate or 2 wt% sodium chloride) was used for rewetting, in order to replenish the brushed off salt. After rewetting, any loose material was brushed off and the specimens started a new cycle. The brushed off material was washed and dried in order to separate the salt efflorescences from the debris. The debris was weighed and the amount of salt calculated by the difference. In total the specimens were tested for 5 cycles. Full details of the experiment can be found in Ref. [10].

RESULTS

Mortar properties

The effect of borax on sodium sulfate crystallization can be observed in the SEM pictures in Figure 2. When Fig. 2A is compared to 2B/C, it is clear that the crystal habit of sodium sulfate without borax is different from the crystal habit in the presence of borax. If subsequently Figures 2B and 2C are compared, a similar crystal habit can be seen in both figures. This means that the carbonation process has no effect on the effectiveness of borax as modifier for sodium sulfate.

A selection of the measured fresh and hardened mortar properties is summarized in Table 1 (additional characterization results can be found in Ref. [9]). When the values for additivated and reference specimens are compared, no notable differences can be observed. It can therefore be concluded that there are no negative consequences to mixing these quantities of modifiers in the mortar during production, as the addition of these modifiers does not negatively affect the mortar properties.

Property	Method	Reference	Ferrocyanide	Borax
Workability	Flow table test	170 mm	161 mm	161 mm
Water content		15.95 wt%	15.14 wt%	14.59 wt%
WAC [$\text{kg/m}^2\text{h}^{1/2}$]	Capillary rise	8.05	7.62	7.84
Density [kg/m^3]	Saturation at	1943	1964	1933
Open porosity (%V/V)	atm pressure	26.7 ± 0.19	25.9 ± 0.24	27.1 ± 0.06
Bulk density [g/ml]	Mercury Intrusion	1.977	1.971	1.961
Open porosity (%V/V)	Porosimetry	25.1 ± 0.11	25.4 ± 0.36	25.1 ± 0.55
Tensile strength (N/mm^2)		0.79 ± 0.11	0.85 ± 0.03	0.92 ± 0.11
Compressive strength (N/mm^2)		2.01 ± 0.33	2.08 ± 0.18	2.61 ± 0.22

Table 1: Fresh and hardened mortar properties of the different 1:3 lime:sand mortar mixtures. Results previously reported in [9].

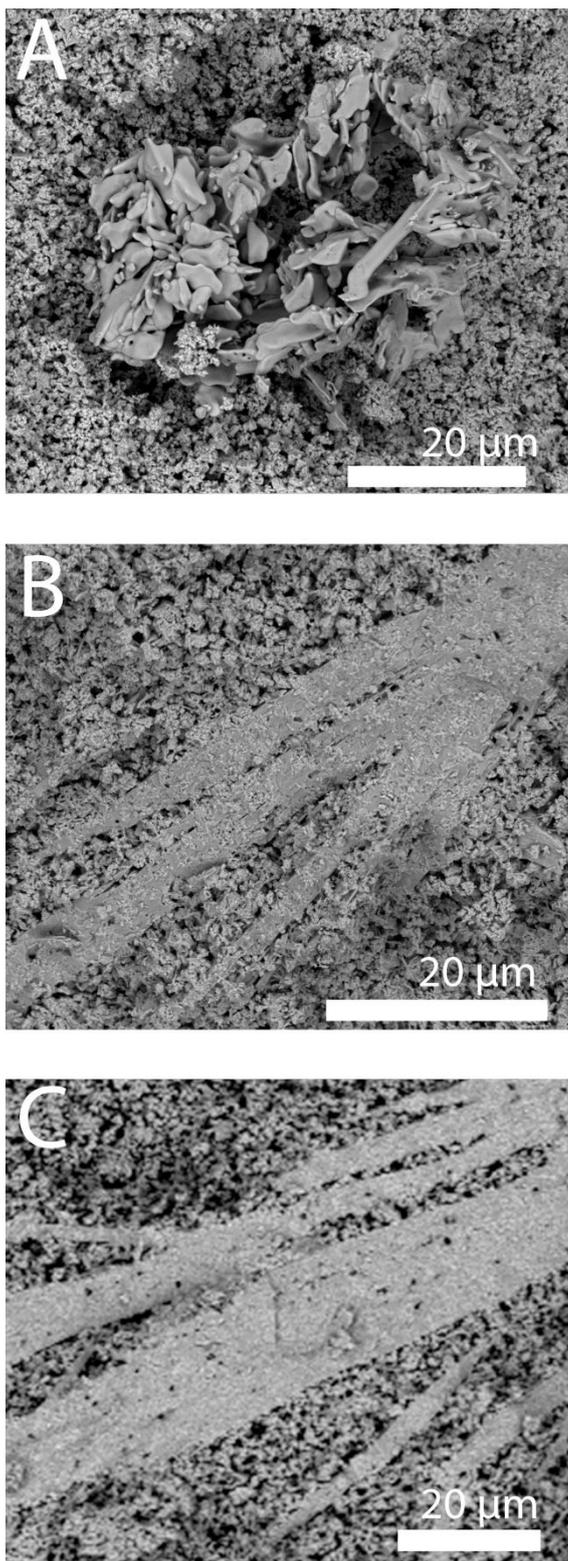


Figure 2: SEM images of lime-only specimens contaminated with sodium sulfate. A: reference specimen; B: specimen with 3.2wt% borax mixed in during preparation (thus before carbonation); C: Specimen additivated with borax after full carbonation of the specimen. A clear difference in crystal habit can be observed between the reference specimen and both specimens with borax. Contrarily, no distinction can be observed between B and C, meaning that the carbonation process has no effect on the borax effectiveness as modifier of sodium sulfate crystallization.

Salt durability [10]

During the accelerated salt weathering test, the specimens were monitored both visually and gravimetrically. The material loss (with respect to the mortar) is plotted in Figure 3, and the salt loss is visualized in Figure 4. It is clear that for both salts, the reference specimens suffer considerable material loss after 5 cycles. Contrarily, the additivated mortars show no or only minor material loss. The ferrocyanide stimulates efflorescence of the salt, i.e. crystallization outside the material, as does borax but to a lesser extent. Figure 5 compares specimens contaminated with sodium chloride at the start and end of the test. The reference specimen shows considerable surface loss at the end of the test. Contrarily, the specimen with ferrocyanide shows no material loss, but extensive efflorescence, which developed very fast just after rewetting and brushing of the specimens. In Figure 6 the specimens contaminated with sodium sulfate are compared. At the end of the test, both specimens show damage at the surface, but this is in the case of the specimen additivated with borax considerably less than in the reference specimen. Both the material loss and the visual observations show that both sodium chloride and sodium sulfate have the potential to cause considerable damage in the reference specimen. However, when the mortars are additivated with modifiers, damage does not occur or is considerably less.

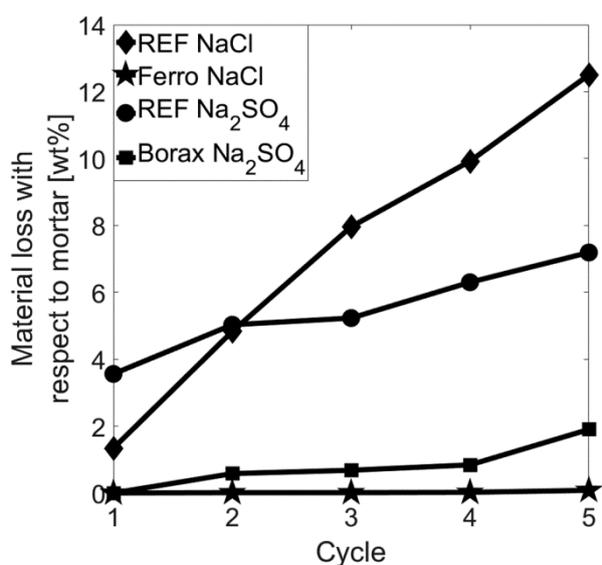


Figure 3: Cumulative material loss, comparison between reference and additivated specimens

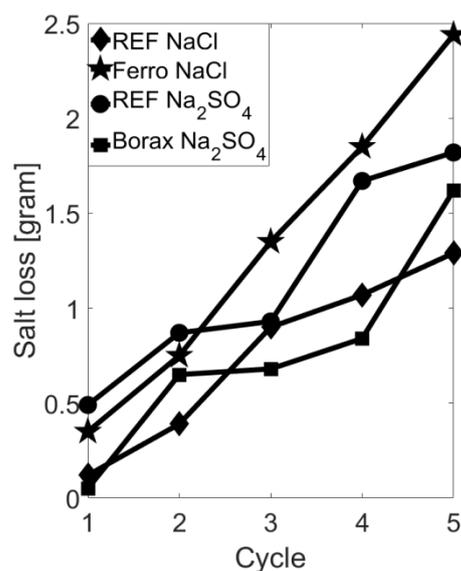


Figure 4: Cumulative salt loss, comparison between reference and additivated specimens.

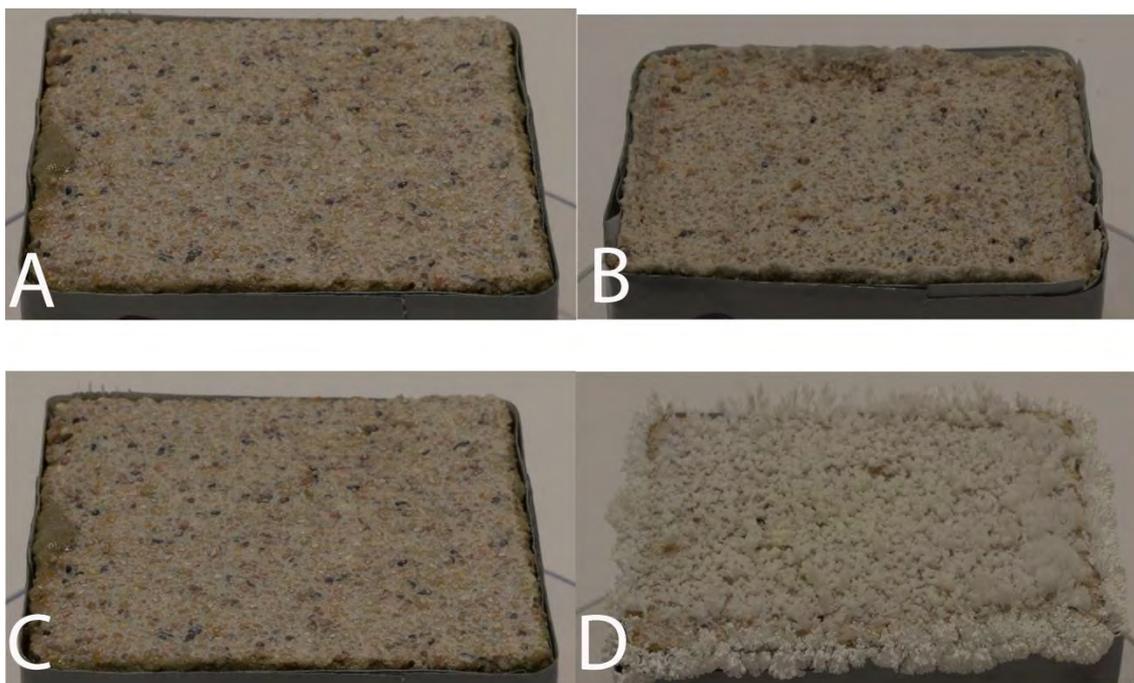


Figure 5: Comparison between reference (A/B) and specimens with mixed-in ferrocyanide (C/D), both contaminated with sodium chloride. A/C show the specimens at the start of the test, B/D show the specimens ~ 15 minutes after brushing after the 5th cycle. The reference specimen (B) shows sanding of the surface. The specimen with ferrocyanide shows no surface damage, only a large amount of efflorescence.

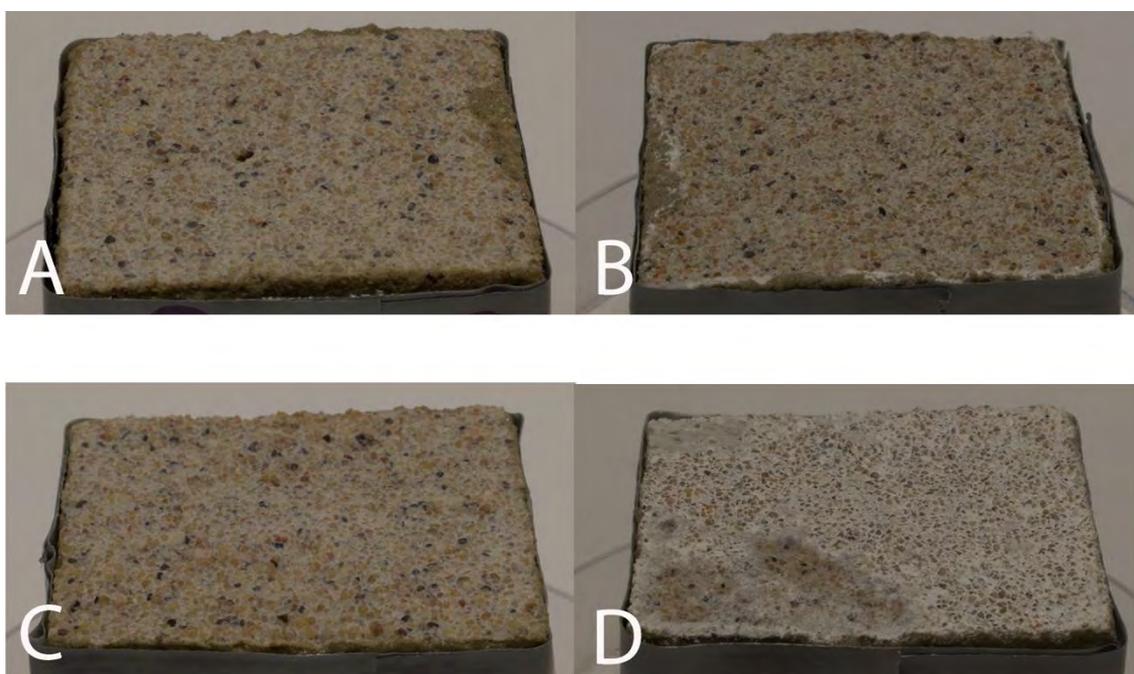


Figure 6: Comparison between reference (A/B) and specimens with mixed-in borax (C/D), both contaminated with sodium sulfate. A/C show the specimens at the start of the test, B/D show the specimens after brushing after the 5th cycle. The reference specimen (B) shows clear damage at the surface. The specimen with borax shows only minor surface damage at the lower left corner (D).

CONCLUSIONS

The additivition of mortars with crystallization modifiers during production has been proposed here to mitigate salt crystallization damage in porous building materials. Suitable crystallization modifiers for sodium chloride (sodium ferrocyanide) and sodium sulfate (borax) were identified to be mixed in a mortar during production. In this research, at first the effectiveness of borax as a modifier for sodium sulfate crystallization when mixed in lime was assessed and confirmed. In a next step, additivated mortars were characterized and compared to reference mortars in order to identify potential (negative) effects on fresh and hardened mortar properties. None of the tested properties was affected by the addition of the modifiers, meaning that there are no contra-indications to mixing them in the mortar in the used concentrations during production.

Finally, the salt crystallization resistance of the additivated mortars was assessed using a custom designed accelerated salt weathering test. The mortars with mixed-in modifiers showed a considerable improvement of the salt resistance when compared to reference mortars. Combining all these results it can be concluded that additivating mortars with crystallization modifiers during their production is a feasible method in order to mitigate salt crystallization damage in porous building materials.

OUTLOOK

The PhD research described in this paper shows the viability of using crystallization modifiers to mitigate salt weathering damage in porous building materials. Although the proof-of-principle has been shown on the laboratory scale, more research is needed to develop the material into a commercial product, suitable for renovation or restoration works. Interesting research paths to further develop the mortar designed in this project are:

- Studying the effect of modifier in mortars with different composition (e.g. cement-based).
- Studying the speed of modifier leaching and if necessary developing possible solutions, e.g. encapsulation.
- Assessing the effect of the identified modifiers on other salts and on salt mixtures and the possibility of combining different modifiers.
- Assessing the workability and effectiveness of the developed mortar (on test panels) in situ.

ACKNOWLEDGEMENT

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LEARNING FROM VERNACULAR BUILDINGS - TRADITIONAL RURAL ARCHITECTURE IN AUSTRIA AND IT'S ADAPTION ON CLIMATIC CONDITIONS

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KEYWORDS

Vernacular Architecture, Climate-Sensitive Building Design, Indoor Comfort

ABSTRACT

Climate is an elementary influencing factor for regionally different architectural design. At diverse locations, people have developed a variety of elementary building forms, that are adapted to their specific environmental conditions and that have to fulfill the need of shelter and comfort of their users. In response to temperature, precipitation, wind and solar radiation-induced effects, construction methods have emerged, which have also been developed on the basis of a limited range of building materials.

The scope of this thesis is the investigation of building-climatic characteristics of vernacular architecture in Austria and its adaptation strategies to local conditions in different landscapes with following questions: Which research methods are suitable for building-climatic analyses of historical objects, which are usually no longer accessible in original state? Which comfort-conditions are to be expected in distinguished examination objects? Which building-climate related characteristics (similarities and differences) can be quantitatively represented?

Building-monitorings and long-term measurements of thermal comfort conditions are carried out in selected objects of the Austrian open air museum in Stübing. Historical drawings and building surveys are the basis for the digital planning of selected buildings. Based on these documents, simulation- and calculation models are formed. The investigations of climatic and topographical conditions at the original locations of these (transferred) buildings refer to climatic data and in-situ observations. As a result, comparisons of object- and climate-data and location parameters are presented and interpreted.

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INTRODUCTION

In the framework of his exhibition "Architecture without Architects" in the Museum of Modern Art in New York (1964) the architect and cultural theorist Bernhard Rudofsky shows architecture in the context of its environment, the changeability of the climate, the challenges of the topography as well as the way of life of its residents. [1] For Rudofsky, the philosophy and know-how of the mostly unknown architects of these buildings represent the greatest untapped source of architectural inspiration for the people of the industrial age, the findings go beyond economic and aesthetic considerations [2].

Due to social and (agrarian-) economic developments historically and ethnically significant buildings in the open landscape are no longer existent [3]. In open-air museums, such as the Austrian open-air museum in Stübing, founded in 1962 by the ethnologist Viktor Pöttler (1924-2013), traditional homesteads transferred from different Austrian landscapes are shown in their (approximate) original form. Institutions such as these offer the possibility for varied investigations of architecture, which is no longer accessible in their original embossing and use.

So far, comfort-relevant properties of vernacular buildings have been analysed qualitatively and quantitatively only to a small extent. Therefore, the thermal building behavior of selected buildings in summer and winter is compared and interpreted in context with the climatic conditions at their original locations. As a result, related differences and similarities between objects from different landscapes can be demonstrated.

BASIC INFORMATION

Thermal comfort

A temperature range of about 16°C to 26° C is perceived as pleasant by humans, depending on activity, clothing and other influencing factors. The recommended relative humidity is in a range between 40% and 60% [4]. The difference to the prevailing ambient temperatures at the respective location must be reduced by corresponding design measures on buildings, such as thermal insulation, sun protection devices, use of heat storage masses, etc. If these "passive", building-integrated measures are not sufficient, the required temperature level can only be kept within the comfort limits by the use of technical components [4].

Climate history

The analysed buildings in this work have emerged in a climatically and agrarian-historically critical period, beginning in about 1570 with outstanding cold winters, rainy summers and hail storms in spring. These climate changes caused repeatedly crop failures and famines. It was only after 1750 that the temperatures consolidated again. [5] A warm decade has never occurred in the entire 17th century, the comparatively warmest ten-year period was between 1604 and 1613, but even at this time temperatures are clearly below the mean value of the whole 20th century. [6]

BUILDING CLIMATIC ANALYSIS

Building-climatic analysis and comparisons are made by selecting a so called "Vierkanter", formerly located in St. Ulrich near Steyr in Upper Austria and a so called "Einhof" from Alpbach in Tyrol. This selection was made because of the affiliation of these objects to non-alpine and alpine building types. Their local proximity in the museum area in

Stübing ensures comparable measurement conditions. Their differences in materiality, dimension and geometry enable a wide range of comparative approaches.

Investigation objects

The typical “Alpbach-house” or house of the Lower Inn Valley is a so called “Einhof”, a two-storey house in which living area, byre and barn are arranged one behind the other and united under a common, flat-sloped roof. Its distribution area ranges from Jenbach to Kufstein and Kitzbühel, and continues to the Salzach- and Ennsvalley to the region of Schladming [7]. The predecessors of this house form are the so called “Gruppenhof” and “Paarhof”, whose elements were brought together in the course of later development steps. An “Alpbach-house” usually shows the principle of a central corridor whereby the house entrance is usually arranged on the gable side. A special form is the so called “Berghaus”. As a result of steep terrain, the entrance is shifted to the eaves. Living room, kitchen and a chamber are located on the gable side. The appearance of the “Alpbach-house” and generally the houses of the Tyrolean lowlands is characterized by outside balconies and open corridors, the so-called “Labn” [8].

A “Vierkanthof” is a two-storey farmhouse, in which living-area, stable, barn and shed are grouped around a courtyard. This creates a closed building complex. The core region of the “Vierkanthof” in Upper Austria is between the cities of Linz, Enns, Steyr and Wels and still characterizes large parts of the landscape. The “Vierkanthof” marks the end of a development of farmsteads, which has gradually extended since the late 16th century from loosely connected buildings to more or less assembled building parts then to the type of a so called “Kleinvierkanter” in the 17th century. The classic “Vierkanter” is in existence since the 19th century. Normally, residential area and barn lie opposite each other at front- and rear side. Stables and sheds form the side wings [9]. The living area consists of an entrance corridor, kitchen with the stove, a representative living room with the stove and usually several chambers. In the first floor there are further chambers and storage rooms. The areas above stable, barn and shed are used as forage. [10]



Figure 1: “Alpbach-house” and “Vierkanthof” in the Austrian open-air museum in Stübing.

Comparison of object- and climate-data

The annual mean temperature at Krimml and Ternberg (the closest measuring points to the original building sites in Alpbach and Steyr) is 5.8°C and 8.6°C. The distribution of hourly temperature- and humidity-levels within an observation period of one year as well as a window of comfort ($20^{\circ}\text{C} \leq T < 26^{\circ}\text{C}$ and absolute humidity $H < 12\text{g H}_2\text{O/kg dry air}$) is illustrated by the following psychrometric chart (HX-diagram). By combining these param-

eters, the climate-related measures for room conditioning can be clearly understood. According to the overall number of hours per year, 8760 measurements per site are shown. (Analysis result Krimml: green, Ternberg: red)

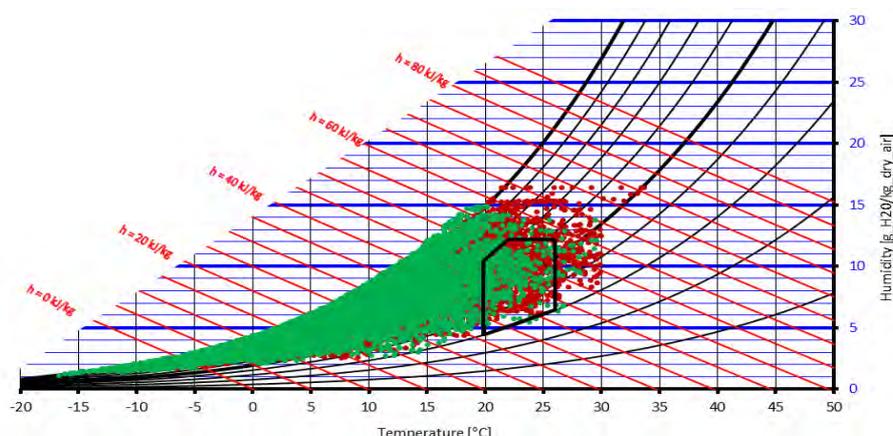


Figure 2: Psychrometric chart Krimml (Alpbach, green) and Steyr (St. Ulrich, red) (source: *Meteonorm 7*).

Building-climatic relevant properties of the two compared objects in terms of dimension, geometry, space structure and building-envelope are indicated by balanced scorecards (BSC). The measurement and calculation results for the reference projects “Vierkanthof” (VK) and “Einhof” (EH) are shown in red and green.



Figure 3: Comparisons of dimensions and compactness of the different areas in “Einhof” and “Vierkanthof”.

Building climatic measurements

For quantitative analysis of comfort-relevant characteristics, temperature- and humidity-measurements are made outside and in different residential rooms. The summer measurements are carried out between July 21st and August 26th in 2016. Autumn- and winter-surveys last from November 21st 2016 to January 13th 2017. The time interval is 15 minutes. Between November 21st and December 4th the historic fireplaces are heated for

visitors-events. The following diagrams show the course of the outside temperature and the parlor temperatures in the observed objects “Vierkanter” and “Einhof” over the entire summer and winter measurement period, including the mentioned heating phase.

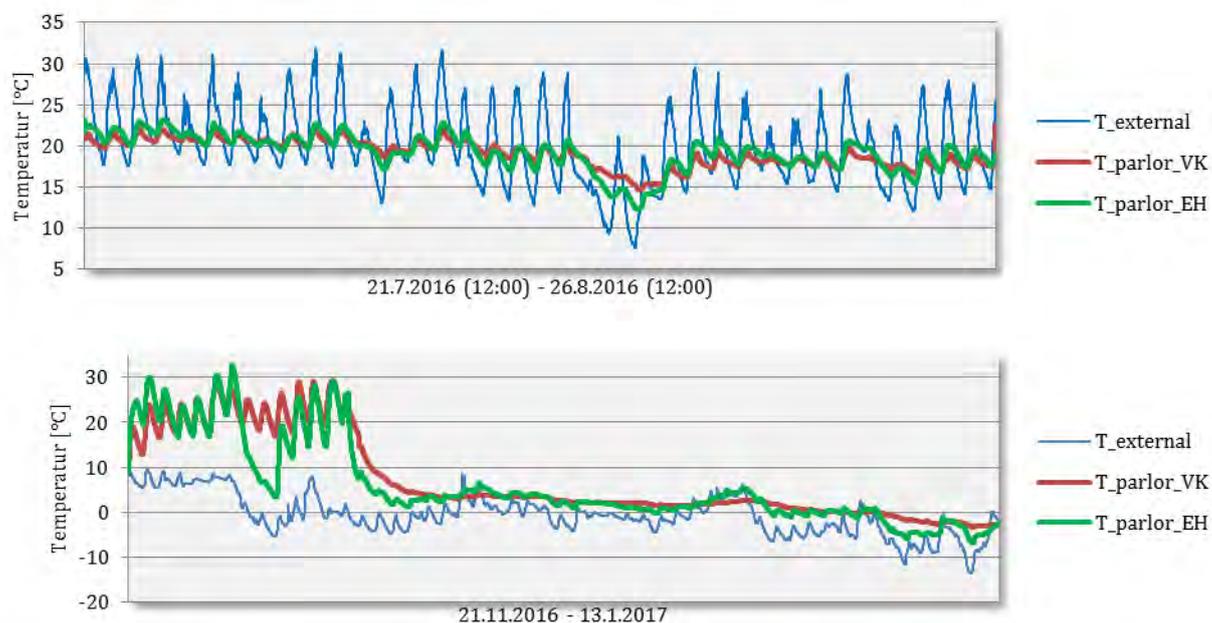


Figure 4: Outdoor and indoor temperature profile during the summer (top) and winter measurement periods.

EVALUATIONS

Solar site analysis

The farmstead in Alpbach is located in a region with a significantly higher annual number of sunshine hours compared to the site of the “Vierkanthof”. The south-oriented residential area of the “Einhof” is sun-exposed, and the surrounding mountains are affecting this sun exposure just a little. Due to the orientation of the building, especially the living room in the south-western building corner is favored. The characteristic roof-overhangs and balconies allow the entry of direct sunlight in winter but shade the southern façade in summer. The window area in the living room is very limited and equals just 9% of the usable area.

Apart from a terrain edge on the eastern side of the plot, the location of the “Vierkanter” is very sun-exposed due to the surrounding topography of the Enns Valley near Steyr. However, the solar probability in winter is low. The main façade of the residential area of the farmstead is north-oriented. Sun exposed building parts are barns and sheds. The window area in the parlor of the “Vierkanter” amounts 12% of the usable space and corresponds to natural lighting requirements in current building regulations.

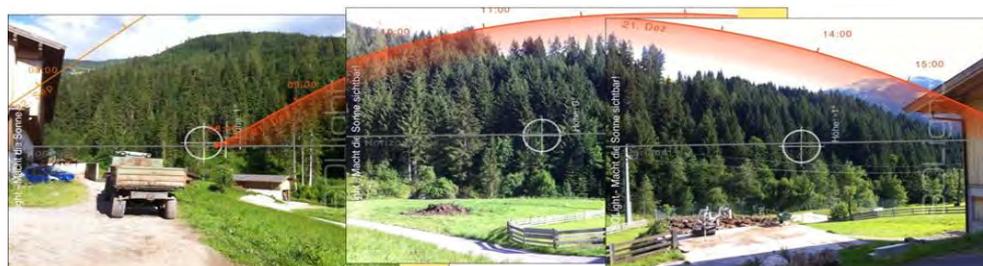




Figure 5: Solar site-analysis on the original locations of the “Alpbach-house” (top) and “Vierkanter”.

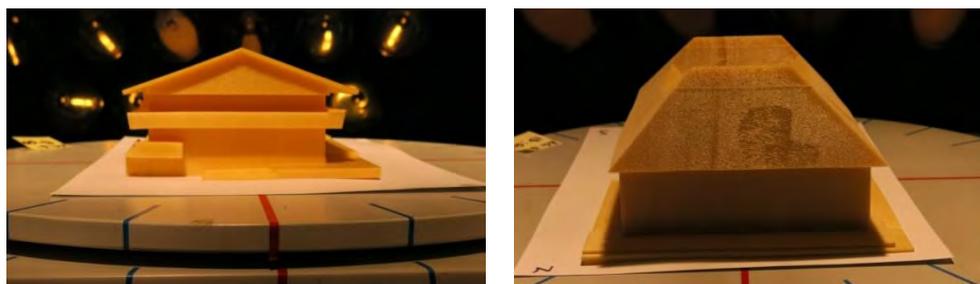


Figure 6: Direct-light simulations in the Light-laboratory in Krems, 21.6. “Einhof” (left) and "Vierkanter”.

External temperatures and building geometries

The annual number of hours when outdoor temperatures are within a thermally comfort range between 16°C and 26°C is in Krimml (Alpbach) only half as high as in Steyr. At both locations, the temperatures between October and April are almost completely below 20°C. Outside temperatures in winter were significantly colder towards the end of the 17th century and the beginning of the 18th century, when the farmsteads were built, compared to current temperature conditions. This made heat protection strategies even more important. Regarding the building geometries, the main differences result in the comparison of the building dimensions and the sizes of stables, barns and sheds. However, the compactness of the entire buildings as well as the residential areas are almost identical. Thus, the A/V-ratio (surface to volume) of the total cubicle of both buildings is 0.55, the compactness of the residential areas is 0.81 (“Einhof”) and 0.82 (“Vierkanter”). The location of the heated rooms in ground floor areas in building-corner positions illustrates the climatic compromise between weather exposure and maximization of light entries.

Temperature and humidity

During the summer measurements temperature fluctuations in the open attic floors and in living areas in the first floor, the so called “Hohe Stuben”, are strongly pronounced in both houses, while they are constant and largely congruent in the living areas in the ground floor. Almost throughout the whole period of observation and especially during "hot days" ($T_{\max} > 30^{\circ}\text{C}$) the temperatures are within a thermally comfortable range.

During the autumn/winter period, only in heated areas temperatures can be maintained in a thermally comfortable range. The adjoining rooms are tempered, but in too little measure for residential purposes. During a daily heating-break of about 16 hours, the room temperatures in the parlors do not drop below a level of 15°C, even at very low outdoor temperatures (with the exception of those days, when the heating process was interrupted in the “Einhof”). The daily fluctuation of the room temperatures during the heating phase is 10°C in the “Vierkanthof” and therefore less pronounced compared to the “Einhof”, where

it is about 15°C. The following cloud-diagrams illustrate the temperature and humidity conditions outside and in the parlor areas of “Einhof” and “Vierkanthof” during the summer and winter period, the measure interval is 15 minutes.

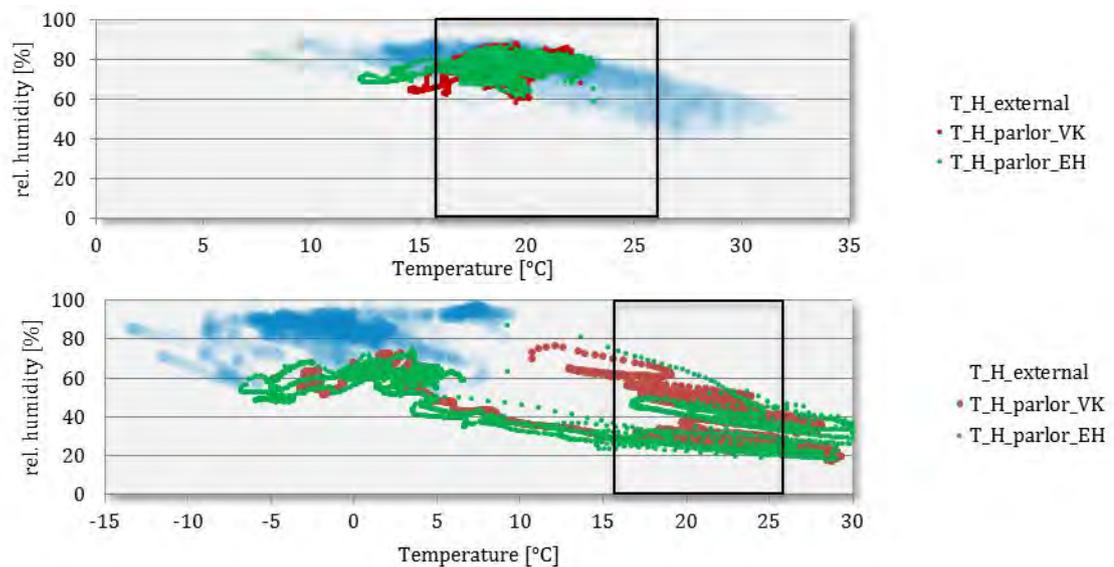


Figure 7: Distribution of outside temperature and rel. humidity and in the parlor areas of “Einhof” and “Vierkanter” during summer (top) and winter period, marked thermal comfort range between 16°C and 26°C.

The rapid reduction of CO₂ concentration of the indoor air after the end of the visitor events is due to the (uncontrolled) air exchange between interior and exterior space caused by leaks. However, the drop of the room temperature level is markedly slower than the air exchange.

CONCLUDING REMARKS AND ACKNOWLEDGMENTS

The described investigations refer to farmsteads from two different regions, Upper Austria and Tyrol, which could be analyzed in their (approximate) original form. According to the measurement results, both objects point out high resiliency in hot periods, especially when looking at the parlor areas. Slowly emitted heat, stored in solid wood, stone components and tiled stoves, cause a retarded cooling process after heating activities at prevailing cold outside temperatures with daily peaks below 0°C. An improvement of this temperature behavior could be achieved easily by a better sealing of the building envelopes and openings.

Additional qualitative and quantitative building-climatic investigations will reveal further relevant aspects such as surface temperatures and daylight entries. This will be examined by observation of additional objects from other Austrian regions. Therefore, Great thanks go to the supervisor of these activities, Professor Caroline Jäger-Klein, and Director Egbert Pöttler and the team of the Austrian open-air museum in Stübing, for their strong support.

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INFLUENCE OF BIO AND NANO FIBERS IN CLAY MORTARS

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KEYWORDS

Clay Mortars, Bio & Nano-Size Fibers, Strength

ABSTRACT

Nowadays, there is an increasing interest in studying and protecting clay-based materials, since they are proven to be sustainable and environmental friendly and a significant number of architectural structures are based on them. Ancient masons used to reinforce clay materials by natural fibers such as straw. This technique, in combination with strong compaction, assisted towards the longevity of such vulnerable materials. The present study, presents an effort that has been made to enhance those abilities by the use of bio- and nano-fibers. The clay mortars used for reconstruction purposes were produced in the laboratory. They were enriched by the use of various fibers, as additives, inside the clay matrix in 1.5%w/w of the clay binder. The fibers used were categorized in two different groups. The first group consists of mortars containing nano-fibers, such as cellulose and carbon fibers, while the second one consists of compositions with bio-fibers such as straw, coconut and cannabis fibers.

The tests conducted on the specimens were to determine the physical and mechanical properties (fresh and harden) of the mortar mixtures. The hydric behavior of the fiber-enriched compositions as well as the mechanical properties of the clay mortars were recorded at the age of 28 days. The results indicate the beneficial role of the fibers to the stabilization of the clay mass. Additionally, organic fibers and specifically straw fibers have a positive effect on the total of the properties tested while nano-carbon fibers also assisted towards compression and volume stability.

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INTRODUCTION

Clay is the oldest building material, used both for brick and mortar production. It is estimated that one third of the structures today, mainly in the developing countries, are concerned with adobes, while prehistoric and historic clay constructions are still preserved. Construction techniques with clay are known more than 9000 years and clay structures are considered a basic and significant element of architectural heritage around the world and specifically around the Mediterranean [1]. Due to the various advantages of clay materials, earth construction has been reconsidered over the last few decades in modern construction, in many European countries such as France and Germany [2]. Earth construction constitutes an alternative way of building in both materials and techniques, providing low-cost and sustainability compared to other conventional ways of construction [3]. Today, the energy crisis and the need for environmental care have redeveloped the construction of clay, aiming at creating environmentally friendly bioclimatic constructions. Because of the peculiarity of the clay and its sensitivity to the environmental conditions, the brickworks present problems of static and structural adequacy. Their conservation status is declining over time, due to insufficient knowledge in the treatment and restoration of clay-based materials. The reconstruction of monuments made of clay requires compatible materials and techniques. Nevertheless, increasing the durability of clay-based materials is always of interest. In this paper, an effort has been made in order to test specific abilities of clay mortars so as to find ways to protect and improve the durability of building materials made of clay. The use of fibers in clay-based mortars and plasters, such as straw, wood fibers etc, is known from ancient times. The inability of these materials to withstand high stresses and the development of micro-cracks on their surface led to the use of natural fibers inside the clay mass in order to offer stability, improved ductility, durability and strength [4, 5]. Many efforts have been made in order to test the abilities of fibers as reinforcements in earth-based structures exploiting their mechanical strength and other abilities for applications in civil engineering [4, 6]. Such examples are the study of Khosrow Ghavami et al., that reports the application of sisal and coconut fibres in soil blocks in order to enhance the physical and mechanical properties of these composites [7], as well as the research by M. Bouhicha that investigates the abilities of composite soil reinforced with chopped barley straw [8]. Additionally, a study of Andréa Aparecida Ribeiro Corrêa et al. used bamboo particles in order to improve the performance of adobes [9], while in the recent study of C. Galán-Marín et al. the stabilization of clay-based composite by use of wool and alginates extracted from seaweed is investigated [10]. Moreover, a recent study of Asghar Vatani Oskouei et al. examines the experimental results of the reinforcement of mud bricks with natural additives, such as straw, wood chips carpentry, rice husk and palm fiber under compressive and tensile tests [11], while the review of J.E. Aubert et al. on earth-based products with plant aggregates as a sustainable material, reports the various studies conducted on the matter, stating out the significance of future research on the topic [12]. In this paper an effort has been made to support the research in sustainable materials and reports the results of the addition of organic fibers such as coconut and cannabis, as well as nano-fibers (cellulose and carbon fibers) in the structure of clay mortars.

MATERIALS AND TECHNIQUES

Clay based mortars were produced in the laboratory and specimens 4x4x16cm were formed. In all mortars, the fibers tested were added in 1.5% w/w of the clay binder. The fibers used are categorized, as mentioned before, in two different groups: i) mortars with

nano-fibers and ii) mortars with bio-fibers. In all cases the clay used was rich in lime coming from the area of Crete and consisted besides aluminum compounds and quartz, of calcite (CaCO_3) and gypsum (CaSO_4) in small percentages. The clay was sieved to have a grain diameter of less than 0,5 mm. The sand used for the mortars was river sand of silica composition with similar color with that of the clay and grain size between 0-4mm. The mixture proportions of the mortars by mass were 1 (clay) : 2.5 (sand ratio) while the water addition varied in order to achieve the desired workability of 15 ± 1 cm (tested by flow table EN1015).

In the case of bio-fibers, cannabis, coconut fiber and straw were used. Since they are highly hydrophilic, they were placed from the previous day in a pre-weighed amount of water which was later inserted into the mortar mixture. In order to avoid agglomeration of the fibers, they were elaborated by hand just before they were inserted into the mixture. Cannabis was trimmed down in length of 0.5 cm, while straw fibers were cut to dimension approximately equal to 0.5 cm. The coconut fibers used, were not trimmed down, and their size varied between 12-22 cm. In the case of nano-sized fibers the procedure followed was ultrasonication with pre-weighted water for one hour. In that case the agglomeration is avoided [13]. The carbon fibers used were pyrolytically stripped and had a size of $100\text{nm} \times 20\text{-}200\mu\text{m}$. The particle size of the cellulose used was of medium size. Finally, a composition with no fiber additives was used as a reference for comparison reasons. The mixtures that were created are accumulated in Table1:

Code	Name	Amount of water used (ml)
A	Reference composition	300
BC	Cannabis composition	350
BCe	Cellulose composition	300
BCF	Carbon fiber composition	350
BCo	Coconut composition	380
BS	Straw composition	320

Table 1: Mortars created with the use of fibers.

The specimens were cured at 65%RH and 20°C until 28 days as the clay is aerial binder. The tests conducted were:

- Porosity based on RILEM CPC11.3
- Capillary absorption based on EN1015-18:2002
- Salt absorption test (1.5% w/w NaCl)
- Compressive and flexural strength tests
- Shrinkage measurements (volume stability)
- Optical observation of color change using Munsell chart
- Stereoscopic observation using microscope LEICA WILD M10

Since the sensitivity of clay towards water solvent is known and due to the lack of EU regulations on clay matrix, some modifications were performed in the tests conducted. The test of porosity was conducted with the use of heptane (organic solution) instead of water, while for the capillary absorption test the measurements taken were in a different timeline considering the inability of the mortars to withstand water for extended periods of time.

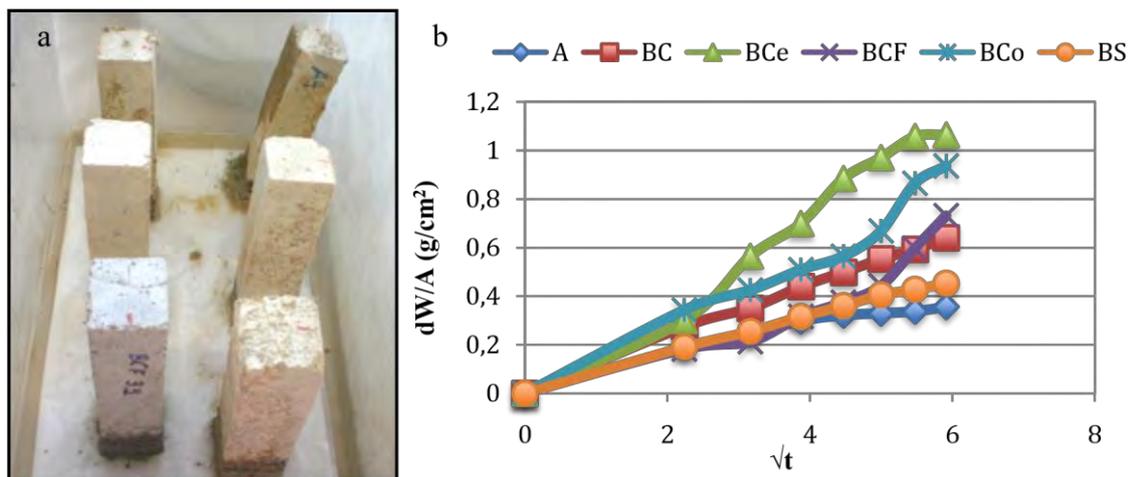
EXPERIMENTAL RESULTS

The porosity test conducted at the age of 28 days, with the samples being submerged for 24 hours. The results of absorption and porosity values are presented below (Table 2). The values were average of two samples used for the test. From Table 1 it seems that the addition of bio-fibers increased the water demand in order to achieve the same workability (compared to the reference sample). This, in combination with the fact that the fibers were already pre-wetted, shows that fiber-reinforced clay mortars require special design in order to avoid water excess (the use of super-plasticizers is recommended). In the case of nano-sized fibers the same trend was recorded in the samples with carbon fibers while the cellulose sample didn't require extra water.

	Absorption (%)	Porosity (%)
A	7.78	16.75
BC	8.70	21.07
BCe	7.85	18.84
BCF	8.63	19.02
BCo	8.67	21.21
BS	8.32	17.86

Table 2: Values of the physical properties of the samples recorded.

The results given above show that both porosity and absorption are high in samples with fibers, as the evaporation of the extra water leaves empty spaces (pores) in the structure. It is observed (Table 2) that the only specimen that shows properties close to the reference one is the mortar with the cellulose additive BCo, while the second in line appears to be the BS mortar, both in case of absorption and porosity values. As shown in Fig. 1b, the results indicate the high absorption of the samples compared with the reference one. However, from the capillary test results is observed that the specimen closer to the behavior of specimen A is the BS sample, with similar amounts of water intake due to capillary, while the sample with the highest water intake is the BCo one. The duration of the test was 35 minutes and the measurements were recorded every five minutes, since the weakness of the specimens towards water is known and the longer duration of the test was not feasible (Fig. 1a). Optical inspection at the end of the test showed that samples with cannabis, coconut and straw fibers presented higher stability compared with the other samples. Nevertheless, and despite the material loss during the experiment, the time was sufficient to record its behavior. The interconnectivity of the pores and height of the water at the end of the experiment indicate the positive role of the bio-fibers and especially the ones of straw and cannabis.



The salt absorption test was conducted in the same way as the water capillary absorption test and decided to last for about the same period of time as the latter due to the problematic nature of the specimens. The aim of the test was to record the height that salts could reach at a specific period of time.

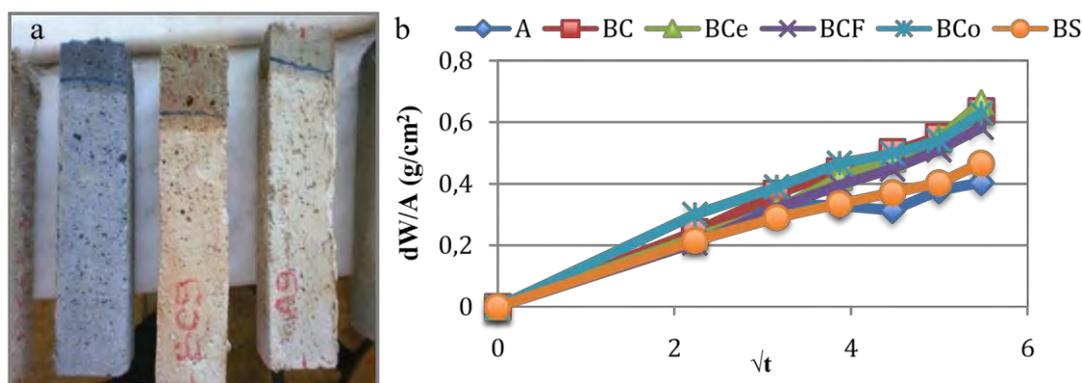


Figure 2a,b: Specimens testing the salt absorption (a), test results (b).

The solution used was 1.5% w/w NaCl and after the test the specimens were analyzed in order to specify the amount of salt absorbed by each of the samples on the surface that was in contact with the solution, the upper limit area observed macroscopically and the center of each prismatic specimen (Fig.2a,b). After the completion of the test the structure of the samples suffered low material losses. The results of the amount of Cl⁻ gathered after the samples dried, are presented at the table below (Table3). As expected, the highest amount of chloride ion absorbed was at the surface of the samples in contact with the solution and it was diminishing towards the center. However, it can be noticed that while all samples present a low Cl⁻ uptake at their center area, the BC sample shows a higher amount of absorption, while being the second one with the highest amount of total absorption of the NaCl solution. This fact can be explained by the interconnectivity of the pore systems and perhaps the cannabis and cellulose fibers assisted towards the uptake of the salt solution. Moreover, the BCo sample is observed to have the lowest amount of chlorides absorbed followed by the BCF and BS samples. Additionally, in Table3 is presented the max-

imum height reached of the salt solution absorbed from the surface of the specimen in contact with the salt solution towards the center of the specimen. It is observed that the amount of the salt solution absorbed is not in terms with the height reached inside the samples. Worth noticing is the fact that the specimen with the highest value of maximum height reached was the BCo sample, while the untreated sample A presented the second higher amount.

Samples	Surface	Limit	Center	Height max (mm)
A	0.36	0.17	0.02	35.20
BC	0.59	0.27	0.14	33.97
BCe	0.52	0.23	0.03	34.87
BCF	0.61	0.11	0.02	31.37
BCo	0.42	0.10	0.01	37.77
BS	0.62	0.11	0.02	27.62

Table 3: Chloride ion (Cl⁻) content absorbed (%w/w) of the specimens.

Besides the physical properties tested the mechanical properties of the samples were examined as well. Compressive and flexural strength tests were conducted after the completion of 28 days. The results presented in Table4 and Fig.3 show that as far as the compressive strength is concerned the BS and BCo samples are the ones closest to the values of the reference one, while the BCF sample followed by the BC sample possess the highest values of compressive strength. However, the contrary applies for the flexural strength of the BCF sample, since it is observed to possess the lowest value of all the samples. The recorded values were taken from three samples for each case and in Table4 the mean values are presented. Also, the Standard Deviation for flexure is presented at Table4.

The elasticity modulus is also relatively low compared with the one of the sample A. The amount of water used for the production of the mortars, as shown in Table1, is high in the mixtures with fibres and should explain the reduced strength [4-6]. Additionally, the amount of water used for the BCo samples was the same as the one of the reference and as depicted in Fig.3 the flexural strength is by approximately 7% higher than that of the sample A, while the compressive strength is 25% lower than the value of the reference sample. The high value of the flexural strength of the BCo sample could be caused by the great length of the fibers inside the clay mass [6]. Moreover, it is observed that the BC values bare the best results compared with the values of the other samples.

Samples	σ (MPa)	E_c (GPa)	f_{stm} (MPa)	SDTV
A	0.62	3.82	0.38	0.03
BC	0.76	0.98	0.63	0.01
BCe	0.46	0.65	0.41	0.01
BCF	0.82	1.04	0.19	0.04
BCo	0.60	2.70	0.57	0.05
BS	0.63	1.83	0.41	0.02

Table 4: Compressive, flexural strength and Young's modulus of the specimens.

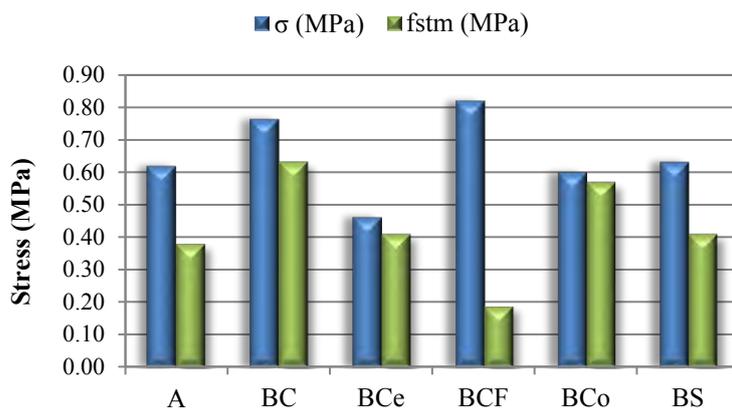


Figure 3: Compressive and flexural strength of the specimens.

The shrinkage of the samples was recorded in order to determine the volume loss of the samples. The specimens were preserved at a chamber of constant conditions of temperature and humidity ($20^{\circ}\text{C} \pm 2$ & 65% RH) and the values of the volume loss were recorded every day for a total period of five months. The results in Fig.4 indicate that the BCo sample has the highest volume loss compared to all the others samples equal to 7.56% perhaps due to the great length of the fibers that did not allow the proper mixture of the clay mass. Additionally, the great loss of water of the BCo sample could be explained due to the great amount of water needed during its production that caused that effect later on. The BCF shows the lowest percentage of volume loss equal to 4.45%. It is significant to mention that all the other samples present lower volume loss than the reference sample, fact that indicates that fibers played a beneficial role to the stabilization of the clay mass.

Through the optical observation of color change using Munsell charts, it should be noted that the color of the specimens was not affected by the use of bio-fibers or the cellulose nano-fiber, yet it was particularly affected in the case of carbon fibers, as it is shown in Table5, that led to a gray color of the samples.

From the stereoscopic observation of the samples, as shown in Fig. 5, it is reported that the similar behavior of sample BS with the reference specimen is due to the low amount of straw added inside the clay mass, yet the agitation is proven to be satisfactory, due to the uniform distribution in the structure. In case of BC sample the best allocation of fibers is observed, that justifies the high values given from the compressive and flexural strength test. In the case of BCe sample, on the other hand, the cellulosic fibers could not be detected inside the clay mass, due to their small size. The BCF specimen showed a great integration with the clay mass, that probably explains the high value of compressive strength, yet many shrinkage cracks were detected. The BCo sample showed loose contact between the fibers and the mortar and quite a few shrinkage cracks in the structure, having nevertheless a relatively good distribution of the fibers. In sample A shrinkage cracks were detected and good aggregate adhesion with the binder.

In an effort to record the behavior of the fibers in clay mortars Table 6 derives. It seems that almost all fibers require a water excess in order to make a workable mixture. Thus the evaporation of water provokes problems such as porosity shrinkage and strength loss. Nevertheless, carbon nano-fibers seem to strengthen the structure while keeping the porosity and the salt uptake relatively low. The color change is significant and only in specific cases they could be proposed.

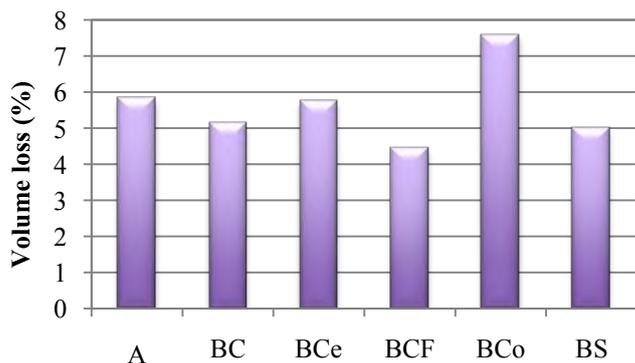


Figure 4: Volume loss of the specimens.

Samples	Hue	Value	Chroma	Name
A	5Y	8	1	White
BC	5Y	8	1	White
BCe	5Y	8	1	White
BCF	5Y	7	1	Light gray
BCo	5Y	8	1	White
BS	5Y	8	1	White

Table 5: Optical observation of color change using Munsell charts.

Samples	Absorption	Porosity	Shrinkage	σ	f _{stm}
A	++	++	--	+	--
BC	--	-	+	+	++
BCe	+	+	+	--	+
BCF	-	+	++	++	---
BCo	--	-	---	-	++
BS	++	+	++	+	+

Table 6: Effect of fibers in various factors: +: positive effect, ++: very positive, +++:extremely positive, -: negative effect, --: very negative, ---:extremely negative

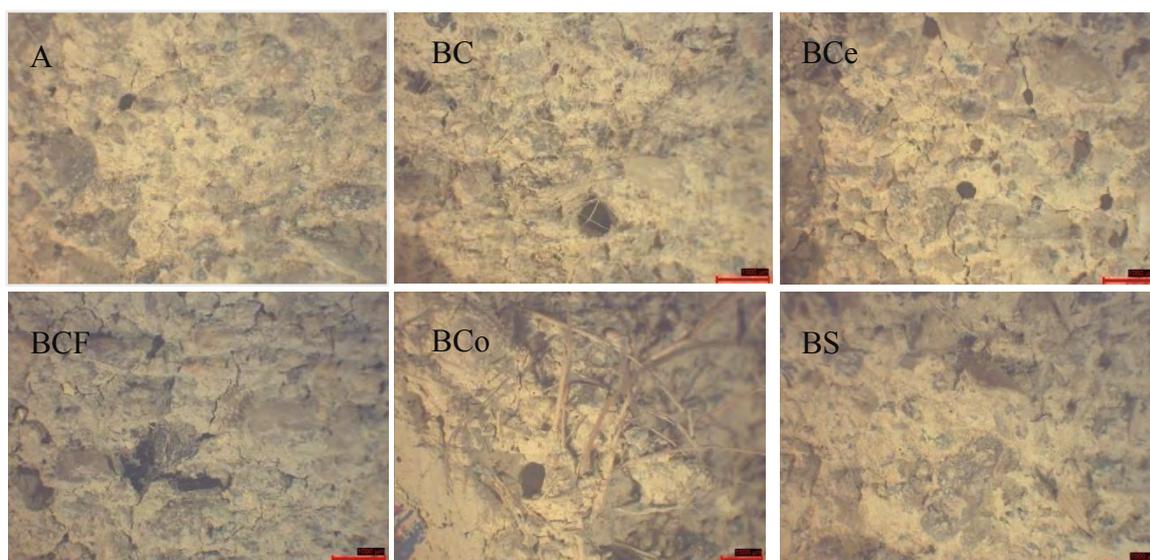


Figure 5: Stereoscopic images of the various specimens (scale-1000µm).

CONCLUSIONS

Studying the role of bio and nano fibers in clay mortars it seems that most of them are highly hydrophilic and require a high quantity of water in order to achieve the desired workability. Additionally, their size seems to affect some of their mechanical and physical properties. In particular, straw specimens present similar properties to the reference sample as their adhesion was satisfactory and they were dispersed in the matrix. Coconut fibers present poor adhesion to the matrix and as a result cracks were formed around them. Thus, porosity and absorption were high, the shrinkage was also high and the compressive strength was low. On the contrary, due to their length they contributed positively to the flexural strength. Cannabis on the other hand, had a positive role in relation to the strength probably due to its size and its homogeneous distribution in the matrix.

Carbon nano-fibres altered the color of the mortars. Nevertheless, they increased the compaction of the matrix and retained the porosity and capillary absorption to low levels. Moreover, the compressive strength was significantly increased and the shrinkage tendency was limited. Nano-cellulose was dispersed in the matrix and could not be observed under common microscope. The properties recorded were not encouraging in relation to the strength and physical properties.

The shape and size of fibers have a significant role especially in relation to the adhesion with the binder. Bio-fibres have a higher tendency to absorb water so their hydrophobic elaboration before used, could be a solution to this problem. The percentage of 1.5%w/w of binders was selected in accordance to the analysis of old clay –based mortars but a different percentage can also be tested keeping in mind the restrictions owned to their nature. Nano-fibres and specifically carbon fibers, had a positive effect especially on the mechanical properties of the samples and they also assisted towards denser structure.

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RELIABILITY MONITORING OF THE RAINWATER DISPOSAL SYSTEM FOR HISTORIC BUILDINGS

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KEYWORDS

Historic Building, Rainwater Disposal System, Reliability, Functional Performance, Durability

ABSTRACT

Within the framework of the CHANGES-project, maintenance practices in the Meche-len urban region are studied based on eleven case studies. The CHANGES-project is a European research project within the framework of the JPI Cultural Heritage. For the Flemish partners, the project's main aims are amongst others to identify maintenance practices and to study their efficacy and the technical quality of executed interventions. This paper focuses on developing a method of analysis for evaluating the reliability of historic buildings' rainwater disposal systems.

The aspects that determine the reliability of a historic buildings' rainwater disposal system were identified based on a case study. The analysis does not consider the importance of the sustainability of the conservation process itself, which together with the rainwater disposal system's reliability defines its quality. The developed method is validated within the CHANGES-project through its application in a larger set of case studies.

The reliability monitoring approach, described in this paper for one case, will allow to understand and evaluate the efficacy of maintenance practices. Furthermore, it analyses the functioning of the historic houses' rainwater disposal system at a conceptual level, which is an added value for the implementation of preventive conservation systems, for future research on the quality of interventions, and for the development of tools and practical implementation of quality management systems in heritage preservation.

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INTRODUCTION

The main goal of the research on maintenance practices that is carried out within the CHANGES-project is to identify maintenance practices and to study their efficacy and the technical quality of the executed interventions. The technical focus in the case study assessments is on the roof's rainwater disposal system, which consists of the roofing as part of the building envelope and the gutters and drainpipes. The research is carried out in collaboration with *Monumentenwacht Flanders (MoWa)*. This organisation comprises five provincial organisations that assist owners with regular condition assessment and technical advice for the management of their buildings, and one umbrella organisation that oversees the uniformity and quality of the provincial services and generates awareness among the owners for the importance of maintenance [1].

The aim of this study was to put forward an approach to evaluate the quality management of a building's rainwater disposal system. This fits within a broader research objective to identify and evaluate the technical quality of interventions on historic buildings. The two concepts that determine the rainwater disposal system's quality are briefly identified in the first part of the paper. The focus of this paper is on the second aspect, namely the system's reliability monitoring. The definition of reliability and the aspects determining the reliability of the rainwater disposal system are identified based on a case study in the second part of the paper. This paper focuses on developing a method for reliability monitoring, but does not go into detail on the levels of reliability that are acceptable for heritage buildings. These levels are being determined based on the validation of the case studies within the CHANGES-project and are therefore part of ongoing research.

THE QUALITY MANAGEMENT OF A BUILDING'S RAINWATER DISPOSAL SYSTEM

In order to investigate the rainwater disposal system's quality management, its concepts were set out based on a study of existing quality management approaches. The major theoretical developments in defining quality date back to the 1980s. One of its main authors is Garvin, who gave a clear overview of the different disciplines that covered the issue of quality in academic literature: philosophy, economics, marketing and operations management [2]. According to these approaches, quality can be determined as an intrinsic and extrinsic property of a product, as well as the efficiency of a process. Accordingly, quality is related to an aim, or to a process. The quality management of the drainage system can therefore be verified based on two assessments: (1) a quality assessment of the technical aim of the conservation process, namely the functional reliability of the system, and (2) a quality assessment of the conservation process itself. This study will focus on the first assessment, which is achieved through a reliability monitoring.

THE RAINWATER DISPOSAL SYSTEM'S FUNCTIONAL RELIABILITY

A roof's rainwater disposal system consists of two main components: the roofing and the system of gutters and drainpipes [3-5]. The roofing is part of the building's envelope and it deals with rainwater through deflection, absorption and transmission. Good envelopes deflect as much rainwater as possible, which is then collected and channelled away in gutters and drainpipes [6]. The management of the roof's rainwater disposal system should be based on a 'holistic understanding of the performance', rather than an assessment of the individual components [4]. The aim of this section is therefore to identify the aspects

contributing to the functioning of the rainwater disposal system, as a means to assess its quality in a holistic manner by means of reliability monitoring.

Kapur and Pecht defined the reliability of a system in engineering as “the ability to perform as intended for a specific time, in its life cycle conditions” [7]. McGeorge and Palmer defined the reliability of a building as “the probability a building or its components will not fail within a specific period of time” [8]. These definitions assign two aspects to the reliability of a system: on the one hand, the correct functioning of the system, and on the other hand, the functioning for a specific time, under the influence of environmental conditions. If these insights are applied for a historic building’s rainwater disposal system, then this implies that the system’s functional reliability should be assessed based on the analyses of its functional performance and its durability.

IDENTIFICATION OF THE PARAMETERS DEFINING THE SYSTEM’S RELIABILITY: CASE STUDY

The parameters defining the rainwater disposal’s reliability will hereafter be identified based on a case study: a 19th century historic urban dwelling with medieval core. The available source data are five inspection reports of Monumentenwacht (inspection reports of 2001, 2004, 2009, 2011 and 2015) and the technical documentation provided by the owner. The building has two saddle roofs, positioned perpendicular to each other. The roof plan in Figure 1 displays the two roofs with respective roof surfaces and gutters. Both roofs have a roof covering in ceramic tiles, roof [1] has a pitch of 50° and roof [2] has a pitch of 60°. Both roofs have eaves gutters (GU 1, GU 2, GU 6) that are lined with zinc. Valley gutters (GU 3, GU 4) are positioned at the connection between the roof surfaces of Roof [1] and Roof [2].



Figure 1: (1) Roof Plan, based on report Monumentenwacht, (2) Eaves gutter GU 1, (3) Eaves gutter GU 6, (4) Valley gutter GU 3, all pictures by Monumentenwacht

THE FUNCTIONAL PERFORMANCE OF THE RAINWATER DISPOSAL SYSTEM

As indicated before, the rainwater disposal system consists of the roofing and the system of gutters and drainpipes. The roofing’s main function is to protect the building’s interior from moisture penetration [3-5, 9]. Both the roofing and the gutters and drainpipes are designed to reliably convey the rainwater away from the building [4, 9]. It can therefore be concluded that the functional performance of the building’s rainwater disposal system is determined by the system’s ability to reliably drain the rainwater away from the building and avoid moisture penetration.

The simplest approach to rain disposal is a roof with projecting eaves, which is a system that can still be found for some rural dwellings, since it requires sufficient open space and surrounding grounds that absorb the water. Most buildings are equipped with a system of gutters and downpipes for rainwater disposal [6]. These systems have the following six main components that determine the system's functioning: (1) roof, (2) connection roof – gutter, (3) gutter, (4) connection gutter – downpipe, (5) downpipe, (6) emergency overflow [6, 9, 10].

The European standard EN 12056-3 allows to design the gutters and downpipes based on the expected local rain intensity levels [10]. Two sets can be used for the expected rain intensity levels. A first set is based on the most recent design rainfall statistics, which are represented in the intensity-duration-frequency (IDF) statistics. For Flanders, historic rainfall series allow determining the expected rain intensities for different durations and frequencies of occurrence (2 years, 5 years, and 20 years) in [11]. A second set takes into account the current knowledge on future climate change trends till 2100 [12]. Based on the rain intensities (I/s), the required dimensions of the gutters (Cross-sectional area of gutter A_E , Width at sole S , width at designed water line T , depth below designed water line W) and drainpipes (Internal diameter d_i) can be determined with the formulas given in EN 12056-3. Calculations are based on short intense rainfall in summer period, since the gutters are a fast responding system. Based on historic rainfall series, the expected rain intensity level for short intense rainfall (10 minutes) with a frequency of occurrence of 20 years is **0.0312 l/(s*m²)**. For a high summer climate change scenario with frequency of occurrence of 1000 years, the expected rain intensity level in 2100 is 2.02 times higher, so **0.063 l/(s*m²)**. For a mean climate change scenario with frequency of occurrence of 1000 years, the expected rain intensity level in 2100 is 1.15 times higher, so **0.036 l/(s*m²)**. These design formulas allow to evaluate for which rain intensity levels the existing system can reliably dispose the rainwater.

Existing manual for the design of roofs, gutters and downpipes [3, 6, 9] allow furthermore to establish a number of additional technical characteristics that influence the reliable disposal of rainwater. The pitch of the roof and the position of the gutter in relation to the eaves are two important technical characteristics that enable rainwater to discharge into the gutters so that water does not overshoot the front edge of the gutter [9]. For slates and tiles, the element size and headlap are determined by the roof pitch. The slope of the gutter enables water to be channelled towards the downpipes due to the forces of gravity [6], while an adequate transverse fall of the gutter will avoid infiltrations [9]. A sufficient number of expansion joints allow thermal movement effects for metals, while the presence of outlet gratings will prevent blockages [9]. Downpipes run ideally straight from the gutters to the ground, since bends or vertical deflections are potential sites for blockages [6].

Table 1 introduces the five main components and the most relevant technical characteristics.

Components	Technical characteristics
1) Roof	effective roof area A , roof pitch, for slates and tiles: element size and headlap
2) Connection roof – gutter	position of gutter
3) Gutter	Cross-sectional area of gutter A_E , Width at sole S , width at designed water line T , depth below designed water line W , slope of gutter, fall of gutter, distance between expansion joints (in case of metal)
4) Connection gutter – downpipe	Diameter gutter outlet, head of outlet h , presence of outlet grating
5) Downpipe	Internal diameter d_i , vertical deflection downpipe
6) Emergency overflow	Diameter, position, length

Table 1: The six main components for the disposing of rainwater for the roof and their main technical characteristics [6, 9, 10].

Based on these technical characteristics, a technical qualitative evaluation can be done of the intensities of rainwater that can be reliably disposed with the existing system. For the investigated case study, the dimensions of gutters GU 1, GU 2 and GU 6 could be derived from the building's restoration plans of 1985. No data was found for the other gutters. The derived dimensions are furthermore inaccurate due to the quality and scale of the plans. In order to have accurate insights in the main technical characteristics of the rainwater disposal system, it would be necessary to perform an on-site geometrical survey. The gutters are not always easily accessible, so this is a liability for the practical implementation of the method for other cases.

Not all the rainwater will be deflected with the rainwater disposal system. Some parts will be absorbed by the materials and even transmitted in case of moisture infiltration. The chances of absorption of rain water and moisture infiltrations rise when the condition of the elements, materials and connections decreases. This means that the functional performance of the rainwater disposal system will change in time as a function of the condition of the elements, connections and materials.

THE DURABILITY OF THE RAINWATER DISPOSAL SYSTEM

The rainwater disposal system's durability is defined as the system's resistance to existing environmental conditions. The system can deteriorate due to inherent problems, environmental problems, inappropriate treatment and neglect, and damage from unforeseen events. Inherent problems are problems that are inherent in the system itself, such as the use of poor quality and inadequate materials, inappropriate design and detailing, and poor workmanship. Environmental problems are rainfall, strong winds, and temperature fluctuations. Inappropriate treatments entail those treatments that cause problems due to incompatibility, such as the use of a strong cement-based mortar for connections with ceramic tiles, or an inappropriate combination of metals causing galvanic corrosion [3]. The durability of the rainwater disposal system is therefore determined by the durability of the applied materials and connections, as well as the technical compatibility between them.

Hereafter, durability issues related to the gutters and roofing materials are discussed for the case study, as a means to better identify these concepts and their practical application.

Regarding the gutters, the reports of Monumentenwacht and the consulted technical documentation demonstrate a shift in the choice of materials after the listing in 2005. Whereas the inner gutters were executed in asphalt during the restoration of 1985, they were replaced with new zinc gutters in 2014. The owner indicated that funding is only granted

when works are done with durable materials. She seemed to be more attentive to these aspects ever since the listing of the building in 2005.



Figure 2: Left: gutters in asphalt, 2011. Right: new gutters in zinc, 2015. Pictures by Monumentenwacht

Concerning the resistance of these materials to weathering influences, today's practice indicates based on experience that zinc is a more durable material than asphalt. For gutters it is generally acknowledged that lead and copper have an excellent resistance in most environments [13]. Zinc has a lower life expectancy than that of the other non-ferrous metals [13]. Asphalt is vulnerable to thermal fluctuations and small cracks due to mechanical damage will cause the asphalt to blister and crack [3].

Regarding the roofing materials, the case study demonstrates durability issues related to the connections between the ceramic tiles. Figure 3 gives three examples of non-durable connections for this case study. The first picture on the left illustrates the consequences of an inappropriate execution. Since the final tile lath was not placed, the lowest row of tiles started shifting, which led to a lack of connection with the upper row and to infiltrations. The second picture in the centre illustrates a repair of a connection between the tiles with building foam. The third picture on the right illustrates the application of a hard mortar at the connection between roof surfaces, which has led to cracks, loss of connection and infiltrations.



Figure 3: Left: lack of tile lath, resulting in shifted tiles, Centre: repair of connection with building foam, Right: hard mortar at connection between tiles, resulting in cracks and loss of connection. Pictures of case study by Monumentenwacht

Based on these examples, it could be concluded that there are four aspects influencing the durability of the rainwater disposal system: the choice of materials, the design and execution of details and connections, workmanship, and the compatibility between materials.

DISCUSSION AND FUTURE RESEARCH

The reliability of a historic building's rainwater disposal system was defined as the system's ability to perform as intended within a specific period of time. Therefore, it depends on its functional performance and durability. The functional performance was determined at a given point in time based on the seventeen technical characteristics that are listed for its five main components in Table 1. A good performance obtained when as much rainwater as possible is collected and channelled away in gutters and drainpipes. Not all the rainwater will be deflected, since some parts will be absorbed by the materials and even transmitted in case of moisture infiltrations. The performance will therefore change in time as a function of the condition of the elements, materials and connections. The rate at which it will change depends on the durability of the system and the environmental conditions. As was illustrated based on the examples in the case study, the durability depends on the choice of materials, the design and execution of details and connections, workmanship, and the compatibility between materials.

Future research consists in setting out the relationship between the rainwater disposal system's reliability, functional performance, condition, and durability based on the statistical analysis of a representative set of case studies.

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USE OF NANOMATERIALS FOR THE PROTECTION OF HISTORIC STONE ARCHITECTURE: LABORATORY METHODS FOR THE EVALUATION AND INVESTIGATION OF PHOTOCATALYTIC ACTIVITY

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KEYWORDS

Nano-TiO₂, Nanocomposites, Stone Protection, Photocatalysis, Self-Cleaning

ABSTRACT

The use of nanomaterials in the conservation of natural and artificial stone materials has been an active research topic over the last fifteen years, showing a potential for tackling different aspects of conservation, from consolidation of de-cohesionated substrates to hydrofobation and protection against chemical and biological decay agents.

Currently, the NanoCathedral H2020 project is aimed at developing a systematic approach to the use of TiO₂-based nanomaterials for stone protection, by evaluating the performance of an array of innovative products for the treatment of a set of lithotypes posing different challenges in terms of conservation.

The products set up in the frame of the NanoCathedral project are nanocomposites relying on the combination of different TiO₂ nanoparticles with a variety of silane/siloxane matrixes. As such, they are expected to provide the treated stone with self-cleaning photocatalytic behaviour and water-repellent properties.

As it is well known, no standard protocol exists to-date for the evaluation of photocatalytic activity on stone substrates. The existing methods, i.e. the organic colourant discolouration and the NO_x degradation tests, suffer from a number of drawbacks, that include issues of reproducibility in the case of the organic colourant discolouration test, and high operational costs, in the case of the NO_x degradation test.

The aim of this paper is compare the two methods by considering their similarities/differences in terms of response. To this purpose, we discuss the photocatalytic performance of two nanocomposites on three different lithotypes. Then, an attempt is made to correlate the experimental values of photocatalytic activity with the properties of the selected lithotypes and their interaction with the considered nanomaterials.

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INTRODUCTION

Stone materials in outdoor architecture are naturally subjected to a host of decay phenomena, among which those related to the penetration of water are particularly relevant. Furthermore, in a polluted environment, as the one offered by most present-day urban areas, natural agents of decay combine with anthropogenic ones, not only represented by carbonaceous particulate matter but also by inorganic gaseous pollutants like sulphur dioxide and nitric oxides, thus making up a synergistic action [1-2].

Strategies for stone protection have become increasingly concerned with tackling these different sources of decay through a multi-functional approach: reducing water penetration on one side and the soiling and corrosion from air-borne pollutants on the other.

Over the last 25 years, photocatalysis has been regarded as a very powerful tool by environmental science, thanks to its potentialities in the fast oxidative degradation of organic pollutants [3]. Photoactive nanomaterials, especially TiO₂ nanoparticles, have also been applied in the manufacturing of building materials, such as cement [4]; more recently, their use in the field of natural stone protection has met encouraging results, also thanks to the good aesthetic compatibility of these products with stone substrates [5]. An improvement in some of the properties of these materials has been achieved through the development of nanocomposites, i.e. nanostructured materials relying on the combination of two or more components, in this case TiO₂ or ZnO nanoparticles and a polymer matrix of silanic or acrylic nature [6-7]. These composite materials show better adhesion to the stone substrates with respect to nanoparticle dispersions and display hydrophobic features combined with a self-cleaning photocatalytic action.

For the characterization of photoactive materials, it is of great importance to have a reliable method for the measurement of photocatalytic activity. As far as stone protection is concerned, such measurements are currently performed through the organic colourant discolouration [8-13] and the NO_x degradation tests [8, 11-12, 14-16]. The latter monitors the degradation of nitric oxide (NO) through the intermediate nitrogen dioxide (NO₂) onwards to nitrate ion (NO₃⁻) as a result of UV irradiation. Similarly, the discolouration test involves depositing a given amount of colourant solution, generally Rhodamine B or Methylene blue, on a treated stone specimen and visually monitoring its degradation at various time intervals while irradiating the specimen by means of a UV/Vis light source. Colourimetric measurements are usually employed for the monitoring.

However, there are a number of drawbacks to these tests. Firstly, the reliability of the measurements can be an issue when dealing with substrates with high surface roughness like natural stone materials, since results strongly depend on the amount of treatment on the surface and its coverage. Then, as far as the NO_x degradation test is concerned, the high cost of the required apparatus sets a limit to the applicability of the test. Finally, regarding the discolouration test, it is difficult to achieve a homogeneous deposition of a water-based colourant solution on a surface with hydrophobic features.

A more detailed knowledge of the factors underlying the measurement of photocatalytic activity, both in terms of substrate variability and test procedure, may thus help to understand the inherent limits of the tests, clarify the differences between them and also contribute to a correct interpretation of results.

In this work, we try to account for these factors by considering three lithotypes of different porosity (open porosity) and two different nanocomposites that are presently under study in the framework of the Nano-Cathedral project (European Project H2020 G.A. n.646178).

We start by discussing the results of the NO_x degradation test in the light of available information on lithotype porosity and of data on the amount of absorbed treatment (§ 3.1).

Then, concerning the organic colourant discolouration test, an adjusted test procedure is adopted with the aim of reducing the variability from the deposition of colourant solution (§ 2.5 and § 3.2). The results are finally discussed and compared with those of the NO_x degradation test (§ 3.2).

MATERIALS AND METHODS

2.1. Products

The two nanocomposites, hereafter referred to as TSA and TSW, consist of TiO₂ nanoparticles embedded in alkyl alkoxy silane matrices, hence they are expected to display water-repellent as well as photocatalytic properties.

2.2. Lithotypes

The stone specimens (2.5x2.5x2 and 5x5x1 cm³ blocks) belong to three different lithotypes: Balegem limestone, Apuan marble and Obernkirchen sandstone. Balegem limestone is a stone from the Ghent region (Belgium), quite compact in texture despite featuring many millimetre-sized cavities. Its open porosity amounts to 8±1 %vol [17] and on a mineralogical level it is composed of siliceous clastic arenite (40.1% quartz and 4.9% feldspars) with sparitic cementation (53.1% calcite). Apuan marble (from Carrara region, Italy) is almost purely made up of calcite (99.6%) and its open porosity is very low, around 0.2 %vol [18]. Obernkirchen sandstone is a fine-grained and porous stone (16-21 %vol, [19]) coming from lower Saxony (Germany), and its composition includes quartz (89.6%) and subordinately kaolinite (7.7%).

2.3. Treatments

Before undergoing any treatment, the specimens were gently polished with abrasive paper (P180 carborundum paper), kept in deionized water for an hour in order to remove soluble salts, dried in oven for 24 hours at 50 °C and finally stored in a silica gel desiccator at 55% RH. The nanocomposites were applied by capillary absorption according to EN16581:2014 for 6 hours. In order to determine the amount of dry matter absorbed, all specimens were weighed before the treatment and then after solvent evaporation until constant weight was achieved (a minimum of 48 hours). Four 5x5x1 cm³ specimens per each lithotype and treatment were prepared for the NO_x degradation test. In addition, four specimens treated with Silres BS290 (Wacker) were chosen as blank for each lithotype. Three 2.5x2.5x2 cm³ specimens (named A, B and C) per each lithotype and treatment were prepared for the organic colourant discolouration test. For each lithotype three untreated specimens were also chosen as reference. The values of dry matter absorbed per unit area are reported in Table 1. For 5x5x1 cm³ specimens, only average values calculated from four specimens per lithotype and treatment are reported (named D).

specimen	BALEGEM		APUAN MARBLE		OBERNKIRCHEN	
	TSW	TSA	TSW	TSA	TSW	TSA
A	0.0044	0.0133	0.0002	0.0006	0.0082	0.0198
B	0.0039	0.0056	<0.0001	0.0003	0.0058	0.0169
C	0.0075	0.0058	0.0001	0.0005	0.0064	0.0120
D	0.005	0.007	0.001	0.007	0.004	0.021

Table 1: values of dry matter per unit area (g/cm²) absorbed by the specimens treated with TSW and TSA.

2.4. NO_x degradation test

The degradation of nitrogen oxides NO_x (NO_x=NO+NO₂) was monitored for 100 minutes in a photoreactor (Colorobbia Consulting S.r.l.) equipped with an Ultravitalux Osram lamp (50 W/m² irradiance) and a chemiluminescence-based detection system. The analysis was conducted by mixing dry air, moist air and NO in such proportions as to obtain a 500±50 ppbv NO concentration and an atmosphere having 41±1 % RH at the temperature of 25±2 °C. Six samplings were performed every 20 minutes during the test, each with a duration of 5 minutes. The values (%) of NO_x degradation for TSW and TSA at 0, 40 and 100 minutes were calculated through the formula

$$\frac{C_0(\text{NO}_x) - C_t(\text{NO}_x)}{C_0(\text{NO}_x)} \cdot 100$$

where C₀ (NO_x) [=C₀ (NO)] is the initial NO_x concentration and C_t (NO_x) [=C_t (NO)+C_t (NO₂)] is the NO_x concentration at time t.

2.5. Organic colourant discolouration test

Before starting the test 10 colour measurements were performed on each specimen through a Konica Minolta CM-600D Vis reflectance spectrophotometer. Then, a 0.05 g/L Rhodamine B solution was prepared by mixing ethanol and water in 7:3 ratio. The addition of ethanol helped to achieve a homogeneous deposition of the colourant. This choice was made after checking by a preliminary test that no significant difference in the value of photocatalytic activity arises from the presence of ethanol with respect to a purely water-based solution. 500 µL of colourant were deposited on each specimen by using a pipette. Then, the specimens were allowed to dry at room temperature for 72 hours, while being kept away from light sources. Finally, they were irradiated for 150 minutes in a solar box (Suntest XLS⁺, URAI S.p.A) equipped with a Xenon arc lamp (cut-off filter for λ<295 nm, 765 W/m² irradiance). The temperature on the surface of the specimens was kept at 65±2 °C throughout the irradiation. Colour measurements (10 measurements per specimen) were performed at 0, 30, 90 and 150 minutes during the test in order to monitor colour change. For the assessment of photocatalytic activity the a* value from each measurement was considered, which represents the red colour component in the CIE Lab colour space. The extent of discolouration (D*) was then evaluated according to the formula

$$D^*(\%) = \frac{a^*(t) - a^*(0)}{a^*(ns) - a^*(0)} \cdot 100$$

where a*(t) and a*(0) stand for the a* value at time t and 0, respectively, while a*(ns) refers to the specimen before the deposition of the Rhodamine solution. In order to take into account the contribution of photolytic and thermal degradation of Rhodamine as distinct from the photocatalytic process itself, D* values for treated specimens (D*_t) at 150 minutes were divided by the corresponding values of untreated lithotypes (D*_{nt}) and will be reported as parameter for the evaluation of photocatalytic activity.

Three repetitions of the test were performed on different specimens (A, B and C). In each test, the standard deviation of a* values (σ a*) of each specimen (resulting from 10 measurements) at the beginning of the test was considered as an indication of the inherent variability of specimen surfaces.

RESULTS AND DISCUSSION

3.1. NO_x degradation test

In Figure 1 the variation of NO, NO₂ and NO_x (=NO+NO₂) concentrations for TSW, TSA and Silres BS290 during the degradation test is shown. The values (%) of NO_x degradation for TSW and TSA at 0, 40 and 100 minutes are reported in Table 2.

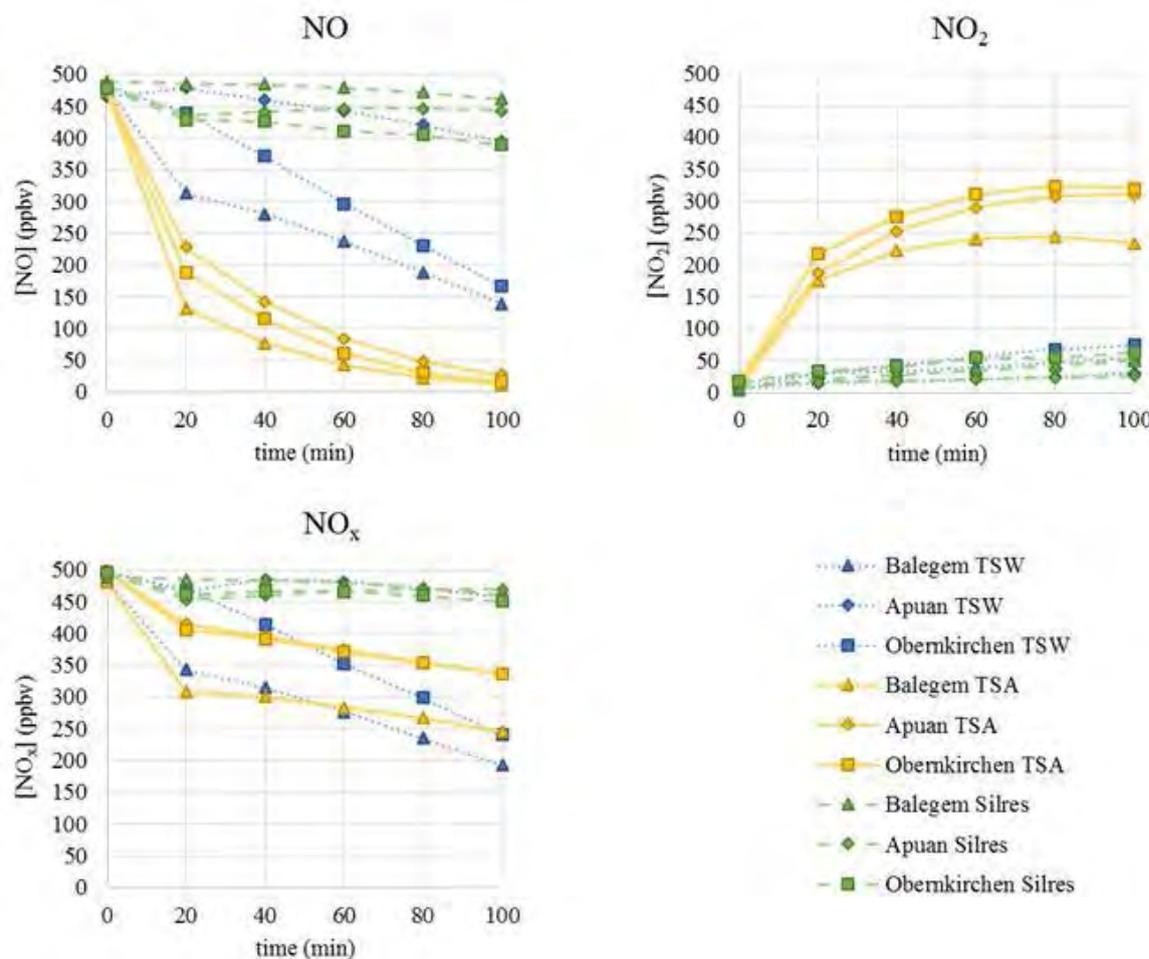


Figure 1: time variation of NO, NO₂ and NO_x concentrations for TSW (···), TSA (—) and Silres BS290 (---) during the degradation test on Balegem stone (▲), Apuan marble (◆) and Obernkirchen stone (■).

time (min)	BALEGEM		APUAN MARBLE		OBERNKIRCHEN	
	TSW	TSA	TSW	TSA	TSW	TSA
0	0	0	0	0	0	0
40	35	38	3	20	16	21
100	60	49	8	32	52	32

Table 2: values (%) of NO_x degradation at 0, 40 and 100 minutes for TSW and TSA.

These results indicate that the two nanocomposite products are both photoactive, but display rather different behaviours. From the graphs (Figure 1), it is clear that:

1. the kinetics of TSA in the first reaction step, i.e. NO degradation, is much faster than in the second NO₂ degradation step. This leads to a rapid increase in NO₂ concentration and negatively affects the overall photocatalytic performance, which is evaluated from

the total, cumulative NO_x degradation;

2. in spite of a lower rate of NO degradation, TSW exhibits comparable rates in the first and second steps, so that only a minor NO₂ increase results and overall a better photocatalytic performance is observed.

Moreover, from an inspection of Table 2, it is clear that a difference between lithotypes also exists:

1. both products yield the best performance on Balegem stone and show less brilliant but still consistent behaviour on Obernkirchen stone;
2. the results from Apuan marble look puzzling: unlike the case of Balegem and Obernkirchen stones, TSW shows almost no activity, whereas the performance of TSA is comparable to that measured on the other two lithotypes;
3. the values of dry matter absorbed by the specimens (see specimens D in Table 1) show that, as compared to TSW, TSA is absorbed to a greater extent. This behaviour is more pronounced on Obernkirchen stone and Apuan marble, while in the case of Balegem stone the two products behave more similarly.

3.2. Organic colourant discolouration test

In Table 3 are reported the D^*_t/D^*_{nt} values at 150 minutes obtained from the three tests A, B and C and in Table 4 the resulting average values.

		BALEGEM		APUAN MARBLE		OBERNKIRCHEN	
		TSW	TSA	TSW	TSA	TSW	TSA
Test A	D^*_t/D^*_{nt} 150 min	1.0	1.2	1.6	1.2	1.1	0.88
	$\sigma a^*(ns)$	0.4	0.2	0.04	0.06	0.9	0.2
	$\sigma a^*(0)$	0.7	2	7	5	0.4	1
Test B	D^*_t/D^*_{nt} 150 min	1.5	1.4	1.1	0.9	1.4	0.90
	$\sigma a^*(ns)$	0.78	0.94	0.09	0.03	0.1	0.2
	$\sigma a^*(0)$	3	2	3	2	0.5	1
Test C	D^*_t/D^*_{nt} 150 min	1.2	1.4	1.2	0.8	1.5	0.89
	$\sigma a^*(ns)$	0.2	0.3	0.04	0.04	0.1	0.2
	$\sigma a^*(0)$	1	1	4	2	0.7	0.6

Table 3: D^*_t/D^*_{nt} values at 150 minutes in the tests A, B and C, standard deviations of a^* values (σa^*) from 10 colour measurements (before Rhodamine deposition and at time 0).

		BALEGEM		APUAN MARBLE		OBERNKIRCHEN	
		TSW	TSA	TSW	TSA	TSW	TSA
μ		1.2	1.3	1.3	1.0	1.3	0.89
σ		0.2	0.1	0.2	0.2	0.3	0.01
RSD (%)		17	8	15	20	23	1
av. dry matter (g/cm ²)		0.005	0.008	0.0002	0.0005	0.007	0.016
σ (g/cm ²)		0.002	0.004	0.0001	0.0002	0.001	0.004

Table 4: average D^*_t/D^*_{nt} values at 150 minutes (μ) from tests A, B and C, with standard deviation (σ) and relative standard deviation (RSD), and average dry matter per unit area absorbed by the specimens (A, B, C), with standard deviation σ (see Table 1 for values of dry matter absorbed by each specimen).

The results shown in Tables 3-4 indicate that:

1. the average value of photocatalytic activity, represented by D^*_t/D^*_{nt} values in Table 4, does not vary much from one lithotype to the other, with two notable exceptions. These are represented by TSA on Apuan marble and especially Obernkirchen stone, for which significantly lower D^*_t/D^*_{nt} values are observed;
2. among the two products, TSW shows an overall better photocatalytic performance, with similar average results on all lithotypes. TSA displays a more variable performance, ranging from results on Balegem stone comparable with those of TSA to negative performances on Apuan marble and Obernkirchen stone (Table 4);
3. the measurement of photocatalytic activity is affected by a marked variability between different specimens of each single lithotype, as indicated by high RSD values (Table 4);
4. considerable variability also exists in the amounts of dry matter absorbed by the specimens of each single lithotype (Table 1);
5. a direct correlation between these amounts and the photocatalytic activity of the corresponding specimens cannot be observed. Although it is evident that increasingly porous lithotypes (for data on lithotype porosity, see Materials and methods § 2.2) absorb greater amounts of product (Obernkirchen stone > Balegem stone > Apuan marble) and that TSA is absorbed in much greater amount than TSW by all lithotypes, it turns out that the amount of absorbed dry matter does not correlate with the value of D^*_t/D^*_{nt} ;
6. as far as the test procedure is concerned, it can be noticed (Table 3) that the standard deviations of a^* values at the beginning of the test $\sigma a^*(0)$ on Balegem and Obernkirchen stones are comparatively low, indicating that no serious issue of homogeneity in the deposition of Rhodamine solution occurs. In Apuan marble a certain inhomogeneity appears to be there, particularly in specimens treated with TSW, but this could be due to the fact that, on a compact surface as that of Apuan marble, TSW tends to accumulate in some areas of the surface, giving rise to an inhomogeneous distribution of the treatment and, consequently, of the colourant solution.

From the above said (in particular, from points 3, 4 and 6), it appears that the variability observed for each lithotype in the results of the organic colourant discolouration test is primarily a result of the inherent substrate variability rather than a limit of the test itself.

In this regard, a comparison between the results of the organic colourant discolouration and the NO_x degradation tests may suggest the following considerations:

1. for Balegem and Obernkirchen stones the two datasets are mutually consistent (see Table 2 and Tables 3-4): indeed, considering the two products as an ensemble, we may say that in both tests the best performance overall is achieved on Balegem stone (1.2 and 1.3, 60% and 49% for TSW and TSA, respectively). Then, the results of TSW on Obernkirchen stone in both tests are comparable with those on Balegem stone (1.3 and 1.2 vs. 52% and 60%), and the results of TSA are likewise consistent (0.89 and 1.3 vs. 32% and 49%);
2. on Apuan marble, the results from the two tests are in good agreement in the case of TSA, but totally divergent as regards the performance of TSW, for a good photocatalytic activity observed in the discolouration test corresponds to almost no activity in the NO_x degradation test. We have not yet come up with a thorough explanation of this phenomenon, but some observations can be made. Firstly, Apuan marble is a low porosity (0.2 %vol.) and low roughness stone and we know that the coverage and protection of such materials is much more critical than the protection of medium and high porosity substrates, because treatments find particularly difficult to penetrate and settle inside the

material. Among the two products we are dealing with, TSW shows in all cases a lower tendency to penetrate as compared to TSA. Furthermore, optical microscope observations on specimen surfaces clarified that in the case of marble TSW is not homogeneously distributed on the surface and it forms aggregates, whose specific surface area is likely very low. We then know that heterogeneous catalytic processes, as is the case of NO_x degradation, occur through a preliminary adsorption step that is all the more efficient if the catalyst displays a high specific surface area, so that a greater number of reactant molecules are able to interact with it. If this is not the case, the adsorption step proceeds at lower rate and the overall reaction rate is accordingly reduced [8]. These qualitative observations only take a pace towards explaining the difference observed between the two tests, but a dedicated investigation would be needed in order to clarify the matter.

It may therefore be concluded that the two tests seem to provide substantially comparable results on Balegem and Obernkirchen stones, most probably related to the high and medium porosities of these lithotypes, whereas the conflicting results observed on Apuan marble require a further investigation.

CONCLUSIONS

In this work, we compared two laboratory methods for the evaluation of photocatalytic activity, the NO_x degradation and the organic colourant discolouration tests, by considering three different lithotypes and two different nanocomposites.

The results of the two tests were discussed and their similarities/differences were highlighted. A good correlation was found between the tests on medium and high porosity substrates, so that we might say that the information provided by them appears to be equivalent. On the other hand, on a low porosity stone like Apuan marble the tests provide conflicting results, so that a complete evaluation of photocatalytic activity requires to perform both tests.

Concerning the discolouration test, we considered a multiplicity of factors that may have an effect on the photocatalytic activity and its variability. In particular, the test procedure itself, the influence of the different stone materials and of the different nanocomposites were taken into account. It emerged that the observed variability is primarily related to the intrinsic variability of stone substrates rather than the test procedure itself. Furthermore, an obvious correlation between stone porosity, the amount of dry matter absorbed and the photocatalytic activity could not be found, suggesting that the properties of stone specimens, in particular their pore-size distribution, the properties of nanocomposites, particularly the size of their components and the solvent, and their distribution on the stone surface should be considered.

The evaluation of the interaction between nanocomposites and lithotypes is under study and we are obtaining promising results from an innovative surface characterization technique based on streaming current measurements.

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HISTORIC WOODEN HOUSES OF ISTANBUL WITH THE INFLUENCE OF EUROPEAN STYLES

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KEYWORDS

Wooden Houses, Istanbul, European Influence, Turkish House

ABSTRACT

With its unique character, Turkish house occupies an important place in the Ottoman architectural heritage. This housing culture was developed throughout the centuries and broad variety was generated according to the location and belonged period of the houses. After the 18th century, traces of westernization started to be showed up on the housing architecture of Istanbul and between the late 19th century early 20th century, European influences on the timber residential heritage became intense. This presentation focuses on the architectural characteristics of the wooden houses from this last period of the Ottoman Empire. As the last Ottoman capital, Istanbul had a pluralist and cosmopolite feature, various different styles such as art nouveau, empire, baroque, Victorian, chalet, rococo, neo-classic, neo-Greek can be encountered in wooden houses. The effects of the European styles on the facades, roofs and plan scheme will be discussed in detail. In this context, a special emphasize will be put on the ornaments, decorations and the distinctness shaped by mass configurations. Architectural elements, which reflect specifically this particular period of time, will be explained. In order to clarify the variety, certain features of the authentic houses will be compiled with systematic classifications. Furthermore, structural system of the wooden houses of Istanbul will be clearly defined and information about the connection methods will be given through the examples still remain with their authenticity.

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INTRODUCTION

Turkish house has a special significance on the Ottoman heritage, with its concept reflecting the habits, traditions and social life of the belonged society, environmental connection and spatial composition. Throughout the centuries, different varieties of Turkish house had developed. Within this research wooden houses of Istanbul from the last period Ottoman Empire, are elaborated. Starting from the 18th century, influences of the European styles were slowly emerged in the housing architecture. However, between the late 19th century and early 20th century, this effect became more significant on the character of the buildings. Political and economic developments and social atmosphere of the period were effective of the pluralism and alteration on the architecture.

Within this research, effected architectural elements of the timber residential heritage will be explained in detail. It is also important to elucidate the structural system and reveal the preservation problems of these historical wooden houses in Istanbul. Specific characters of this cultural heritage are examined through authentic examples that still remain standing. These examples are found mostly in Bosphorus villages, Princes Islands and newly developed residential areas of its period like Kadıkoy, Moda, Yeşilkoy and Bakırkoy.

EFFECTED ARCHITECTURAL ELEMENTS

The characteristic elements of traditional Ottoman wooden house architecture were preserved until the 19th century, while forms and details from European styles were introduced to the core architecture. [1] The structures built after the late 19th century signify a radical change characterized by a strong shift to the western models resulting from the increasing Europeanization.

Effect of Baroque, Rococo, Empire, Neo-classic, neo-Greek, Art-Nouveau, Victorian style, Swiss Chalet style appear on the wooden residential architecture of Istanbul (Figure 1). Moreover, eclectic buildings, which compromise more than one style, were often used. The variety of styles were so intense that it converts Istanbul at the period of the second half of the 19th- early 20th century into a unique architectural museum for the wooden residential heritage [2]. Unquestionably, such effects were apparent on the ornaments. Besides, traces of the western influence are also encountered on the general design of the building. Alterations are also seen in roofs, facades and plans.



Figure 1: Timber house in Yesilkoy with Art Nouveau details, 2015

Roofs

The typical character of the Turkish timber roof system was simplicity and complicated roof forms were never favored. Usually applied form for the traditional Turkish timber house was hipped or gable roof, or a combination of the two. [3] With the gradually changing interest towards European styles, diversified patterns of the roof forms reflected expressively in different styles from the common ones of the traditional Turkish house. Certainly, the skills of the craftsmen and desire of the proprietor played an important role on the expression of these forms having a new sense of visual impact.

The curvilinearity, which was not the characteristic feature of the earlier periods, initiated a new attitude in the last period of Ottoman Empire. S and C figures of the baroque and rococo styles were represented in different combinations in the roofs, especially in the eaves, of timber houses. Such curvilinearity on the roofs can be seen in both horizontal and vertical planes (Figure 2). Another common preference of the same period is the usage of the roof with different levels. Additional space could be generated at the elevated position of the roof in rectangle, T-shaped or cross-similar forms. With the belvederes and differentiated slopes various housing types were obtained. Besides those factors, the roof pitch is an additional issue originating differences. Swiss chalet and Austrian mountain houses inspired the use of steeply pitch roofs in Istanbul's timber housing architecture after the 19th century. [4] While the presence of pitch roofs in Istanbul before the 18th century was the subject of long discussions [5], it can be deduced from the surviving buildings and old photos that the pitch roofed houses built after the westernization period were different from the examples of the 18th century. The increased slope provided the opportunity to create a new living space, which in turn brought along the need for openings such as windows and balcony, resulting in the complete change of the roof structure. It is worth to mention that there are many eclectic houses, which cannot be classified as one defined style because of having traces from more than one approach. In addition to the European influences, an orientalist approach for the roof structures should also be taken into consideration [4].



Figure 2: Curvilinearity on the eaves in both horizontal and vertical planes, 2017

At last but not least, the appendant elements have also an effect on the view and form of the roof structure. Decorative elements and ornaments on the roofs are reflecting different styles with various compositions. Curvilinear eaves, striking brackets, arrows on the ridge of a steep roof, pointed arches, spires or eaves with scallops and latticework are examples of the popular decorations of the houses from that period. Additionally, balconies, windows and towers on the roof are also part of the design and structure. (Figure 3)



Figure 3: Pitch roofed wooden house with appendant elements on roof, 2016

Facades

Cladding and Ornaments

Facades of the wooden houses are covered with horizontally rowed timber cladding boards. There are different kinds of the cladding boards but usually monotype boards are preferred in the same house. If dissimilarities in the cladding boards are observed, it gives clear evidence of possible intervention like repair, restoration or annexing.

There are numerous ornaments reflecting various styles. Each style has a different way of representing and most of the houses have unique decoration in a harmony with the features of the building. Façade decorations are nailed above the cladding board with small nails. (Figure 4) Small pieces are brought together to create a variety of figures for back bands or appropriate façade surfaces. Besides the straight-lined and plain decorations, flower motives, neo-Greek elements, curvilinear forms and original figures consisting of several pieces are also encountered.



Figure 4: Decorative wooden pieces nailed on the cladding boards, 2017

Openings

While, especially until the 18th century, Turkish house reflected an introverted way of living, visual relationship with the external environment received importance at later periods. Window surfaces became larger and their proportion to the façade area increased. Specific spaces facing the backyard like *sofa*, *hayat*, *eyvan* were converted into a middle hall and the important volumes like *divanhane* (central hall) opened out to a view. Such alterations exhibited some similarities with European baroque in which main importance is given to the street façades and front façades are facing a scenery as possible. [6]

With the 17th century, traditional Ottoman decoration elements' ornamented examples, which consist of fixed windows above, timber shutters and balustrades below, are found today in the outside region of Istanbul.

Between the end of 18th century and early 19th century, the upper windows became smaller and the bottom line got taller. [7] According to Eldem, after the 19th century upper windows were totally not preferred but it has to be mentioned that some fixed upper windows are still found in Istanbul. [8]

Uluengin states that the proportion of the windows were changed from 3/5 to 1/2 [7]. Guillotine windows were mainly used on the last Ottoman period houses, which still remain today in Istanbul. (Figure 5) In addition, casement windows or diversified windows with different forms like elliptic, rounded, arched were encountered as well. (Figure 6)



Figure 5: Guillotine windows and European style motives on the wooden cladding, 2016



Figure 6: Interior view of arched and casement windows of a seaside mansion, 2017

Furthermore, a special emphasis was given to the entrances on the houses built after the late 19th century. Glorious entrances finalized with decorative stairs are catching attention on the yalis (seaside mansions) and konaks (mansions). While majority of the doors were made of wooden, glass and metal were also used in recent examples in order to reflect an attractive appearance. Plentiful houses have special ornaments below the door or on the area to highlight the entrance. Today, most of doors are renewed and therefore, especially in luxury houses it is not easy to find an original door from that period.

Balconies, Oriels and Additional Elements

There are various projections on the façades. Some of them are closed space like oriels or Avant-corps, as the others are semi-open spaces like balcony. While oriels are symbolic

element of the traditional Turkish house, balconies represent the influence of westernization on the wooden houses. After the 19th century balconies on the front façade are encountered especially in the summer houses of the period. Although the variety of the balconies have a remarkable appearance, an extensive study about them is lacking. Balconies can be classified according to their structural system, shape of the floor space (Table 1), shape of the eaves, connections, combinations, styles etc. Due to the variety of the decoration, it is not easy to categorize the balustrades. Balustrades are mainly made of wood and brilliant figures were implemented by the skills of the workmen. As the balconies became a symbol of the European effect, they had significant role on the emphasis of the belonged style. Balconies can also be used together with oriels on the same façade and they could be connected horizontally or vertically. (Table 2)

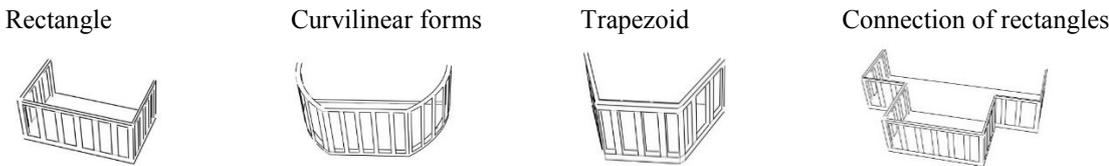


Table 1: Classification of the balconies according to the shape of floor space

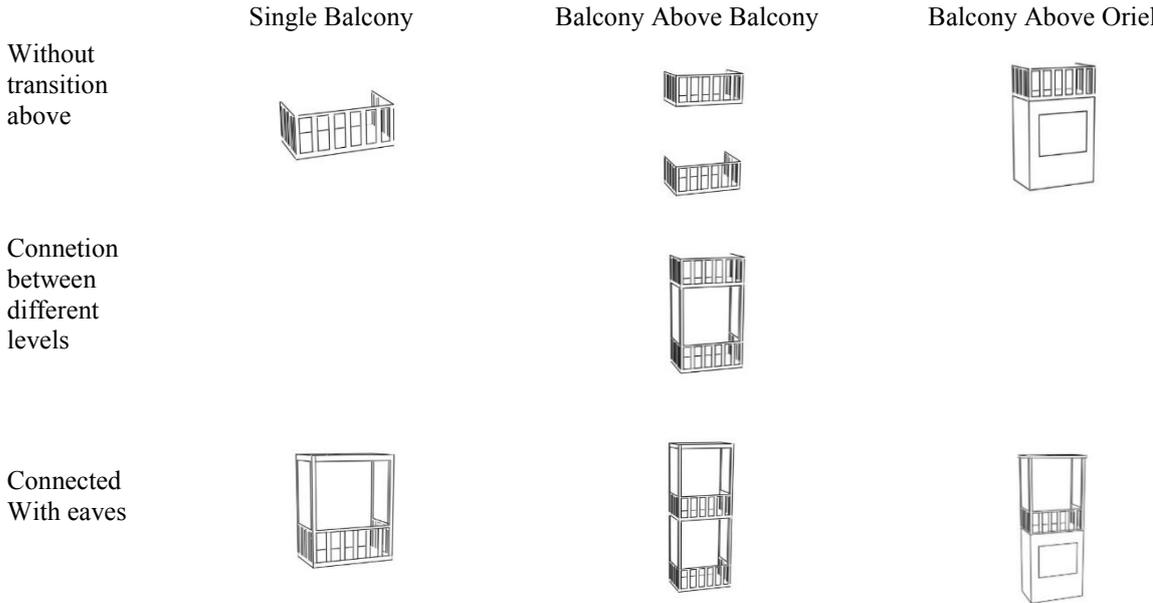


Table 2: Classification of the balconies with their connections on vertical line

In addition to all above mentioned segments, tower is also one of the elements defining the characteristic of the facade. Being a foreign element to the traditional Turkish house, it gives the houses a similar feel to the European mansions. Different utilizations can be described for the interior space of tower. On the Yali of Muazzez Hanim in Cengelkoy, the tower is used as the stair house, whereas in a mansion at Erenköy it created a space where the rooms grew into.

Plans

Throughout the centuries the plan scheme of Turkish house had also been under significant changes. Traces of the different styles can be noted as from 18th century. Seaside mansion of Sadullah Pasha, which was built in 18th century in Cengelkoy is a typical example that baroque influence is perceived in the plan and section level. Middle hall was transformed into an elliptic form with the effect of baroque style. [6] After the 19th century, simplification started on the plan scheme. The vast choice of decoration of the previous periods was partially disappeared. Straight lines were dominant on the plans and uninter-rupted rectangular were preferred for the rooms. [8] Moreover, reflections of the elements like tower, which were added to the housing architecture after the 19th century with the European influence, can also be seen on the plan scheme.

STRUCTURAL SYSTEM OF THE WOODEN HOUSES

The wooden houses from the last period of Ottoman Empire were constructed with timber frame system without infill. Load bearing studs are supported with plates and diagonal brace. The structural system is enveloped with timber broads from the outer side and Bagdadi technique from the inner side. (Figure 7) In this technique, plaster is applied to thin horizontal timber laths. Join of the timber pieces are fixed with nails which can be in various shapes according to their usage. Typically, while large nails are banged to a thick load bearing oak, thin ones are preferred for hanging the decorative elements on the façade to preserve the visual quality. Connection methods of the wooden pieces are simple and strengthened with nails. (Figure 8) The decision of the exact point of nailing and the number of nails is up to the workman on site. When the connection points are carefully examined and compared to each other, systematic construct is not seen even in details of the same room. While a connection was consolidated with 3 nails, in another point 2 nails were found adequate for the same connection technique.

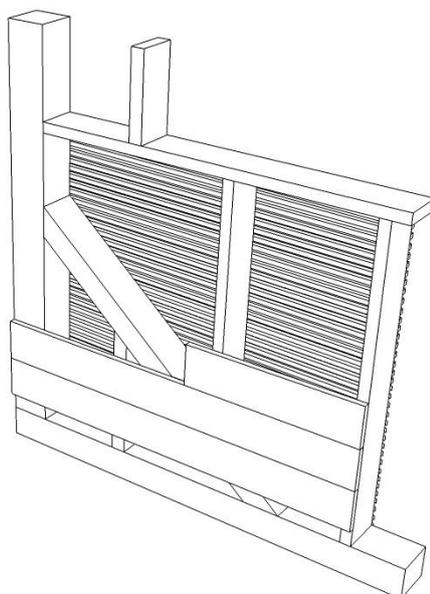


Figure 7: Structural system of the houses

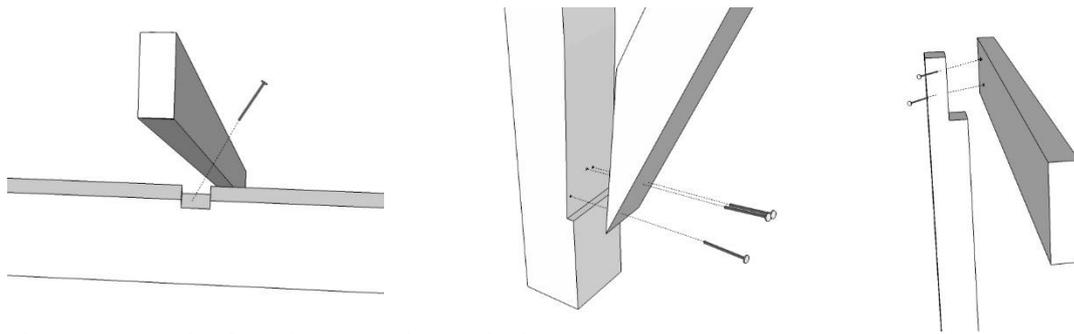


Figure 8: Examples from the connection methods

CONSERVATION STATUS OF HOUSES

Even though timber usage was intense on the houses of Istanbul in the early 20th century, the number of the timber houses are apparently decreasing by time. Especially, social and economic reasons are dominant factors for losing the wooden heritage. [9] Previously discussed some preservation problems still continue to be relevant.

Wooden houses generate relatively a specific pattern on some of the districts studied in detail. However, in some other locations, they remain in between the high rise concrete buildings and lose the explicit character. Traditional timber buildings are valuable not only as the individual architectural elements but also they create a meaningful unity with the neighborhood concept they constitute with the other houses. In this case, although being authentic, some houses lost their attraction for the users because of the economical reason, affecting privacy and changing socio-cultural environment. Aiming to document the cultural heritage under the threat of disappearance with the intense metropolitan atmosphere, the research is conducted through the houses present today. Preserved and observable authentic elements are evaluated. Despite the loss of huge number, today there are still more than 400 timber houses in Istanbul and most of them are usable.

CONCLUSION

Preserved wooden houses of Istanbul are mainly from the last period of Ottoman Empire. Therefore, the characteristic architectural approach of this period is explained through the remaining original buildings. Wooden houses, relationship of the users with the house and society and the significant changes in the architectural taste also play an important role to describe the social life. [10] Accurate understanding of the features of this cultural heritage and conveying the true information are the most important steps of the conservation. The loss of the examples without sufficient documentation would essentially lead to the loss of the data that might enlighten today's methodology on restoration or architectural decisions. In this work, it was aimed to reveal the characteristics of the historic wooden houses of Istanbul with the influence of European styles, as well as increase the awareness on the timber heritage.

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EXTERNAL STRENGTHENING OF STABILISED EARTH-BLOCKS MASONRY

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KEYWORDS

Stabilised Compressed Earth-Block, Masonry, External Mesh Reinforcement, Strengthening, Rehabilitation

ABSTRACT

Earth-blocks were for many centuries the main building material and as a consequence, many historical buildings and monuments around the world are made of this material. After cement and concrete invention, this type of construction has been abandoned mainly because of the low bearing capacity of earth-blocks, that makes difficult the building of multi-story structures in urban areas, as well as due to their low resistance to moisture. Therefore, building with earth was given up and in some areas this traditional way of building has vanished completely.

However, the benefits obtained from the use of earth in construction, such as complete recycling, low energy consumption during production and service life, high health and comfort performance especially in hot Mediterranean climates, have lead engineers and architects to reconsider this type of dwellings. The revival of traditional building with earth-blocks is nowadays considered to be a sustainable alternative for rural housing with low energy embodied, low CO₂ footprint and completely recyclable materials. As a result, combined with the fact that earth buildings constitute a significant part of the built Heritage and their repair and retrofitting is constantly pursued, earth-block construction has gained many supporters around the world.

The current study, taking under consideration the need of strengthening of earth-block constructions and having reviewed the various existing methodologies of strengthening, reviews the existing literature and experimental research, and focuses on the proposal of a research plan for external superficial strengthening with meshes embodied in the structural member with mud mortar. The parameters under investigation are the type of stabilized earth-block (morphology, strength etc.), different types of earth-block masonry (structure, thickness etc.), different types of meshes (polyethylene, glass fiber, metal etc.), different techniques of external attachment of the meshes, different scenarios of loading for testing the masonry behavior.

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INTRODUCTION

The great availability of earth on the planet, the easy manufacture of earth-blocks as well as the adequate strength and stiffness are the properties that established their wide use from ancient times until today. The substitution of traditional masonry by reinforced concrete began with the industrial revolution and cement invention by which the multistory buildings and megacities were constructed. However, in many historical centers, in particular in South Europe, there is a stock of earth buildings which are listed buildings and need restoration to be used as houses.

As the development of engineering coincided with the evolution of new durable and flexible in use construction materials, which gradually limited the role of masonry from bearing to filling element. It is well known that the knowledge about the mechanical behavior of masonry and bearing masonry structures is even nowadays relatively restricted. Moreover, the fact that masonry is a multi-phase and multi-shape material makes necessary the investigation of the individual phases (brick-mortar) separately as well as united as one material, in order to understand the behavior of the masonry.

From the past decades up to now there is great interest for the preservation and reuse of built cultural heritage. Modern methods of conservation require respect to the authenticity of the structure and intervention solutions which are compatible with the original structure and do not cause alterations to its character and structural function. The research is directed towards the study of earth masonry behavior not only because a majority of preserved buildings, still in service, consist of earth masonry but also because the fundamental advantages of earth masonry, such as good thermal and insulation properties, fire and time resistance, as well as aesthetic excellence, are being re-discovered and re-appreciated, in building technology, under the prism of sustainability and energy saving concept.

One of the most important weak point of earth-blocks is the poor response to earthquake ground motions, which results in severe structural damages or collapse. The seismic strengthening of earth-block constructions has been investigated the past few decades and the results point out the fact that it is possible to have such structures with adequate seismic capacity, complying with modern anti-seismic requirements.

The current study aims to explore the impact of external reinforcement of masonry elements for new earth masonry cases as well as for cases of repair of existing ones. More specifically, it focuses on seismic behavior and how this is affected by the application of external reinforcing systems consisted of carbon fiber or other stainless steel fiber meshes and earth based mortar. Taking under consideration the results of previous, related to the subject, research, the effects of different types of meshes and different types of anchorages are investigated in relation with the factors that affect the response of the masonry, aiming to result in the optimum conditions for application of the reinforcing system on the masonry.

ADVANTAGES AND DISADVANTAGES OF EARTH-BLOCKS AS BUILDING MATERIAL

In order to understand the behavior of earth structures, it is essential to comprehend first their strong and weak characteristics that made earth-blocks initially a dominant building material and lead to its abandonment later on.

The advantages of earth-block as a building material include:

- Low cost, raw materials are easily obtained

- Easy to work with, skilled technicians are not required for manufacturing and construction
- Low cost and environmentally friendly manufacturing process
- Energy efficient and environmentally friendly, 100% natural raw materials which makes it 100% recyclable
- Low cost function and maintenance of structure
- Durable and extended life
- High resistance to fire
- High thermal capacity
- Balance of moisture levels
- Flexibility of form and application

The most important deficiencies of adobe as a building material are:

- Demand for intensive labor that leads to slow construction process
- Vulnerability to earthquakes due to heavy weight, low strength and brittle behavior
- Shrinkage and cracking
- Susceptibility to water and frost
- Lack of homogeneity of composition between different extraction sites
- Lack of standardization
- Lack of legal framework

STRUCTURAL PERFORMANCE OF EARTH STRUCTURES

It is common for earth-block walls to be cracked due to unexpected loads (overloading, seismic vibration), inadequate foundations, and/or differential settlements, shrinkage. Part of the cultural tradition in areas where earth construction is integral to local vernacular architecture, is to repair cracks regularly by renewing the mud-plaster surface finishes [1, 2]. A typical example is the annual festival of the Great Mosque of Djenné in Mali, where the entire community of Djenné takes an active role in the mosque's maintenance by applying new plaster on the walls in order to repair the damage inflicted on the mosque in the past year [3]. However, in many cases, the initial earth structure may have undergone major additions and modifications resulting to a considerably altered configuration.



Figure 1-2: Crepissage de la Grande Mosquée (Plastering of the Great Mosque [3]).

The fundamentals of the post-elastic behavior of earth-block buildings are entirely different from those of ductile building materials. Typical unreinforced earth-block masonry may remain standing and carry vertical loads even if it is cracked but with no tensile strength capacity at all. Typically, historic earth-block masonry is quite thick and therefore

difficult to destabilize even when severely cracked. Support provided at the top end of the walls by a roof system may add additional stability, especially when the roof system is anchored to the walls [2].

Structural performance of earth structures under earthquake loads

The typical damage patterns in earth-block masonry are mostly vertical cracking and separation of the walls at corners, diagonal cracks, out-of-plane collapse and separation of the roof from the walls (when there is inadequate connection between them) that can lead to total collapse of the structure.

Earth-block constructions are particularly vulnerable to earthquakes. They respond poorly to seismic loads, suffering serious structural damages or brittle collapse. This vulnerability is caused by the combination of the heavy weight, the low tensile strength capacity and the brittle behavior of the structure, which leads to the development of increased seismic loads to which the structure cannot resist. Another weak point of earth-block buildings is that, although they usually have thick walls that enhance their seismic stability, the roof system is in many cases insufficiently attached to the walls.

REINFORCE AND REPAIR METHODS

In the following table the current practices of rehabilitation of earth structures are summarized and commented.

Retrofitting method	Economic criteria	Sustainability criteria	Application criteria
Surface treatment (shotcrete)	Expensive due to the high cost of shot-creting system	Use of concrete is unsustainable.	Application requires trained specialists.
Stitching & grout/epoxy injection	Minimal costs as the products are readily available and can be easily applied.	Minimal amount of material required and very 'light' application.	Little technical knowledge required. Materials can be easily transported and applied. Not reversible intervention.
Re-pointing	Minimal costs as only require the manufacture of the mortar.	Minimal amount of material required and very 'light' application.	Little technical knowledge required. Temporary works may be needed to support the structure.
Bamboo reinforcement	Cost of reinforcing ~ \$225 for 1000 sq. ft house, (\$400 for steel reinforcement).	Sustainable, if bamboo is responsibly sourced. Requires very little processing.	Method is easily buildable, if fixed to external wall. Installation is quick to learn for local builders.
Confinement		This is a relatively 'heavy' en-	Application is very intrusive requiring

	Cost-effective for application in new building. As a retrofit, requires demolition and reconstruction of wall.			gineering solution - unsustainable.	demolition of wall sections.
Polymer mesh reinforcement	<i>Industrial geogrid</i>	Mesh cost: \$2/m ²	Application cost: \$19/m ²	Polymer mesh requires use and processing of petrochemicals, which is not so sustainable.	<i>Industrial geo-grid:</i> Tough nature of material and lack of flexibility makes application difficult.
	<i>Soft polymer mesh</i>	Mesh cost: \$0.5/m ²	Application cost: \$4/m ²		<i>Soft polymer mesh:</i> Mesh can be easily deformed so transportation, application and removal

Table 1: Comparison of various retrofitting methodologies [4].

It is important to notice that in the case of historic and monumental earth structures, the compatibility and reversibility of retrofitting techniques must be taken under consideration. Although there have been developed many different methods for the reinforcement of earth structures during the past decades, not all of them comply with the principles of modern conservation, compatibility and reversibility, which aim to maintain the authenticity and the cultural identity of the historic building. Modern research should be more oriented towards the development of retrofitting techniques more adaptable to the nature of historic structures. In that way, conservation and preservation methods that are adjusted to the particularities of traditional materials can be established and their use in historic buildings would have minimum and reversible impact on the historic and cultural identity of the structure.

EXPERIMENTAL PROCEDURE PLANNING

The experimental part of the study is conducted at the Laboratory of Building Materials of the Aristotle University of Thessaloniki. The stages of the experimental procedure are the following:

Manufacturing of stabilized compressed earth-blocks

In order to verify that the raw earth material provided from a specific location is suitable and in order to identify the correct composition for the production of earth-blocks the following tests are required:

- In-situ empirical exam (quality estimation by visual, olfactory, grasping and gripping control, empirical workability control etc)
- Determination of moisture content (w%)
- Determination of granulometry (use of standard shieves, American standard ASTM E-11 & D-422, German standard DIN 4188/4187 & 18123)
- Determination of Atterberg limits and plasticity index (LL%, PL%, SL%, PI)
- Mineralogical composition control (Scanning electron microscope –SEM, X-Ray Diffraction-XRD, Differential Thermal Analysis –DTA)
- Determination of maximum dry density (Proctor test)

- Soil bearing capacity

By determining the physical properties of the soil, it is possible to choose the proper conditions for compression and the proper stabilizers for the mixture to be used in the production of the earth-blocks.

The compression during the manufacturing process improves the mechanical properties, reduces the attrition, the permeability and consequently the susceptibility to moisture and water and increases the durability. Those benefits are achieved by the compaction of the granules which reduces their movement and eliminates the containing air to minimum levels, resulting to a reduced overall volume.

The stabilization contributes to higher levels of compressive strength, decreased shrinkage phenomena for both earth-blocks and mortars and overall increased masonry resistance. Most common stabilizers are sand, fibers (natural or artificial), lime, cement and hydraulic mortars.

Determination of the properties of the earth-blocks

After the production and the proper drying of the earth-blocks their physical and mechanical properties are tested in order to verify that they meet the requirements of modern regulations. More specifically, the change of weight and volume is measured, the dynamic modulus of elasticity and the density are estimated (speed of transition of hyper sounds through the specimens) and the compressive and bending strength are tested.

Masonry specimens

After the determination of the properties of the stabilized compressed earth-blocks, masonry specimens are built with different morphology (structure, thickness etc.). Then, the masonry specimens are reinforced using different types of meshes (polyethylene, glass fiber, metal etc.), different techniques of external attachment of the meshes (staples, earth based mortar layer etc.) and submitted to different scenarios of loading for testing their behavior (compressive loading, combined vertical and horizontal loads, base shaking etc.).

SCOPE OF EXPERIMENTAL PROCEDURE

The experimental part of the study aims to further investigate the confinement the reinforced mud based mortar layer offers to earth-block masonry and how it affects the overall seismic response of it. Moreover, the study contributes towards the better understanding of masonry behavior and the establishment of the effectiveness of such reinforcing systems on earth-block constructions, accumulating knowledge that can be applied not only for retrofitting existing but also build new earth-block structures.

Preliminary research work done at the Laboratory of Building Materials of Aristotle university of Thessaloniki showed that the behavior of earth-block wall segments reinforced externally with steel and glass fiber meshes to compression and combined vertical and horizontal loading is significantly improved. An increase of over 50% of horizontal load capacity and energy absorption was observed [1].

Furthermore, research conducted at the Institute of Theoretical and Applied Mechanics in Prague has revealed that the reinforcement of wall segments with meshes offers confinement that allows them to withstand higher loads and results into a less brittle behavior upon failure [5].

These encouraging results opened the way towards a furthermore investigation on retrofitting of earth structures.

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STUDYING THE TECHNOLOGY AND THE ARCHITECTURE OF DIFFERENT MOSQUES LEFT IN NORTHERN GREECE

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KEYWORDS

Ottoman Mosque, Restoration of Monuments, Traditional Materials

ABSTRACT

The present paper is focusing on the methodology applied for the study of the mosques built during the Ottoman period (from the 14th century until the early 20th century) in North Greece. In this particular era, cities are changing to meet both the religion and the social ideals of the new Muslim citizens and obtain new public buildings, commercial and religious. The mosque was the most important building, it is located in the center of the daily life, around which the city space and social living is organized.

Nowadays, only a few examples of these monuments have been preserved and consist an important part of the historical and cultural heritage. For the most of them, it is difficult to identify their construction phases and determine their original morphology due to their preservation state. A step towards the Ottoman mosques preservation is made by exploring their pathology, their construction technology and their building materials.

The study is in progress, and follows the methodology steps that are described in the paper.

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INTRODUCTION

Greece is a part of south Europe where many and different cultures have left their footprints. Preserving the remnants of all these cultures constitute an act of civilization according to the principles of International Declarations and Charters [1]. North Greece is especially rich in monuments and buildings from the Byzantine and the Ottoman period.

This study is about the methodology followed for the architectural and construction design of the Ottoman mosques that are preserved today in Macedonia, northern Greece. All of the monuments firstly, recorded and chosen with geographical criteria, are examples of Ottoman architecture and at the same time an important piece of historical and cultural heritage.

Important stage in the study was the comprehension of the pathology of monuments. The mechanism through which specific actions or causes, are leading to deterioration of the construction. In most cases this is a combination of aging of building materials, climatic and environmental conditions, operations or transforms that have altered the buildings and lack of maintenance.

The building materials were mapped, the construction of these buildings was investigated with the purpose of carrying out the conclusions for the building techniques used to construct them. All the monuments show common elements in terms of general construction principles, but exhibit and diversification materials, proportions and decoration according to the place, the operation and the period in which they are implemented. The available materials of the area is inextricably linked with construction techniques and played an important role in architectural approach and methods to be followed to construct the building. The building materials were stones, bricks, mortar and wood with which they made the foundations (walls, arches and domes). Secondary materials such as marble, tiles, lead sheets and metal were used to carry construction in final form.

The data collection was completed with the analysis of selective samples of construction materials from each monument. The laboratory experiments of the properties and the chemical composition of the materials lead to conclusions about the technology used. The specimens collected were mainly building mortars, plasters and bricks from different positions, as much as possible similar, to each monument so that the results are comparable.

Finally, combining and comparing of all of the above data, provide an understanding of the current preservation of monuments, the clarification of their components and the causes of deterioration. The purpose of this study is the evaluation of the results about the architecture and construction structure of these monuments. These results may be applied to the better determination of the intervention way for their protection, restoration and ultimately their accessibility in modern cities' life.

HISTORICAL CONTEXT

The Ottoman Empire covers a period from the 14th century until the early 20th century. [2] Central province of the Ottoman Empire was the Greek region of Macedonia, where religious and cultural buildings were constructed with a wide variety of morphology and typology. Cities were reformed and developed, such as Serres, Thessaloniki, Veria, Drama, Kavala and Kastoria or new ones were founded such as Giannitsa [3]. Despite the multicultural character of the cities, each community had its own characteristics. The social and economic organization of the Islamic cities had a serious impact on their civil form. According to that, new public buildings, commercial and religious were constructed. Consequently, the image of the public space was influenced by the location of the central mosque

and its dependent buildings as well as the covered market and inns. The importance of the mosque as a building in everyday life is clearly indicated by its location at the center of the city and revolves around the fulfillment of religious duties and social ideals of Muslim citizens.

STUDY STAGES

1. Recording of the Ottoman mosques

In the cities of Macedonia today, very few samples of the Ottoman past have survived. The study relates to the mosques built by the Ottomans for the religious needs of Muslim residents.

The recording of monuments was originally based in a continuous list [4] of listed archaeological sites and monuments of the Greek Ministry of Culture and the book: the Ottoman Architecture in Greece (2008) published by the Directorate of Byzantine and post-Byzantine Antiquities. Overall, from the bibliographic research, recorded 24 mosques in the study area, which are located in different conservation status (Table 1). Some of these monuments have been fully restored and are used as places of culture, other have held small-scale maintenance and conservation, some have interventions and alterations or have received other use and finally some are in state of ruins.

#	monument name	City	State
1	Koursoum mosque	Kastoria	without interventions
2	minaret of Florina	Florina	ruins
3	Minaret of Arnissa	Arnissa	ruins
4	Geni mosque	Edessa	without interventions
5	Houngiar mosque	Edessa	ruins
6	Orta mosque	Veria	without interventions
7	Medresse mosque	Veria	restored
8	Mahmut Tselebi mosque	Veria	private-ruin
9	Iskender Bey mosque	Gianitsa	multiple interventions
10	Ahmet Bey mosque	Gianitsa	without interventions
11	Minaret	Gianitsa	without interventions
12	Hamza Bey mosque	Thessaloniki	restored
13	Alatza Imaret	Thessaloniki	restored
14	Mosque in Thermi	Thermi	ruins
15	Mehmet Bey mosque	Serres	without interventions
16	Moustafa Bey mosque	Serres	without interventions
17	Zinzirli mosque	Serres	restored
18	Eski mosque- Church of St. Nicholas	Drama	change of use
19	Arap mosque	Drama	without interventions
20	Sandirvan mosque	Drama	private-restored
21	Koursoum mosque- Church of Agia Triada	Drama	change of use
22	Mosque in Exochi	Exochi Dramas	without interventions
23	Ibrahim Pasa mosque- Church of St. Nicholas	Kavala	change of use
24	Halil Bey mosque	Kavala	restored

Table 1: Elements of the mosques in the study area.

By recording the mosques in the study area various problems occurred, such as: the lack of ranking-dating mosques in the 17th and 18th centuries, the dating is based on individual items or incomplete documents and cases where the lack of information leads to weakness dating of some monuments. This is because the historical documents are limited and based on a few case studies and references.

2. Description of the current preservation of mosques

Prior to the study, authorization was requested from the local Ephorate of antiquities to be granted permission to access and study of Ottoman mosques of their competence. Also, the study excluded the mosques that have been restored and those who are proven to have been manufactured in the 20th century.

The description of the current situation of mosques was with gathering of the typological and morphological characteristics for clarification of their components. This was achieved with the clipping of published notices in conjunction with in situ investigation and photography. In some cases, the lack of available data has resulted in the need to design specific monuments to be able to record the required information.

The combining of typological characteristics resulted in two main categories, based on their individual areas that make up the mosques in today's state of preservation (Capt. 1). The first category includes eight mosques that have an almost square floor plan single prayer space. The second category includes ten mosques, which besides the main quadrangle prayer space have smaller rooms serving social gatherings.



Capture 1: 1st and 2nd mosques are of the first category, 3rd and 4th are of the second category.

The morphological data gathered regarding the volume of each building formed by a quadrangle or multifaceted space with pointed or semi-circular openings on all sides, roofed by dome.

3. Mapping of Pathology

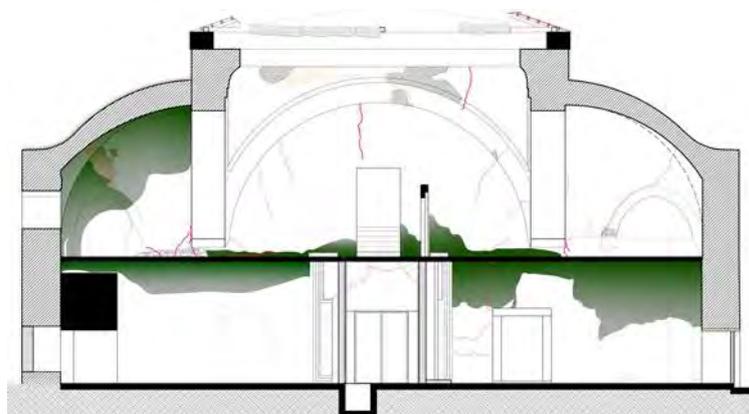


Figure 1: Pathology in section drawing at Iskender Bey mosque in Giannitsa

The pathology of each monument recorded in drawings (external views and internal sections). In this way, the building materials, the construction phases, the type of deterioration and the visible alterations were mapped.

The in situ observation let us record the deterioration problems. Moisture, vegetation, cracks, deterioration of building materials and detachments of morphological features are the most common sources of deterioration (Fig. 2).

A second state for mapping pathology is deriving of the laboratory analysis and concerns salt content, cracking, scaling, color alterations of the building materials (Capt. 2).



Capture 2: Salts in a sample of mortar (left), black crust (centre) and section of a brick (right).

4. Sampling building materials

Evaluating the information gathered from the previous study stages for each monument separately (extent and conservation status), identified the potential sample building materials and their locations. Sampling locations were selected following specific principles (in order to take representative samples) and the type of materials to be collected and once again authorization from the local Ephorate of Antiquities was requested.

The fragments collected were non-pictorial. They were taken from marked locations (Fig. 2) or were already detached and there was no risk of causing further damage to the monument. The location of the samples was also documented photographically and each one received unique code per monument.

Samples were taken from 12 monuments. The samples collected were bricks, structural mortars and plasters from external or internal walls, openings and the minaret.

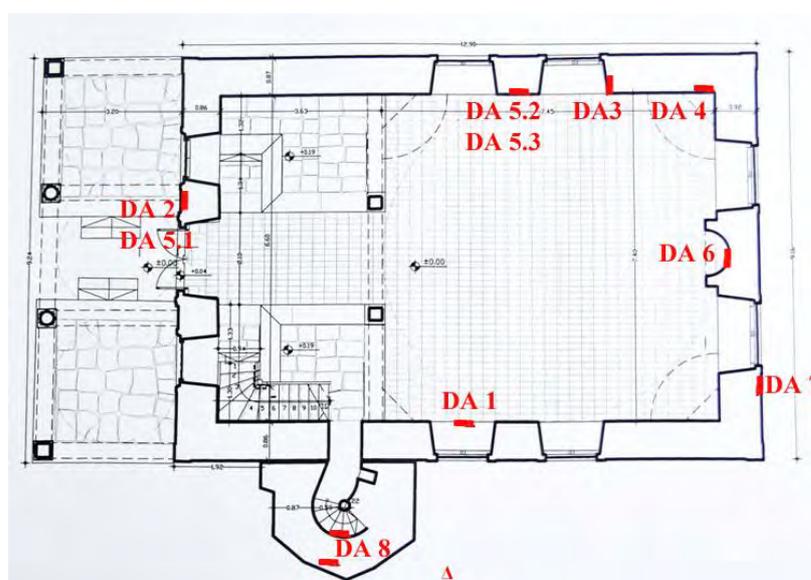


Figure 2: The location of the samples at Arap mosque in Drama

5. Laboratory experiments

The fragments of the materials and mortars were taken to the Laboratory of Building Materials in the Department of Civil Engineering of the Aristotle University of Thessaloniki and examined in accordance to the methodology of the laboratory. The analysis is based on a holistic approach in order to record the physic-chemical, mechanical properties and microstructural of materials and determine their composition [5]. Initially, each sample was photographed, described and measured. In total, approximately 120 samples were examined.

The physical-mechanical properties of mortars were determined with the following techniques:

1. Sieve analysis according to European Standard
2. Determination of open porosity (RILEM CPC 11.3),
3. Determination of compressive strength

For the bricks the following were determined:

1. Open porosity,
2. Capillary absorption (EN 1015/18),
3. Roughness of the surface
4. Homogeneity (measured with an ultrasound device),
5. Flexural and compressive strength,
6. Color

All samples were observed by a stereoscope.

The chemical properties in some samples of mortar were identified with:

1. Atomic Absorption Spectrometry (AAS) for the determination of metal oxides %wt,
2. Ionic Chromatography (IC) για for the determination of water soluble salts %wt,
3. X-Ray Diffraction Analysis (XRD) for mineralogical determination
4. Differential Thermal Analysis- Thermogravimetric Analysis (DTA-TG) for the determination of calcium carbonate (%wt) in calcite lumps

Through the laboratory experiments, the research focused on the study of construction materials in order to identify the construction materials.

6. Comparative data evaluation

The data gathered from all the study earlier stages, were processed per monument. The results in each monument are related mainly to the combination of deterioration factors and the building techniques and materials. In this way the record produced from each monument are available for comparisons and evaluation in order to conclude to the factors affecting the preservation state of each monument and they can be used by restorers and architects in order to choose the right policy to perform preservation acts to an important part of cultural heritage.

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DETERMINATION OF WATER PENETRATION AND REACTION SITES IN LIMESTONES FROM THE CULTURAL HERITAGE

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KEYWORDS

Limestone, Alteration, Cultural Heritage, Isotopic Labeling, Nano-SIMS

ABSTRACT

Considerable part of French built cultural heritage is made out of limestone. The preservation of this natural stone is therefore an economic, scientific and cultural challenge. Limestones used on the monuments are exposed to a polluted environment, especially in urban areas, and their degradation is already well documented. Several alteration patterns, such as black crust or salt efflorescence, are likely to occur. Two main chemical processes are at the origin of these patterns: dissolution and precipitation. In urban environments, the most common alteration secondary phase is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) formed from the reaction between stones, environmental water and sulfuric acid from the atmosphere.

Whatever the alteration process, water is the major alteration agent. This study aims to investigate the effect of the alteration layer formed on limestone on the subsequent alteration. To this purpose, we developed an original methodology based on water isotopic tracers (D and ^{18}O). Deuterium was used to localize water penetration front in the material, while ^{18}O enabled to determine secondary phase reaction sites, mainly composed of gypsum.

Freshly quarried samples and weathered samples from Parisian monuments were selected to compare different alteration stages. Samples were subjected to relative humidity changes in simulation chambers in isotopically labelled and controlled conditions (temperature and relative humidity). The reaction zones were analysed by nano-Secondary Ion Mass Spectrometry (nano-SIMS) on transverse sections of the limestones. This experimentation enabled determining that unaltered limestone and limestone from the monuments show similar behaviour. Water entirely penetrated in and no specific reactive zones have been observed. In this experiment the alteration layer does not seem to have a role on the subsequent alteration.

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INTRODUCTION

The alteration of monuments results from the interaction between the materials composing of the buildings and their environment. In France 52 % of the built cultural heritage is made out of limestone. Therefore, conservation of this material is a cultural and economic challenge.

In order to supply proper conservation strategies, the alteration mechanisms need to be well understood, which is a scientific challenge.

The selected sample in this study is a limestone widely used for restoration in France, the so called “Saint-Maximin roche fine”. Two types of samples have been studied, an unaltered limestone from quarry and a weathered one from Saint-Denis Basilica near Paris (F) exposed for 70 years in an urban polluted area. The physical and chemical properties of the unaltered and weathered materials from the monument have been previously studied [1]. The quarry limestone from the Lutetian period (45 My) is mainly composed of calcite CaCO_3 (95%) and quartz SiO_2 (5%) and presents homogeneous petrophysical properties with a high open porosity (36.2%) and significant transfer properties. Moreover, the alteration leads to a modification of the mineralogy and the microstructure of the stone. On the sample from Saint-Denis Basilica, an alteration layer is formed from the surface up to a depth of 12 mm underlined by the significant presence of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Its presence results from the reaction of the calcite with sulfate from atmospheric SO_2 and atmospheric water (relative humidity) [2,3]. Moreover and especially between 2 mm and 3 mm below the surface the formation of a compact layer reduces the porosity [1]. On other zones, the modifications in the porosity result from the dissolution [4] and recrystallization of CaCO_3 caused by the action of meteoric water [5]. At a macroscopic scale, these modifications influence the water capillarity properties of the materials. The compact layer at 2 mm below the exposed surface of the stone constitutes a water barrier and could influence the reactivity of the stone.

This study aims to evaluate the effect of this alteration layer on the water penetration and the phase precipitation, using laboratory-weathering experiment in a controlled environment. To discriminate the laboratory alteration from the previous alteration, we have developed a methodology based on the use of isotopic tracers from water, with a deuterated (D) and oxygen-18 (^{18}O) enriched altering solution [6]. The use of deuterium allows to locate the water penetration front inside the material, and the zones likely to alter due to the enrichment of D. The use of ^{18}O enables to locate the reactive zones.

MATERIALS AND METHODS

Materials

Stone cores were exposed to controlled environmental conditions, aiming to reproduce natural relative humidity (RH) variations. Limestone samples were parallelepipeds of $5 \times 1 \times 1 \text{ cm}^3$. To reproduce limestone condition in a monument only one face of the samples was exposed to the environmental conditions, the others being protected by an aluminum foil.

Weathering experiment

Freshly quarried samples and weathered samples were called respectively Ω and SD (from Saint-Denis Basilica). Ω and SD samples were exposed during two months to relative humidity cycles corresponding to a period of 5 days at high relative humidity ($85.0 \pm 1.1\%$)

followed by a period of 2 days at low relative humidity ($25.0 \pm 0.5\%$). Cycles were set according to weather data collected in Paris.

Samples were altered in two alteration chambers installed in a 20°C thermoregulated enclosure. The RH was regulated using hygroscopic salts dissolved in 300 mL of $\text{D}_2\text{O}/\text{H}_2^{18}\text{O}$ solution, (Table 1). A Veriteq captor (Spectrum software) measured the RH and temperature. A mass was daily monitored using a Melter (AE240) balance with 10^{-4} g accuracy.

Salt	Solubility (g.L^{-1})	Salt mass (g)	D_2O initial volume (mL)	H_2^{18}O initial volume (mL)	RH (%)
Potassium sulfate (K_2SO_4)	111	33.3	270	30	85.6 ± 1.1
Potassium acetate (CH_3COOK)	2000	600	270	30	24.8 ± 0.5

Table 1 : Composition of the solutions used to control the RH during the alteration experiment.

After RH cycles, samples were cut in cross-sections for subsampling. Then, they were embedded with an epoxy resin, and polished with silicon carbide and diamond paste under 95% ethanol. Polished sections were prepared for observation and isotopic analysis.

In order to locate interfacial zones related to water diffusion zones, cross sections were observed using SEM with a tabletop LV-SEM TM3030 Hitachi, a low-vacuum scanning electron microscope equipped with EDS system Quantax 70 EDS Bruker.

Isotopic analysis

Distribution of H^- , D^- , $^{16}\text{O}^-$, $^{18}\text{O}^-$, $^{28}\text{Si}^-$ and $^{32}\text{S}^-$, were recorded on a Cameca nano-SIMS 50 at the MNHN in Paris. A 16 keV primary Cs^+ beam was used to collect secondary ions in multicollection mode. Quantitative images covering surface areas of $20 \times 20 \mu\text{m}^2$, divided into 256 by 256 pixels were acquired at a raster speed of 1ms/pixel on transverse sections of the limestone embedded in resin. An electron gun (EGun) was used to offset charge effect. Before, each analysis, the sample area of $25 \times 25 \mu\text{m}^2$ was pre-sputtered with a current of 200 pA for about 8 minutes in order to remove surface contamination and to reach a steady sputtering rate. Due to instrumental limitations, $^{16}\text{O}^-$, $^{18}\text{O}^-$, $^{28}\text{Si}^-$, $^{32}\text{S}^-$ and were analyzed in a first set with a current of 1.5 pA. Then D^- and H^- images were acquired at the exact same location during a second set of image acquisitions with a 650 pA current for pre-sputtering (20 minutes) and 50 pA current for analysis.

RESULTS AND DISCUSSION

Mass Monitoring

Figure 1 presents RH evolution and mass gain for the unaltered (Ω) and weathered (SD) samples as a function of time. At high RH, the mass of the unaltered sample increases, while the mass decreases at low RH. After 4 cycles, the amplitude of the mass change seems to stabilize, ranging from 0.07% to 0.40%. SD sample presents the same behavior as Ω sample with a mass change ranging from 0.09% to 0.40%

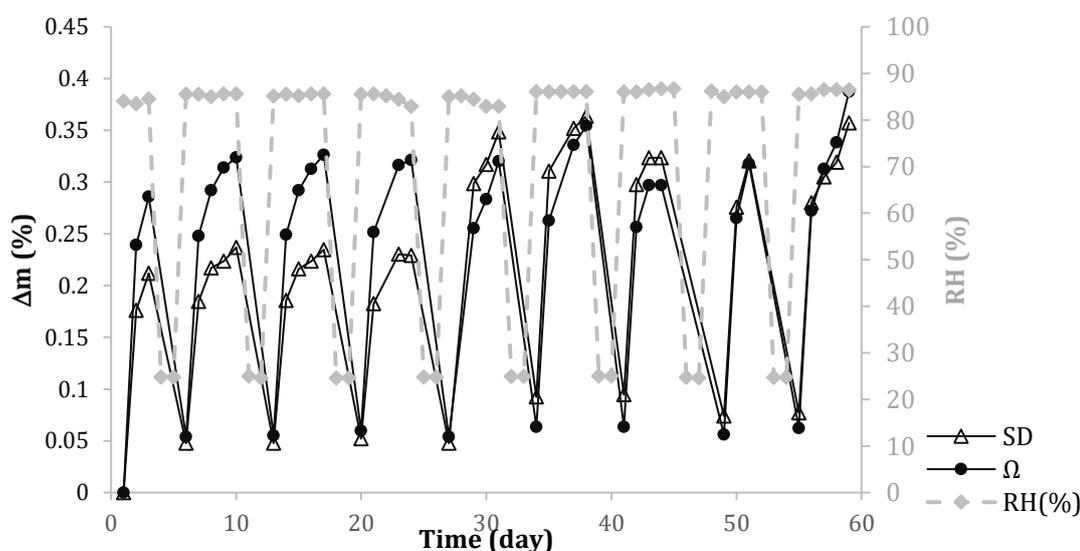


Figure 1: Mass monitoring of samples submitted to high (85%) and low (25%) RH cycles. Ω = unaltered limestone from quarry, SD= Saint-Denis Basilica weathered sample. The RH inside the chamber is represented in dotted lines (secondary axe).

Water front penetration

Deuterium labelling enables determining water penetration front. Its ratio is expressed as δD calculated following Eq (1).

$$\delta D(\text{‰}) = \left(\left(\frac{(D/H)_{\text{sample}}}{(D/H)_{\text{standard}}} - 1 \right) * 1000 \right) \quad (1)$$

D/H isotopic ratio ($1.5576 \pm 0.0001 \times 10^{-4}$) defined by Vienna Standard Mean Ocean Water (VSMOW) was used as standard to calculate δD .

Figure 2 presents the evolution of δD as a function of depth, in the SD sample. For both samples, and without any relation with the distance to the surface, the sample is deuterium enriched comparing to the natural ratio. However, no deuterium gradient is highlighted from the surface to the interior of the samples. Then, water goes through the pore network inside the whole samples. Both unaltered (Ω) and altered (SD) samples present the same trend due to the high connectivity of the pore network.

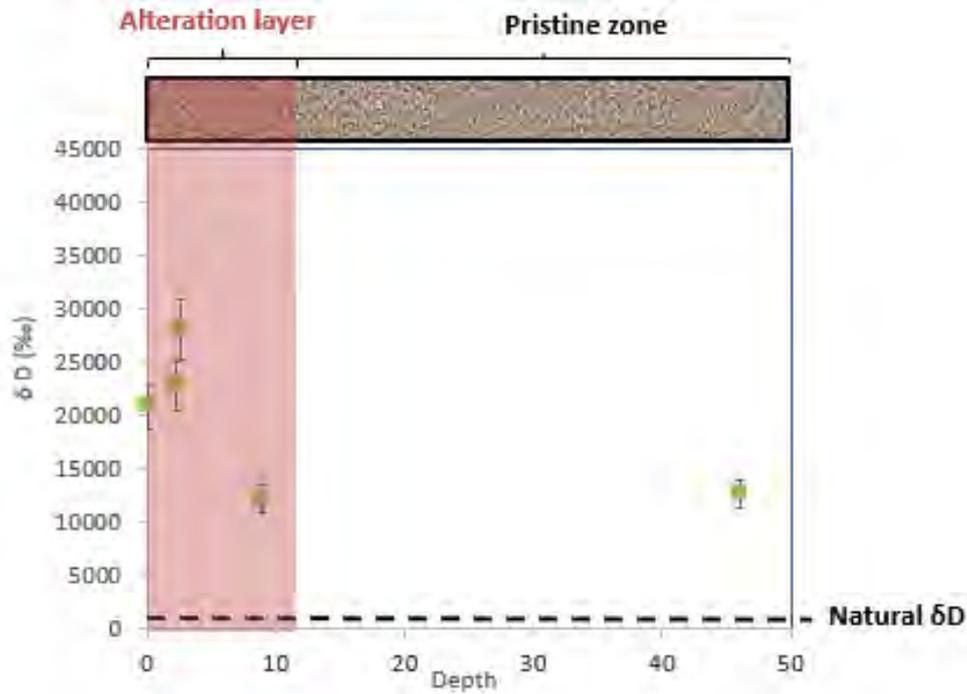


Figure 2: δD as a function of the depth for SD limestone. The alteration layer corresponds to the redish zone.

Location of the reactive zones

Reactive zones have been determined using the ^{18}O enrichment, expressed as $\delta^{18}O$ calculated following Eq (2).

$$\delta^{18}O(\text{‰}) = \left(\left(\frac{\left(\frac{^{18}O}{^{16}O} \right)_{\text{sample}}}{\left(\frac{^{18}O}{^{16}O} \right)_{\text{standard}}} - 1 \right) * 1000 \right) \quad (2)$$

$\delta^{18}O$ was determined using $^{18}O/^{16}O$ standard isotopic ratio ($2.0052 \pm 0.0005 \times 10^{-4}$) defined by VSMOW.

Figure 3A, 3B and 3C respectively present an example of ^{32}S , ^{16}O , ^{18}O elemental mappings measured by nano-SIMS on a cross-section of the SD sample. The analyzed zone is located at 9 mm below the sample surface. This zone is relevant to the interface between several phases: quartz, gypsum and calcite (Figure 3E). ^{16}O and ^{18}O elemental mapping are combined to calculate in each pixel the $\delta^{18}O$ value and to obtain the $\delta^{18}O$ mapping (Figure 3D).

On each analyzed zone on unaltered and weathered samples, a global ^{18}O enrichment has been observed (i.e. $\delta^{18}O = 330 \pm 33\text{‰}$ instead of $\delta^{18}O = 0\text{‰}$ expected for non-enriched samples). This enrichment is homogeneous, as it is the case on Figure 3D.

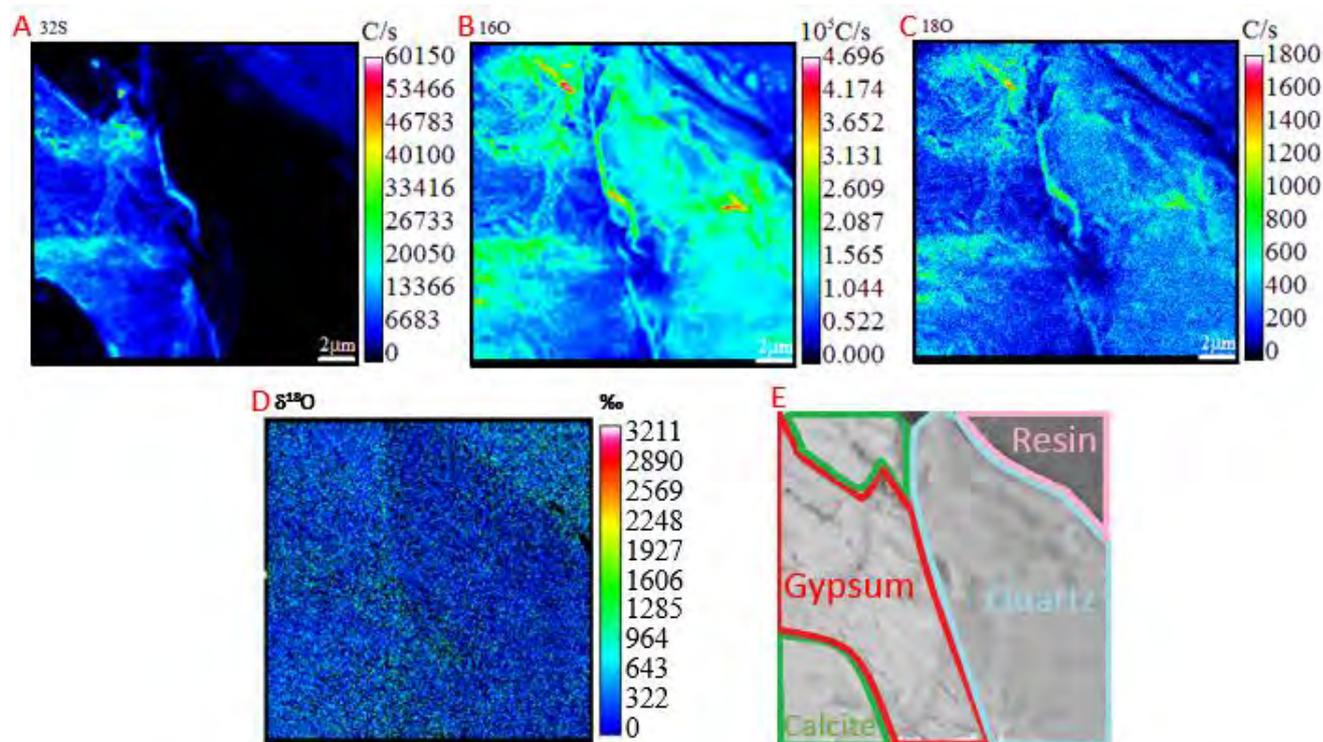


Figure 3 : Nano-SIMS ^{32}S mapping (A), ^{16}O mapping (B), ^{18}O mapping (C) and $^{18}\text{O}/^{16}\text{O}$ ratio mapping (D) on a cross section of SD sample exposed to an isotopically labelled solution and the associated SEM micrography (E) at 9 mm deep location.

Interpretation of the results

The mass monitoring of the samples shows that the unaltered (Ω) and weathered (SD) samples have the same macroscopic behavior regarding their water transfer properties, which suggests that the alteration layer has no impact on the vapour penetration during a two month experiment. The observations at a microscopic scale confirm this hypothesis. Indeed, the δD evolution in the unaltered and the weathered samples shows similar behavior, suggesting that water penetrates inside the whole porous samples. $\delta^{18}\text{O}$ homogeneous mappings can be interpreted as a penetration of the water without reaction because no specific enrichment has been observed. These results highlight that the alteration layer of the sample from the Saint-Denis Basilica monument does not act any specific role on the water uptake and loss and thus subsequent alteration.

CONCLUSION

The methodology based on the use of isotopic tracing has allowed comparing the alteration processes on unaltered and weathered limestone samples. After 2 months of alteration by relative humidity cycles, the alteration layer on limestone does not seem to play a role on the water penetration. This result is of interest for next restoration strategies. Moreover, it needs to be further investigated. New experiments are underway, in order to study the role of the alteration layer at a longer timescale (1 year) and with other altering conditions (switch of rainy and dry episodes).

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PUBLIC PRIVATE PARTNERSHIP IN CONSERVATION AND VALORIZATION PROCESSES: SPONSORSHIP INITIATIVES

Cristina Boniotti¹

KEYWORDS

Management, Conservation, Valorization, Public Private Partnership, Sponsorship

ABSTRACT

Considering that recent conservation approaches promote the merging of investments from different sectors into the cultural heritage field and the exchange of benefits developed through adequate negotiation, an interest towards public private agreements is increasing. In fact, public private partnership (PPP) is a management tool that implies a cooperation between diverse subjects, a multiplicity of interactions and a variety of operational instruments through which it is implemented. Combining competences derived from various sectors, it represents the expression of the need of integration between the different public bodies, private companies, non-profit entities, etc. and it represents the necessity to link together activities, functions, experts, roles, in order to face the complexity of a conservation project.

Since PPP models constitute an emerging phenomenon of transactions between public and private organizations and they still have not been widely tested in the cultural heritage field, the study is aimed at describing and analyzing this alternative funding mechanism through recent outcomes.

Amongst all funding policies involving private subjects in the management of common goods, sponsorship agreements could constitute a possible juridical model ensuring conservation and valorization activities upon built heritage in situations where the governmental entities cannot provide resources for this purpose.

The comparison between different examples in the Italian context, which is the subject of the study, allows the sharing of evaluations and considerations related to the definition of the simplest procedure for the provision of money from private to public entities, of the best way whereby public administrations can manage these funds effectively and supervise activities. The forthcoming strategies for built heritage management try to enhance the understanding and the awareness of the full potential of cultural heritage. The spread of these approaches could represent the basis for future projects, developing effective policies for heritage on a large scale, strengthening the relationship with private sectors, involving other kinds of market-based partners and stakeholders participating in the management process.

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ALTERNATIVE FINANCING MODELS: INTERACTIONS AND NEGOTIATIONS IN THE CULTURAL HERITAGE FIELD

Taking into account the diffused need and emergency of finding resources aimed at protecting and valorizing the public built heritage and at remedying the situation of neglect which characterizes numerous cultural sites, new approaches and business models become required in the cultural heritage field.

On the one hand, previous theories stated that money invested in cultural heritage can contribute not only to the enhancement of culture, but also to other production areas at the economic, social and environmental levels. On the other hand, an up-to-date approach, moving the concept of cultural heritage beyond its traditional definition, foresees the converging of investments from different divisions into the cultural heritage field, making other contributions interact with it. In fact, recent viewpoints foster the introduction of non-heritage funding, derived from other domains (labor market, regional development, creative industries, digital technologies, etc.), to achieve heritage and non-heritage goals. Therefore, a shift from a “downstream perspective” to an “upstream perspective” occurs, providing a new opportunity that enhances cultural heritage with new financial resources. The interaction with different productive sectors, the possible participation of private funds and the coalition with enterprises can represent, for public administration, a contribution to intercept financing not originally directed to heritage [1].

This innovative approach is aimed at bringing resources for conservation of built heritage through negotiation dialogues, fostering the exchange of good practices and abilities, the involvement of new kinds of public and the creation of a network that can enrich future conservation projects upon public built heritage. It implies a trade between different parts and consequently the introduction of the concept of trading zone, which represents a dialogue and a collaboration between different parts, despite the divergences between the various sectors. It illustrates a situation in which different actors provide their values, resources, activities, policies and facts and share them within a sole economic circulation, in order to reach pre-established goals, overcoming the divergences in languages, methods and cultural systems [2] [3].

Once cultural heritage starts collaborating with other productive areas, it is unavoidable for the private sector to become more deeply implicated in exploiting its potential. Even the H2020 Expert Group on Cultural Heritage, during a workshop organized by the Directorate-General for Research and Innovation of the European Commission, highlighted that the public sector should refocus its own approach, incentivizing and encouraging the private sector to get involved and invest in cultural heritage through new financial instruments, such as tax breaks, differentiated VAT rates, well designed grants, loan programs and public private partnership (PPP) schemes [4] [5].

In coherence with the previously illustrated models, partnerships are an organizational issue that implies a cooperation between different subjects. The interest towards partnership schemes is related to the multiplicity of interactions they create and to the variety of operational instruments through which they are implemented. The importance given to the relations established in PPPs, implies the study of the respective theoretical models, their way of organization and some considerations concerning normative aspects. Since PPP schemes have been already adopted in the past, the study does not focus on the innovation of these alternative financing mechanisms. Rather, the study is aimed at describing and analyzing this emerging phenomenon of transactions between public and private organizations in the cultural heritage field, specifically in PPP initiatives of sponsorship.

PUBLIC PRIVATE PARTNERSHIP (PPP)

Definition and characteristics of PPP

PPP is a long term collaboration between public and private entities aimed at realizing public duties (design, construction, management, maintenance of public works or public services), in which resources and risks are proportionally shared on the basis of their own skills [6]. It identifies a transaction between governmental and non-governmental actors and it represents a coordination between different organizations aimed at the production of goods or services for the community. Usually, a social entity and stakeholders from different sectors interact, combining their resources, negotiating profits, pursuing economic benefits and public aims. In the cultural heritage field, it could constitute a new financing model, where private investors/operators compete, repair, adapt heritage assets, deliver cultural and environmental services in historic areas and be remunerated through proportional risk sharing of revenues generated. Indeed, risk analysis has an important role for the achievement of the value for money.

The expression is not yet completely defined and it often alludes to several and diversified arrangements and juridical models, from voluntary agreements to procurement forms, in which organizations from the private sectors assume public administration activities [7]. Anyway, some features can be considered effective and constant: resource pooling in order to face situations of complexity, uncertainty and risk, and knowledge and responsibility pooling, as a form of co-production, between subjects who pursue different logics. In fact, one important aspect is that the partners involved are not only interested in the return on investment, but also in the exploitation of the specific differences between each actor-organization. The gathering of resources of differing nature and the combination of different cultures and interests, create synergy, constitute an added value and a potential, define innovative policies and solutions. The sharing of ideas, besides the sharing of financial resources, fosters the involvement of weaker partners, that are usually marginalized in situations focused on economic aspects [8].

Besides, private resources can bring advantages for the finance and the fruition owing to their:

- Combination of public interest (social utility) and private interest (profit).
- Efficiency, related to the time and to the ways of implementing the project as necessary conditions for the achievement of expected cash flows.
- Effectiveness, as a public activity transformed into a business is evaluated using the profitability and competitiveness criteria.
- Transparency, as the involvement of subjects required to work in close interdependence provides cross-checks.

In this way, public administrators are able to involve more economic operators in the heritage game and private subjects are able to provide their managerial, commercial and innovative skills, obtaining an economic return [6].

Since PPP schemes typically require a networking of resources, a cooperation and a coordination between several actors, which are different in terms of interests and differently constraint at a juridical and economic level, it is necessary to strongly define roles, responsibilities and risks of all subjects involved. According to the different circumstances, the public administration could exercise its function of protection, verifying the process through different project documents, contracts, establishment of subsidiary companies, groups and project referents. Therefore, each PPP scheme needs its own specifications.

Defining “public” and “private”

The PPP scheme is often associated to a situation in which the private is considered as a profit subject who acts for the sake of earnings and owns the resources necessary to realize a project. However, some remarks have been made against this simple interpretation. As stated by Pietro Petrarola, diversified private subjects play in the heritage game [9], such as: natural persons, legal persons which can have or not have for-profit objectives, economic operators which work with predominantly private capital and resources, non-profit organizations of social utility, foundations of various types, associations. There are also several ways in which the concept of public can be implemented: entities and institutions, entities with a public legal personality, economic operators which work with a financial capital, often upon singular and predominantly public interventions [10].

Diversified instruments of PPP

Several instruments of PPP were introduced in the last few decades. These tools through which the PPP is applied are quite diversified: in some cases they can be classified as contract forms, in other cases as subsidiary companies [7]. They can also vary on the basis of the field they belong to. In fact, the idea of PPP often refers to a wide range of management alternatives and instruments, each aimed at different public objectives. It represents a flexible model, which is frequently interpreted in different ways and translated in various procedures [11]. However, all these forms of joint participation between public and private subjects have the same objective, namely the use of financial, managerial and creative private resources, in order to realize or manage activities or facilities of public services [12]. Apart from concession of construction, concession of management and project financing, which are the most diffused models, there are also other several mechanisms for the involvement of private subjects. The progressive increase of private sector involvement is proportional to the increasing of the private sector risk. According to some reference texts [13] [14], possible ways to strengthen collaborations with private entities are grouped here in table 1:

<<< Extent of Private Sector Involvement and Risk <<<	World Bank Group, PPP Arrangements / Types of Public-Private Partnership Agreements		Rypkema D., Cheong C., Public-Private Partnerships and Heritage: A Practitioner’s Guide	
	Public sector owns and operates assets	Utility		Government Quasi-Public Corporation
		Restructuring		
		Corporatization		
		Decentralization		
		Civil Works		
		Service Contracts		
	Public Private Partnership	Management and Operating Contracts		O & M Contract
				Finance Only
		Leases/Affermage		
Concessions				
Build-Operate-Transfer (BOT) Projects		Design-Build-Finance-Operate		
		Lease-Develop-Operate		
		Build-Lease-Operate-Transfer		
		Build-Own-Operate-Transfer		
		Build-Own-Operate		
Design-Build-Operate (DBO) Projects		Buy-Build-Operate		
Joint Venture/Partial Divestiture of Public Assets		Design-Build		
Private sector owns and operates assets	Full Divestiture		Privatization	

Table 1: Diversified instruments of PPP identified by the World Bank Group (PPPIRC: PPP in Infrastructure Resource Center) for infrastructure projects and by D. Rypkema & C. Cheong for heritage projects. Within partnership agreements, sponsorship can be considered a “Finance Only” instrument of PPP.

SPONSORSHIP

Definition and characteristics of sponsorship

Amongst all funding policies involving private subjects in the management of common goods, sponsorship agreements could constitute a possible juridical model ensuring conservation and valorization activities upon built heritage in situations where the governmental entities cannot provide resources for this purpose.

Sponsorship is a contract whereby a sponsee, e.g. the public administration, offers a sponsor the possibility of advertising its name, logo, brand or products in exchange for money, goods, services or other benefits. In the cultural heritage field, it is defined as a PPP relationship, characterized by the association of a name, brand, image or a company product to a cultural heritage or initiative. On the one hand, for the public administration it represents a quite straightforward and flexible way to find resources, on the other hand economic operators can obtain a promotional advantage thanks to the juxtaposition of the company to the cultural heritage [15].

These agreements are increasingly used in conservation activities, such as the recent restoration of the Colosseum in Rome, which involved the fashion company Tod's and the Italian Ministry of Cultural Heritage and Activities. It represents one of the most relevant sponsorships in the Italian context for its importance, the issues faced during the procedure and the amount of money invested, that constitutes a large percentage of the total expenditures for heritage sponsorships in the last few years. In this example the public entity decided to avoid the common advertising banners installed on the scaffolding of the restoration site in order to foster a cultural revenue for the sponsor, to be implemented through communication activities such as publishing products, organization of conferences and events aimed at presenting the project and the sponsor role, etc.

A recently issued report by the Italian Court of Auditors analyzed sponsorship initiatives developed during the last four years in the framework of PPP operations directed at the valorization of heritage. It recognizes that the public is incapable of meeting all the social needs due to the well known lack of public resources and it incentivizes managers responsible for the cultural heritage sector to adopt these kinds of actions involving privates, such as sponsorships and project financing. Thanks to the visibility of several public properties, the cultural sector can be attractive for private companies [16].

Within financing arrangements, sponsorship implies a return on the investment in terms of image or public perception, instead of monetary revenues. When people realize the benefits of the sponsorship, they appreciate and feel grateful to the sponsor and, consequently to its company [17]. Potential customers' perception can also vary on the basis of the link between the sponsor and the activities developed [18]. Another reason encouraging this kind of operations could be the will to support the territory in which the corporation is located and to create relationships with the local government and population, influencing the urban development decisions and operating actively in the community. At the same time employees can strengthen the sense of belonging to the corporation and competitors can think that the company is in an economic good position and can also be incentivized to develop other sponsorship initiatives [19]. Since the operation image reflects the sponsor image, it is necessary that the restoration activities are conducted and concluded in a correct way. Perceptions of the restoration site, for example, could positively or negatively influence the perceptions of the sponsor image.

Due to the analogy with commercial advertising, often projects developed through sponsorship are not considered tax-deductible, but business expenses that are taxed.

Typologies of sponsorship

The different initiatives can be classified as “pure sponsorship”, when the sponsor is solely committed to finance, as “technical sponsorship”, in case the partnership is extended also to the design and works execution, or as “mixed sponsorship”, in situations where, for example, the sponsor provides for the design and only finances the execution of works. The public administration has the possibility to choose the most convenient form, considering that technical sponsorship allows to avoid the tenders management and the subsequent contract and construction phases and pure sponsorship could be the solution in situations where projects, possibilities to manage tenders and contracts are already available. In all these cases, they constitute an active contract for the State, since they imply an economic advantage and profit for the public administration. Government has to maximize the profit resulted from the sponsorship, adequately estimating the proposals on the basis of the transaction appeal on the market, in order to prevent overestimations alienating traders or underestimations penalizing governments. The hypothetical surplus derived from the economic operation could be devoted to other purposes, such as the planned conservation upon the restored built heritage object of sponsorship.

Tendering procedure and contract

Despite patronage, in which the advertising return is an indirect consequence of the donation, sponsorship initiatives foresee a compensation. In fact, if charitable donations are not aimed at lucrative purposes or any kind of personal benefits beyond moral recognition, sponsorship initiatives require a counter-performance. Therefore, sponsorship agreements, unlike the cases of patronage, are subjected to competitive procedures and conditions.

The process necessary to entrust the task is simpler in case of pure sponsorship, since it is only based on the higher economic offering and the firms have to submit a higher tender than the minimum funding foreseen in the call. Otherwise, within technical and mixed sponsorships the call for tenders is more complex, due to the evaluation of parameters related to the design and execution modalities. Thus, the award parameter of a pure sponsorship is generally considered the higher proposal compared to the contract starting price and the award parameter of a technical sponsorship should also take into account the quality of the project. At the same time, technical sponsorships, in the face of a greater burden in the choice of the sponsor, present for the public administration the advantage of avoiding a direct involvement in the demanding execution phase, assuming only the supervision role. Another important aspect in the decision is the evaluation of the promotional strategy planned, also in terms of knowledge dissemination. Considering that each initiative is implemented with its own features and that the communication programs can be personalized by the different promoters, the decisions taken to develop the promotion should be defined in the contract and conducted in a compatible and respectful way towards the cultural heritage. For this reason the public administration is required to supervise the communication plan. Contracts for advertising spaces and for entrusting restoration works could be different or could be unique, in tenders where a joint participation between advertising companies and restoration companies is required.

Since the private subject merely finances or realizes at its own expense the intervention, obtaining the brand promotion as counter-performance, sponsorship differs from project financing, where the partnership is more complex and the promoter/financier not only realizes the public work, but also manage it, obtaining a return on the investment thanks to the generated cash flow (for example in concession initiatives) [15].

OPPORTUNITIES GIVEN BY PPP

Some positions claim that sponsorship initiatives do not constitute innovative operations, since they represent a simple way to make profits in return of money. They can work only with the best known buildings located in relevant locations and could also raise problems concerning the erection of scaffolding for a prolonged period of time. Moreover, the State needs to find resources in order to take care of heritage also after the restoration interventions, during the management phase, and to find mechanisms incentivizing actions across the territory and involving the third sector. Nevertheless sponsorship, as any other PPP arrangements, is inevitable to avoid inaction in some governmental situations [20], among which there is the management of public properties. The analysis of adopted business models and a reflection on possible improvements of private participation modalities is necessary to finance public buildings' conservation and valorization.

Together with public bodies, privates as decision makers and as participants in the management of common goods could provide expertise and know-how in all-inclusive and long term projects to guide future actions. It is necessary to completely recognize public real estate as a resource and to move towards valorizations aimed at increasing the economic and social values of the state properties, fostering the integration of different forms of cultural and economic activities on a large scale and increasing awareness and social participation in the protection of heritage [21].

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MATERIALS TESTED BY TIME. QUALITY AND DURABILITY OF THE RESTORATIONS OF THE TEMPLES OF PAESTUM FROM THE NINETEENTH-CENTURY APPROACHES TO THE CONTEMPORARY ISSUES OF CONSERVATION

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KEYWORDS

Paestum Heritage, Archaeological Restoration, Durability, Compatibility

ABSTRACT

The issues linked to the physical, mechanical and aesthetical compatibility between pre-existences and additions, as well as to their durability, represent one of the main challenges of a restoration project. An archaeological context makes such issues even more complex, as it requires more attention due to the need of preserving the fragile ancient materials. Starting from these premises, this paper proposes the archaeological site of Paestum – one of the most significant town of Magna Graecia – as a particular testing ground for the evolution of restoration principles and practices. In this case, in fact, the conservation proposals and the restorations of the temples – carried out since the end of the 18th century – show the high quality of the choices, all aimed at ensuring the compatibility between new and old materials, the durability of the additions, and their distinguishability. The results of these restorations, still well preserved today, testify the accuracy of the technical expedients and the durability of the materials chosen for the additions, and acquire even more importance if compared with the outcomes of the twentieth-century yards. Despite the methodological lesson provided by those earlier restoration projects, works performed on the site of Paestum during the first decades of the Twentieth century were instead characterized by a much less careful approach, in terms of both the compatibility of interventions and their durability. Specifically, such interventions led to a larger use of concrete injections, reinforced concrete additions, armed perforations, as well as undocumented reconstructions in correspondence of the city walls.

Taking these considerations into account, this paper's aim is to interpret the evolution of the techniques and the approaches used throughout the 19th century, by comparison with those carried out during the 20th century. Such an interpretation will allow us to evaluate the level of quality of the choices made, in terms of both durability and compatibility between old and new parts. This analysis is carried on considering the present state of conservation of the temples. In this respect, it emerges as a critical instance the fact that, after only few decades, the most recent materials have answered to the test of time worse than the older ones.

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INTRODUCTION

The late Eighteenth century represents a key-period for defining the cultural basis and the principles of modern restoration. The approach and the analytic method defined by the academies of architecture within the Italian context – first of all by the French Academy in Rome – stimulated an increasingly aware dialogue with the vestiges of the antiquity to be scientifically interpreted. Moreover, the opening in the Neapolitan area of the main excavation yards of the cities of Pompeii and Herculaneum – rediscovered during the first half of the century – made possible unexpected and direct contact with ancient and fragile architectures which required new forms of interventions. Indeed, the conditions of great vulnerability of these structures required a large amount of urgent works of strengthening and protection that was carried starting from the second half of the century. Despite the heaviness of some additions, which sometimes determined the reconstruction of missing or collapsed parts and elements, these interventions can be considered as an early experimentation within the field of the archaeological restoration. These experiences were refined later, during the French Decade, when some of the most relevant restoration programs were carried out between the Roman and the Neapolitan contexts. During those years, and even after the retour of the Bourbon, technicians deepened their knowledge about issues related to protection and conservation, and started devoting more attention to the respect of the authenticity of the materials, as well as to the recognizability between additions and ancient parts.

Within this phase of cultural and methodological evolution, the restoration process of the temples of Paestum (in the province of Salerno, Campania) played a major role both for the precocity of the solutions and the variety of the conservation approaches [1]. Since the second half of the 18th century, the ancient city of Paestum – one of the most significant example of settlement of Magna Graecia, in which structures and stratifications belonging to Greek, Lucan, Roman and Medieval Ages coexist – began to attract the attention of Italian and European scholars, first of all for the presence of three well-preserved Doric temples: the so-called Basilica and the temples of Athena and Neptune. The methodological proposals and the operating practices employed on the temples since 1805, testify a relevant variability both in the choice of techniques and in the use of materials, as well as a strong connection with the aim of the contemporary archaeological restoration. Moreover, the possibility to make a comparison between the results of the nineteenth-century restorations and of those of the following century allows the analysis of the evolution of approaches and methods. This interpretation may become even more relevant once taking into account the relationship between theoretical assumptions and actual effects on ancient materials in terms of compatibility, recognizability and durability.

‘INSIDE’ AND ‘AROUND’ THE ANCIENT. THE TEMPLES OF PAESTUM AS ATLAS OF METHODOLOGIES AND TECHNICAL APPROACHES

The nineteenth-century experimentations

Although the ancient city of Paestum attracted the national and international interest since the Forties of the Eighteenth century, at that time the central government focused its attention and resources almost entirely on the sites of Pompeii and Herculaneum. However, the precarious condition of conservation of the ancient temples of Paestum and their rapidly progressing damages, due to the state of abandonment and the lack of maintenance, urged intervention towards the end of the 18th century. All the restorations carried

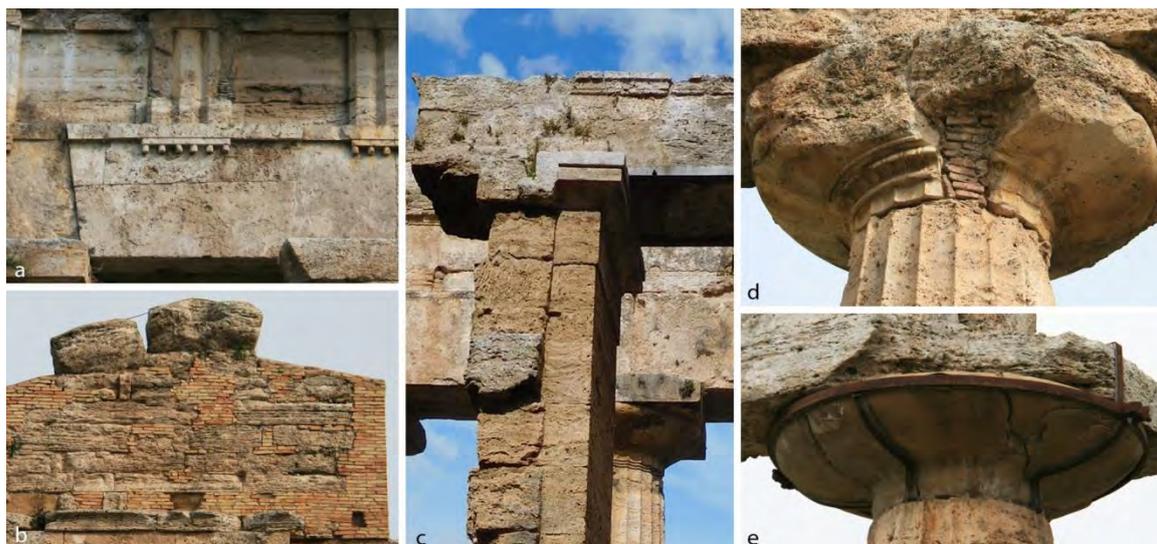


Figure 1: a) temple of Neptune, western architrave. Integrations in travertine blocks (1805); b) temple of Athena, eastern gable. Additions in brick masonry (1829-30); c) temple of Neptune, architrave and pillar of the order of the cell. Additions in travertine blocks and iron chains (1850-53); d) temple of Athena, column of the eastern side. Addition in fragments of bricks (1853-54); e) Basilica, capital of an internal column. Strengthening with iron devices (1855-56).

out on the temples – from the first proposals (1795) until the works performed in the Eighties of the Nineteenth century – appear to be characterized by conscious choices, aimed at ensuring the necessary compatibility between additions and old parts, as well as the durability and distinguishability of the new materials. This awareness, gained over time through the experiences of many architects and technicians, brought to culturally advanced approaches, close to the aims of the contemporary archaeological restoration – in particular for the will of adjusting the extent of the intervention to the actual conservation needs, having due regard not to adulterate the portions of the ancient structures.

Basing on an in-depth knowledge of the material and mechanical properties of these temples, the methodological acquisitions and the practical skills of the first half of the 19th century showed an increased attention in the selection of materials considered more compatible with the travertine of the temples. These experimentations were characterized by a high variability in terms of building materials and constructive techniques, in the case of the necessary integrations. Among these it emerges the choice of using blocks of the same travertine of the temples – well-finished and shaped in simplified geometries – connected to the ancient parts through iron braces and chains. Elsewhere, instead, some portions of brick masonries were defined and made recognizable, where possible, from the ancient palimpsest through the use of clearly different materials and constructive techniques. In addition to these stereotomic integrations, where the type of damage did not need integrations or additions, the reinforcement of stone elements were obtained through the installation of iron braces and chains.

In this context, the proposals by Francesco La Vega (1795), a military engineer already involved in direction of the excavations of Pompeii, emerged. After an in-depth analysis of the state of conservation of the temple of Neptune, La Vega proposed to strengthen a portion of an architrave using iron bars covered with «a good concrete», made of lime mortar «suited to the nature of the stone blocks», in such a way to prevent the oxidation [2]. Therefore, together with proposing the use of simple iron elements to brake the collapse of the architrave, La Vega also considered necessary to ensure the durability of the intervention

by the apposition of a layer to protect the metals from the weathering. Although these interventions did not take place, the principles of compatibility and durability behind them guided the work carried out by Antonio Bonucci in 1805 on the same temple [3]. The technician filled the largest gaps of the architrave of the western front and of the underlying columns using travertine blocks fixed with visible iron clamps and the smaller ones with stone splinters tied with lime mortar. These additions, well preserved today, appear materially and chromatically compatible, while remaining always distinguishable from the ancient layers because of their regular geometry or particular finishing. In the case of the temple of Athena, Bonucci opted for iron chains – removed during more recent restoration yards – as a way to connect and bind some collapsing elements in correspondence of the north-eastern corner.

Another remarkable intervention is the partial reconfiguration of the gables of the same temple with brick masonry intentionally chosen by Ciro Cuciniello in order to ensure the distinguishability of the new parts [4]. After a detailed work of analysis of the state of conservation of the structure (1829), the architect decided to use the brick masonry to redefine the geometry of the missing portions «so as not to confuse – he wrote – the modern work of restoration with the venerable ruins of that ancient monument». In this case the additions, well-preserved over time, appear today like prostheses with simplified geometries which adhere to the profile of the ancient portions without compromising their perception. The same constructive expedient was used for smaller gaps where Cuciniello realized local brick insertions.

During his Direction of the site of Paestum (1849-1860), Ulisse Rizzi showed a notable ability in adding, only where indispensable, iron chains, limited portions of brick masonry or travertine blocks with well-smoothed surfaces, all clearly different materials from the ancient ones [5]. In his contribution to the restoration works of the three temples, the technician was able to adjust the entity of the intervention and choose technical expedients and material solutions in relation to the specific structural issues to deal with. In the case of the temple of Neptune, the architect defined the integrations, necessary to avoid the collapse of the western portions of the inner order of the cell, by reusing some of the fallen stone blocks and by adding new parts made of the same travertine and connected by iron chains. This intervention successfully combined the aesthetical and historical instances carrying on a culturally aware dialogue between existent parts and additions. Whilst retaining the same material and geometries of the ancient parts, the new blocks were indeed well-smoothed in the surfaces in order to ensure the differentiation from the ancient rough finishes. Elsewhere, in case of limited integrations, the technician used brick blocks tied with lime mortar as to fill the smaller gaps and to redefine single elements. For the Basilica and the Athena's temple, which did not display equivalent critical situations, Rizzi decided to curb some limited collapse mechanisms of the columns by placing iron chains and circles, adapted to the profile of the different elements – abacus, capitals, shafts – and adjustable as needed. Many of these interventions, well-preserved today, show the good quality of the formal and technical choices. In particular, the travertine integrations appear in good state of conservation and remain always well recognizable from the nearby ancient portions, despite the effects of time and weathering on surfaces.

Between 1889 and 1890, some other restoration interventions were carried out and their outcomes are still visible. Even in this case the works were limited to the extent necessary to curb the deformations of portions of architraves and the problems were solved by adding iron braces and chains [6].

Restoration works between 1907 and 1962

As seen, the acquisitions deriving from the experimentations of the Nineteenth century were all aimed at reaching a right balance between aesthetical and historical instances without forgetting the issues of compatibility and durability. Despite this cultural and methodological lesson, the works carried out starting from the first decades of the Twentieth century were less careful about these problems. These interventions led indeed to a larger use of integrations in cement-based mortars, concrete injections, reinforced concrete additions, armed perforations, as well as undocumented anastylosis and reconstructions in correspondence mainly of the city walls. The trust in ‘modern’ materials as the reinforced concrete – also supported by the official guidelines of the Athens Charter (1931) and of the Italian Charter of Restoration (1932) – determined a widespread use of these latter. The prudent stone additions and the removable iron chains were abandoned in favour of heavier and not reversible integrations realized with wet mixtures, scarcely compatible with the travertine of the temples in terms of physical and mechanical behaviour.

Starting from 1907, further restoration works were carried out following the new and more systematic excavation yards led by Vittorio Spinazzola [7]. In a first phase, the interventions determined the reconstruction of some of the columns of the forum mixing tambours found on site with other stone integrations [8]. Later, during the Twenties and the Thirties, Amedeo Maiuri carried out restoration yards characterized by a generalized inclination toward the replacement of the nineteenth-century iron devices with thinner bars placed at the intrados of the architraves, as in the case of the north-eastern corner of the Athena’s temple. Elsewhere, Maiuri replaced some of the nineteenth-century stone additions – considered mechanically and aesthetically unsuited – with new integrations realized by «working from inside» the columns with localized injections of a mixture of cement and volcanic sand filled, in some cases, with a core of brick blocks [9]. Let alone his undocumented reconstructions of a large portions of the northern city-walls, Maiuri also completed the anastylosis of one of the columns of the so-called temple of the Peace within the forum of the city. In this case, he reused three ancient tambours and one capital found on site and integrated these latter with six new stone tambours, tied through brass bars and cement. Starting from the Fifties, new and heavier works were carried out, in a first phase, by Pellegrino Claudio Sestieri: in particular, some structures of the forum, the so-called Votive column and two columns of the upper order of the cell of the Neptune’s temple were integrated by resorting to extensive cement additions [10]. Within the same structure, several gaps of the shafts of the columns of the inner order were filled with cement mortars coloured in shades of orange in order to chromatically level out additions and existent parts [11].

Furthermore, what emerges from the following works, carried out during the Sixties, is the complete indifference shown with respect to the comprehension of the construction history and structural functioning of the temples – elements that should be considered, instead, as cultural guidelines. The project, in fact, determined the realization of a heavy strengthening intervention which was not aimed at all at ensuring the material and mechanical compatibility with the ancient structures. In particular, the eastern front of the Athena’s temple – already object of the nineteenth-century restorations, partially removed during the previous works – was strengthened by the definition of a dense network of steel bars linked to capitals by reinforced concrete anchors and diffused integrations with cement mortar. In addition, hundreds of armed perforations were realized to connect architraves and capitals, as well as to strengthen the shafts of the columns [12].



Figure 2: a) temple of Athena, column of the northern side. Addition in fragments of bricks and concrete (1926); b) temple of Neptune, column of the upper order. Integrations in bricks and concrete (Fifties); c) temple of Athena, column of the eastern front. Reinforced perforations (1962); d) temple of Neptune, column of the northern front. Integration made of lime mortars (1997-2002).

This intervention showed immediately its technical and cultural limits: in addition to being particularly invasive and totally irreversible, it determined the complete and definitive alteration of the structural behaviour of the temple. Moreover, it showed over the years several problems linked, including an increased vulnerability to damages caused by lightning strikes – attracted by the presence of metallic devices –, and limited durability and resistance in the interaction with the ancient materials. These issues remain critical nowadays for the conservation and protection of those architectures.

THE TEST OF TIME. SOME RECENT ISSUES IN CONSERVATION

Starting from the late Eighties, new and culturally aware restorations concerning the three temples were carried out by multidisciplinary teams of scholars and technicians. These interventions were particularly significant both for their experimentation in the use of innovative and more compatible materials, and for their consideration of the previous restorations, with the aim of evaluate the solutions in terms of their durability and compatibility with the ancient substratum. In particular, these studies highlighted substantial differences between nineteenth-century and twentieth-century interventions [13]. Analysis carried out at the time of these more recent restorations verified the higher level of resistance of the additions performed in the 19th century and their stronger congruence with the structural behaviour of the ancient temples. The stone integrations, designed and built according to the ancient constructive technique and use of materials, resulted in excellent conditions of conservation. Despite the presence of some discontinuities, the brick masonries seemed respectful of the constructive system, while the materials and building techniques, although different from the ancient ones, showed several similarities with these latter in terms of behaviour and durability. Furthermore, the analyses of the iron devices – totally reversible, replaceable and maintainable –, testified of the accuracy in the choice of materials and in the design of the shapes, always suited to the different elements to strengthen. In particular, iron chains, braces and clamps, despite some physiological phenomena of oxidation – which however did not have negative effects on the stone surfaces – appeared well-preserved and partially still in action.

By contrast, the analyses of the twentieth-century interventions showed a more rapid obsolescence of materials and a worse state of conservation, mostly due to a lack of aware-

ness in the technical choices. The diffused cement additions displayed advanced phenomena of decay as erosion, disintegration, and pulverization, only a few decades after their realisation. Moreover, the cement integrations carried out during the Fifties on the columns of the Neptune's temple in absence of the preventive cleaning operations, have determined diffused detachment, scaling and delamination. The evaluation of the state of conservation of the eastern front of the Athena's temple represented an even more complex issue. In this case, the presence of the armed perforations determined two relevant problems: first, this system – characterized by the definition of strong bonds between architraves and columns – had completely changed the structural identity of the building by introducing a hyperstatic behaviour. Second, the choice to carry out totally irreversible and invisible perforations and cement injections did not allow technicians to evaluate the state of conservation of the internal reinforcing steel. In addition, the study that preceded the more recent restorations highlighted the general incompatibility between this system and the physical and mechanical characteristics of the travertine, whose porosity did not react well to the injected mixtures, and favoured, at the same time, the penetration of meteoric water and moisture, increasing the risk of oxidation.

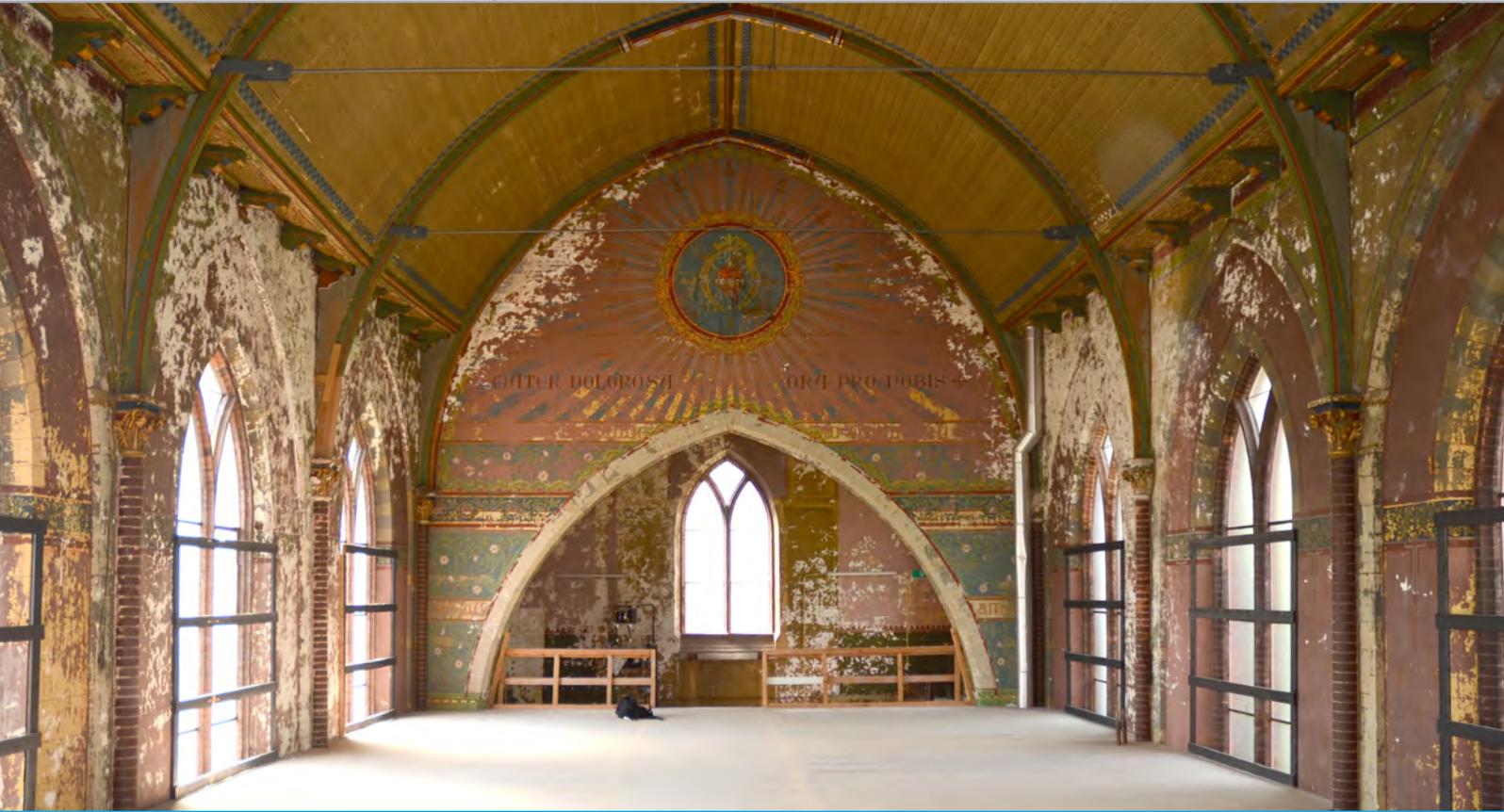
Following a culturally aware approach, the restorations carried out starting from the end of the Eighties were aimed at preserving all the stratifications as much as possible, removing only the most degraded additions or what considered harmful for the ancient structures. Taking into account the results of the nineteenth-century acquisitions and the negative impacts of the use of heavy and incompatible materials, the overall logic of these interventions was to minimize the extent of the operations, as well as to ensure the durability and compatibility of the additions. After an accurate study and a first critical phase of cleaning of the surfaces, in the case of the Athena's temple the works consisted in fixings and micro-fillings made with resins and lime mortars added with pozzolan, chromatically uniformed with the pre-existence. The cement plugs at the beginning of the perforations of the eastern front were removed, in order to protect the steel bars, and, subsequently, reintegrated with lime mortars [14]. For the temple of Neptune, stone elements that were cracked or at risk of a collapse were anchored with steel or fiberglass pins, resin reinforcements, or more simple bonding, calibrated according to the different needs. In most of the cases, the iron devices were fixed and, only if necessary, replaced with new steel elements; the gaps were filled with particular mixtures of lime mortars placed undercut and calibrated in their textures in order to be chromatically and aesthetically compatible with the travertine surfaces [15].

As seen, the approach recognizable in the last restorations of the temples of Paestum appears to be largely influenced both by an interpretation of the methodology of the interventions carried out starting from 1805 and an analysis of their outcomes. If, in the intentions, one can recognize the will to minimize the operations, and to ensure the compatibility and the reversibility of the additions, even in these case, the good quality of the practical results – obtained even by an extensive use of innovative materials – can be verified only after having passed the test of time.

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**FRIDAY
15 SEPTEMBER**

ANALYSIS OF RARE EVENTS AND WEATHER IMITATION FOR THE REALISTIC TESTING OF CONSOLIDATED CLAY-BEARING STONES IN BUILDING FACADES

Ylenia Praticò¹, Fred Girardet², and Robert J. Flatt¹

KEYWORDS

Swelling Inhibitors, Accelerated Testing, Analysis of Rare Events, Ethyl-Silicates, On-Site Monitoring

ABSTRACT

Consolidation treatments applied on swelling clay-bearing stones are claimed to have a particularly limited durability. This has been attributed to the occurrence of cycles of wetting and drying, which induce a dimensional change in the material that ultimately leads to the accumulation of stresses that the consolidant is not able to sustain.

Swelling inhibitors have been suggested as a solution to improve the durability of consolidation treatments, however their long-term performance is still to be investigated.

The aim of this project is to examine the durability of such combined treatments, with a particular focus on the development of a methodology for laboratory testing that is realistic and relevant for on-site practice.

With the aim of avoiding unrealistically intense testing conditions – typical of accelerated laboratory testing –, our approach consists in first identifying the most significant wetting/drying conditions occurring on-site, and then reproducing them as faithfully as possible in the laboratory. In particular, we carry out on-site monitoring campaigns to determine temperature, humidity and water content profile variations.

These are then studied with statistical methods such as the dragon king theory and the grey swan theory – methods of analysis of rare events – to individuate the worst-case scenarios that induce the most degradation. These critical conditions are then reproduced in the laboratory with a machine especially built for this purpose, capable of accurately simulating conditions of rain, wind and thermal profiles. By increasing the frequency of the most detrimental – but nonetheless realistic – conditions, this approach provides a reliable accelerated testing of possible consolidation treatments.

Although this methodology is here specifically applied to study the behavior of consolidated stones, it could be of more general relevance – performing a much higher number of cycles – for the study of the degradation of stones exposed to the outdoor.

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INTRODUCTION

Sandstones containing swelling clays have been widely used in built heritage in different geographical areas. However, this type of stone is very prone to degradation when exposed to weather. This is because swelling clay-bearing stones can expand and shrink in cycles of wetting and drying. This phenomenon leads to the formation of stress and strain gradients in the material, which result in damage such as cracking or buckling, depending on the wetting/drying conditions. The effect of clays in building stones is exacerbated in stones consolidated with ethyl silicates. Indeed, the dimensional changes of these clays seem to be causing the cracking of the consolidant and the loss of most of the restored strength already in the first wetting cycle, when subjected to laboratory testing [1].

Swelling inhibitors have been shown to reduce the swelling strain of clays [2], and are useful in mitigating the damage to the consolidant. More specifically, an α,ω -diaminoalkane treatment was found to be effective on some swelling sandstones [3], thanks to the hindrance of the intra-crystalline swelling mechanism. This treatment consists of a linear hydrophobic alkane chain with protonated amine groups at each end; the amines are believed to substitute for the cations in the interlayer of the clay and act to bind opposing sheets together, while the hydrophobic chain discourages water entry [4]. If used as a pre-treatment, swelling inhibitors could enhance the durability of consolidation treatments.

Recent work investigated the role of a swelling inhibitor on the durability of the Villarlod molasses, previously consolidated with commercial ethyl silicates, Conservare OH and Wacker OH 100 [5]. It was shown that wetting and drying cycles alter the stone whether untreated, consolidated, or consolidated after treatment with the swelling inhibitor. These changes are similar in relative terms, but, for the consolidated samples, there is a significantly reduced consolidation loss if the swelling inhibitor is present. This confirms the relevance of applying such (or similar) products before the consolidation of swelling clay-bearing stones with ethyl silicates. However, questions about the much longer-term behavior subsist.

As a matter of fact, the above-mentioned results are drawn from laboratory studies based on unrealistically intense wetting/drying cycles performed by full submersion and oven-drying. This substantially distorts the evaluation of the performance of consolidants on-site. In particular, such cycles fail to take into account the effect that a partial saturation can have on stones used in building façades, for example.

The aim of this project is to investigate the durability of combined treatments for swelling clay-bearing sandstones, with a particular focus on the development of a methodology for laboratory testing that is realistic and relevant for the on-site practice. Our approach consists in first identifying the most significant wetting/drying conditions and then reproducing them in the laboratory. In particular, we carry out on-site monitoring campaigns to determine temperature, humidity and water content profile variations. These are then studied with statistical methods such as the dragon king theory – a method of analysis of rare events – to individuate the worst-case scenarios that induce the most degradation. These most critical conditions are then reproduced in the laboratory with a machine especially built for this purpose, capable of accurately simulating conditions of rain, wind and thermal profiles. By increasing the frequency of the most detrimental – but nonetheless realistic – conditions, this approach provides a reliable accelerated testing of possible consolidation treatments.

Although this methodology is here specifically applied to study the behavior of consolidated stones, it could be of more general relevance – performing a much higher number of cycles – for the study of the degradation of stones exposed to the outdoor.

ON-SITE MONITORING

The Cathedral of Lausanne, in Switzerland, was chosen as a representative case study for the determination of the on-site conditions leading to damage in swelling clay-bearing sandstones. Indeed, the cathedral has always presented problems related to the conservation of its structure and façade, due to the vulnerability of the building materials chosen for its construction and subsequent restorations (various local soft sandstones, often containing a significant amount of swelling clays).

In view of the next planned restoration campaign, this study aims to provide useful suggestions on the possible application of preventive or consolidation treatments depending on the exposure of different locations on the façade.

In this context, various sensors for on-site monitoring were applied at different locations on the cathedral. Most of these sensors were developed in collaboration with Rino S.A.R.L, a Swiss SME active in consulting for the preservation of cultural heritage. The sensors in question measure the temperature and relative humidity in the atmosphere, at the surface of stones, as well as at various depths [6]. We are further considering the use of impedance measurements, which should support quantification of the water content profile in the stone.

On-site monitoring also requires meteorological data in addition to temperature and humidity monitoring at the stone façade. These weather data include precipitation, wind speed, and wind direction, and allow for the estimation of wind driven rain amount on the façade.

Temperature and relative humidity

The sensors for temperature and relative humidity (RH) are capacitive iButtons Temperature/Humidity loggers DS1923 (Maxim Integrated, San Jose, CA, USA). The sensors applied at the surface of the materials are encapsulated in expanded PVC, and the thermal contact is ensured with a metallic washer surrounded by a filter of PTFE. The sensors measuring the temperature and humidity in the air are positioned a few centimeters from the wall, protected from direct sun radiations by a white screen. Measurements of temperature and relative humidity at different depths were performed by means of a custom set-up consisting of iButtons stacked in a cylindrical shape.

Wind-driven rain (WDR) and wind speed

The research on the quantification of wind-driven rain on building facades is extensive [7]. There exist several methods to estimate wind-driven rain quantities, including semi-empirical calculations and direct on-site measurements. In this work, the ISO method [8] and the Straube-Burnett method [9] are used in combination with WDR gauges for the quantification of the WDR at different orientations. The WDR gauges consist of a 40 cm x 100 cm vertical panel for the collection of water and a tipping bucket mechanism with continuous data logging to register the WDR quantity. Tipping buckets were obtained from DAVIS Instruments Corp., Hayward, California, USA. The data loggers were EL-USB-5 event data loggers, by LASCAR Electronics Ltd., Salisbury, United Kingdom. Wind speed and direction is recorded with a cup anemometer with a WindmasterMark3 for signal acquisition, provided by Schiltknecht Messtechnik AG, Gossau ZH, Switzerland.

Water distribution in the stone

Water content profiles, as well as measurements of temperature and RH at different depths were obtained by means of a SMARTMOTE wireless monitoring system (TTI

GmbH - TGU Smartmote, Stuttgart, Germany). The system consists of two basic components: a Smartbase for signal acquisition and network data transmission, and a Smartmote wireless sensor node, which can be equipped with different sensors. In the present study, Smartmotes are equipped with 6 couples of electrodes for impedance measurements at different depths, and 6 sensors for temperature and humidity (SHT25 by SENSIRION, Staefa (ZH), Switzerland) for the correction and calibration of the impedance signals at each depth.

ANALYSIS OF RARE EVENTS

The Dragon-King theory [10] is a chaos theory for the prediction and prevention of crises, recently developed in the Chair of Entrepreneurial Risks at ETH Zurich. It shows how critical events can occur more often and earlier than predicted by the statistical description of the small or medium intensity events. The “dragon-kings” correspond to the so-called meaningful outliers, which reveal the presence of self-organized systems, *i.e.* a failure regime, which are not apparent otherwise. The presence and importance of dragon-kings were empirically observed in different systems – from economics to materials sciences – using different diagnostic methodologies [11].

The “Grey-Swan” theory [12] defines the grey swans as some high-consequence events that are unobserved and unanticipated but may nevertheless be predictable (although perhaps with large uncertainty).

In stone conservation, the “Dragon-Kings” or “Grey-Swans” would correspond to a specific combination of damaging conditions, during which most degradation occurs.

In this work, these statistical methods are applied to identify the wetting drying conditions that are most significant for the degradation of swelling clay-bearing sandstones.

These cycles are then reproduced in the laboratory with a machine specially built for this purpose. Hence, accelerated aging becomes a question of reproducing the selected critical cycles, increasing their frequency without changing their intensity or nature.

LABORATORY TESTING

For the development of a machine that could mimic the weathering of a building façade, the following aspects were taken into consideration:

1. During wetting cycles, the swelling of non-protruding elements stones is partially restrained by the deeper parts that will tend to remain dry. This influences the level of stress development and is something that a laboratory test ought to reproduce;

2. The rate of water uptake and loss plays an important role in the depth, at which the stone will get wet and will develop stresses owing to clay swelling. This is another behavior that ought to be reproduced, but also monitored over time during laboratory testing;

3. Consolidation never fully restores initial strength and is only effective within a limited depth (typically millimeters to centimeters). One consequence of this is that the properties of the material will change with a gradient that is a consequence of the distribution of the consolidant in the porous structure up to a certain depth. This leads to the development of stresses in an outer layer. This also ought to be reproduced by laboratory testing by consolidating the material from one surface only.

Given the above-mentioned premises, the experimental set up was developed as illustrated in Figure 1 and 2.

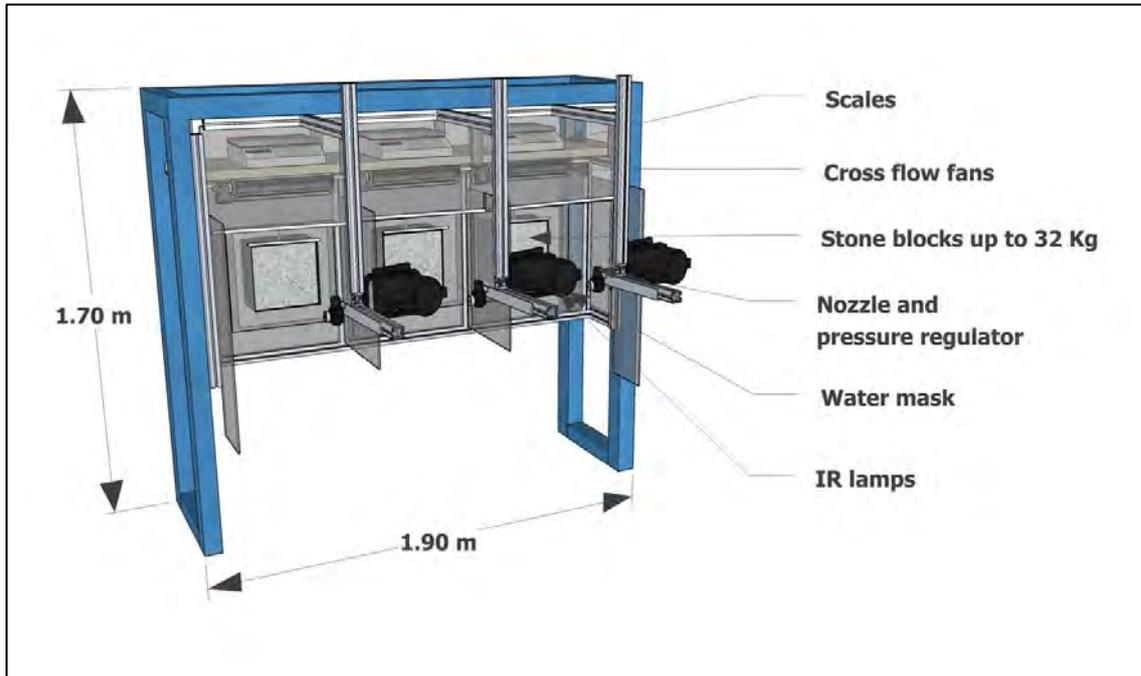


Figure 1: Sketch of the experimental set-up for accelerated laboratory testing



Figure 2: Custom-built machine for the reproduction of weathering conditions on a building facade

The set-up is placed in a controlled environment chamber. The temperature can be adjusted between $-10\text{ }^{\circ}\text{C}$ and $+40\text{ }^{\circ}\text{C}$, the humidity can be controlled between 30% and 95%, depending on the chosen temperature. Samples of up to 32 kg are suspended below a scale, so that their weight evolution may be measured overtime. Only the front surface of the samples is exposed, while the sides and the back are sealed off with a water-based silicon to avoid evaporation. In front of them, a water spray is set up to deliver a defined amount

of water. Flux, drop size and impact angle can be adjusted by regulating distance, inclination and working pressure of the nozzles. A system for masking of the sprayed water is also present to simulate wetting cycles happening on one side only; the position of the mask can be adjusted to guarantee no contact with the sample and use with samples of different dimensions.

The evolution over time of the mass balance makes it possible to follow the rate of water ingress, but also to infer the depth reached by the water, given that the moisture transport properties of the material are characterized (sorptivity coefficient, liquid permeability, moisture diffusivity). Such measurements are complemented by impedance measurements between electrodes inserted in drill holes made on the backside at different depths. Sensors inserted in the samples also monitor temperature and humidity changes at different depths.

Drying conditions such as temperature, radiation and wind speed are regulated by means of IR lamps and cross-flow fans, with adjustable air flow speed and inclination. The objective is to impose wetting and drying rates, which will be representative of different on-site exposures.

OUTPUTS AND PERSPECTIVES

The on-site monitoring has been running for 18 months. The data obtained are now being analyzed using the dragon king theory in order to identify specific combination of damaging conditions, during which most degradation occurs.

In parallel, the weathering machine is now operational.

The first studies on the effect of consolidants and on the coupled effect of consolidants and swelling inhibitors under the most detrimental – but nonetheless realistic – conditions will be started in the coming weeks.

We are confident that the procedure developed here will allow for a better assessment of the performance of consolidants on-site. We moreover trust that such a procedure could be applied to more generic studies of long term behavior of complex systems in the cultural heritage field.

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RENOVATING FUSEE CERAMIQUE VAULTS

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KEYWORDS

Fusée Céramique Vaults, Strengthening, Stiffening, Buckling Risk

ABSTRACT

Just before WW2 the French architect Jacques Couëlle invented a system to build structures, using ceramic tubes embedded in concrete, known as Fusée Céramique. During WW2 this system was used in France and Germany to construct barracks and shelters. After the war this system was applied in France, North Africa and The Netherlands to construct low-rise cylindrical vaults and domes for workshops, swimming halls, stations, schools and churches. Thanks to the ceramic infill the need of material and the dead weight of the vaults was minimal. For example in the city of Woerden, The Netherlands, a cylindrical low-rise vault was built with a span of 19,8 m, a thickness of 135 mm and a ratio thickness-span of 1:147. In 2012 this workshop was pulled down. During the sixties the costs of labour were rising and this system could not compete with other systems. Fifty years later most of these structures are pulled down. The remaining buildings do not meet the demands of the present concerning comfort, safety, insulation and need of energy. Nevertheless these structures are a fine example of engineering, so at least some of these vaults have to be preserved for the coming generations. In the past the low-rise vaults were designed for the permanent load and a modest live load. Unfortunately due to temperature variations and time dependent deformations the Fusée Céramique roofs are subjected to internal forces, which can cause cracks and reduce the stiffness and load bearing capacity substantially. Consequently some vaults are not safe and have to be strengthened.

This paper describes for cylindrical Fusée Céramique vaults, composed of concrete and ceramics, the effect of the time dependent deformations concerning strength, stiffness, buckling risk and bearing capacity. To strengthen these vaults a cost-effective method is described, using the potentiality of the hangers, connecting the ties with the vaults, to reduce deformations and buckling length. Possibly this method can be used to strengthen and stiffen arches and vaults of concrete, masonry, steel and timber too.

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INTRODUCTION

Just before WW2 the French architect Jacques Couëlle invented a system to build structures, using ceramic tubes embedded in concrete vaults, known as Fusée Céramique, to reduce the dead weight and save materials. In 1954 this system was introduced in the Netherlands [1] to construct low-rise vaults and domes. During the sixties the costs of labour were rising and this system could not compete with other systems. Fifty years later most of these structures are pulled down. The remaining buildings do not meet the demands of the present concerning comfort, safety, insulation and need of energy. Nevertheless these structures are a fine example of engineering, so at least some of these vaults have to be preserved for the coming generations. Due to temperature variations and time dependent deformations Fusée Céramique structures are subjected to internal forces, which can cause cracks and reduce the stiffness and load bearing capacity substantially [2]. Probably some remaining Fusée Céramique vaults are not safe and have to be strengthened. This paper describes for these vaults a cost-effective method to increase the buckling resistance and load bearing capacity.



Figure 1: Low-rise Fusée Céramique vault, Woerden, The Netherlands [2].

STRUCTURAL DESIGN

A Fusée Céramique element is a tube with a conical top, which can be shoved into the open rear of the next element. The elements have a length of 350 mm, an outer diameter of 80 mm and a thickness of 10 mm, see figure 2.



Figure 2: Fusée Céramique element used in Woerden, The Netherlands.

The roofs were made on the site. A thin layer of concrete of 25 mm was poured on the mould, The fusées were pushed into the concrete and a second layer was poured on top of the first layer. In a section with a width of 1,0 m eleven elements were placed with a spacing of 10 mm and a centre to centre distance of 90 mm, see figure 3.

Generally the low rise cylindrical vaults were designed with a ratio rise to the span of 1:8 [3]. Low-rise vaults with a span smaller than 15 m were constructed with one layer of fusées and a thickness of 110 mm. For vaults with a span larger than 15 m the thickness had to be increased. So was for a vault in Woerden, with a span of 19,8 m, the thickness increased to 135 mm [2].

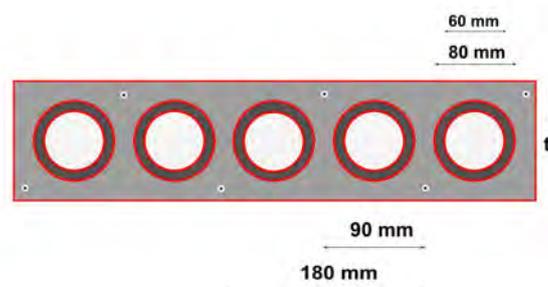


Figure 3: section of a fusée vault perpendicular to the span.

In the past the low rise vaults were designed according to the Theory of Elasticity [3]. The effect of cracks was neglected. The vaults were assumed to be subjected to an equally distributed permanent load q_g and live load q_e acting symmetrically or asymmetrically at one side, see figure 4.

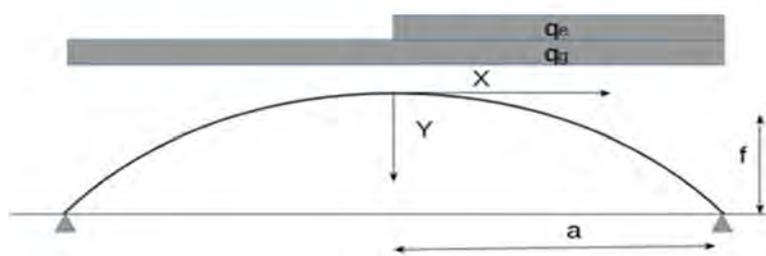


Figure 4: Vault subjected to symmetrical permanent load and asymmetrical live load.

The effect of the stiffness will be shown for a cylindrical vault, following a parabola, with a span of 14,4 m, a thickness of 110 mm and a rise of 1,8 m. The centre of the coordinates is positioned at the crown. To resist the bending moments due to asymmetrical live load this vault was reinforced with bars $\text{Ø}6 - 180$ in the top and bottom. In practice these vaults were not reinforced with distribution bars. Table 1 shows the area and second moment of the area of the Fusées, concrete and steel reinforcement.

Area of the fusées:	$A_f = 11 \times \frac{1}{4} \pi \times (80^2 - 60^2) =$	$24,2 \times 10^3 \text{ mm}^2$
Area of the concrete:	$A_c = 1000 \times 110 - 11 \times \frac{1}{4} \pi \times 80^2 =$	$54,7 \times 10^3 \text{ mm}^2$
Area of the re-bars 2Ø6-180:	$A_s = 2 \times \frac{1}{4} \pi \times \text{Ø}6^2 \times 1000/180 =$	314 mm^2
Second moment of the area, fusées:	$I_f = 11 \times \pi \times (80^4 - 60^4) / 64 =$	$15,1 \times 10^6 \text{ mm}^4$
Second moment of the area, concrete;	$I_c = 1000 \times 110^3 / 12 - 11 \times \pi \times 80^4 / 64 =$	$88,8 \times 10^6 \text{ mm}^4$
Second moment of the area, steel:	$I_s = 2 \times 157 \times (\frac{1}{2} \times 110 - 15 - \frac{1}{2} \times 6)^2 =$	$0,43 \times 10^6 \text{ mm}^4$

Table 1: Area and second moment of the area of the Fusées, concrete and steel for a width of 1,0 m.

The stiffness of the fusées, concrete and reinforcement was assumed to be respectively: $E_f = 17000$ MPa, $E_c = 21000$ MPa and $E_s = 2,1 \times 10^5$ MPa. The stiffness of the vault with a width of 1,0 m was calculated with $EA = \sum E_i A_i = 1,63 \times 10^9$ N and $EI = \sum E_i I_i = 2,2 \times 10^{12}$ Nmm².

For an equally distributed load q the thrust follows from: $H = \frac{1}{2} q \times a^2/f$. For an asymmetrical live load q_e the thrust follows from: $H = \frac{1}{4} q_e \times a^2/f$. At a distance x from the top the normal force follows from: $N_x = (H^2 + V_x^2)^{0.5}$. The permanent load due to the dead load and finishing is equal to $p_g = 2,2$ kN/m². According to the TGB 1955 the live load is assumed to be $p_e = 0,5$ kN/m². Table 2 shows the forces due to the permanent load, a symmetrical and an asymmetrical live load at a distance $x = \frac{1}{2} a$ from the top.

		Sym.		Asym.		
		perm. load	live load	perm. + live load	live load	perm. + live load
shear force:	V	7,9 kN	1,8 kN	9,7 kN	0,9 kN	8,8 kN
thrust:	H	31,7 kN	7,2 kN	38,9 kN	3,6 kN	35,3 kN
normal force:	N	32,7 kN	7,4 kN	40,1 kN	3,7 kN	36,4 kN

Table 2: Resulting forces conform the Theory of Elasticity, for $t = 0$, $x = \frac{1}{2} a$

The critical buckling load was calculated with the well known expression given by Euler: $N_{cr} = \pi^2 EI/(\psi s)^2$. With s the length of the vault from the top to the support. For asymmetrical buckling $\psi = 1$. For a parabolic vault with a ratio $f/l = 1:8$ the length of the vault from the crown to support $s = 1,04 \times a$. Substituting the stiffness and length gives: $N_{cr} = 387,3$ kN. The ratio buckling force with respect to the normal force follows from: $n = N_{cr}/N_d$. For the permanent and asymmetrical live load: $n = N_{cr}/N_d = 387,3/36,4 = 10,6$, thus the effect of the second order is small.

The vault is subjected to bending moments in case the live load acts asymmetrically at one side. The bending moment due to this load q_e is equal to: $M_o = q_e \times a^2/16 = 1,62$ kNm. For $x = \frac{1}{2} a$ the concrete stresses due to the permanent and asymmetrical live load, including second order, are quite small: $\sigma_c = -0,48 \pm 0,85 \times 10,6/(10,6 - 1)$ MPa.

Actually the stresses are effected due to the time dependent deformations. Possibly the vault is cracked and these cracks can reduce the stiffness substantially.

INSTANTANEOUS AND TIME DEPENDENT DEFORMATIONS

The normal load acting at a section of the vault is resisted by the concrete, fusées and reinforcement. Due to a compressive load N the instantaneous specific deformation of the concrete, fusées and reinforcement is $\varepsilon_0 = N/EA$. The forces in the concrete, fusées and reinforcement follow from: $N_c = \varepsilon_0 E_c A_c$; $N_f = \varepsilon_0 E_f A_f$; $N_s = \varepsilon_0 E_s A_s$. For the permanent load $q_g = 2,2$ kN/m the average value of the normal force: $N = 32,7$ kN. For $t = 0$ the specific deformation: $\varepsilon_0 = N/AE = 32700/1,63 \times 10^9 = 2,0 \times 10^{-5}$. Table 3 shows for the fusées, concrete and reinforcement the distribution of the permanent load for time $t = 0$.

$$\begin{array}{ll}
 \sigma_c = 0.020 \times 10^{-3} \times 2.1 \times 10^4 = & 0.42 \text{ MPa} & N_c = 0.42 \times 54,7 \times 10^3 = & 23,0 \times 10^3 \text{ N} \\
 \sigma_f = 0.020 \times 10^{-3} \times 1.7 \times 10^4 = & 0.34 \text{ MPa} & N_f = 0.34 \times 24,2 \times 10^3 = & 8,2 \times 10^3 \text{ N} \\
 \sigma_s = 0.020 \times 10^{-3} \times 2.1 \times 10^5 = & 4.20 \text{ MPa} & N_s = 4,20 \times 314 = & 1,3 \times 10^3 \text{ N}
 \end{array}$$

Table 3: Stresses and forces due to the permanent load for time $t = 0$

The distribution of the loads will change due to the creep and shrinkage of the concrete. Due to shrinkage and creep the specific deformation of the concrete will rise during

time t with $\varepsilon_{sc} + \phi \varepsilon_0$. The total time dependent specific deformation during time t is equal to: $\varepsilon_{sc} + \varepsilon_0 \times (1 + \phi)$. The concrete is firmly attached to the fusées and reinforcement. The fusées and reinforcement will prevent partly the time dependent deformation of the concrete. The concrete, fusées and reinforcement are subjected to inner forces F_c , F_f and F_s . These forces are in balance, thus: $F_c = F_f + F_s$.

Due to the internal forces the composite structure is subjected to a specific deformation $\Delta\varepsilon$. Due to the internal force F_c the specific deformation of the concrete is decreased by $F_c/A_c E_c$. During the time t this specific deformation increases by creep with $F_c k \phi/A_c E_c$. The force F_c is not constant but is increasing during the time t , the factor k compensates for the time dependency of this force. Scherpbier [4] showed that this factor $k = 1/2$. The specific deformation due to the internal force F_c including the creep is: $F_c (1 + k \phi)/A_c E_c$.

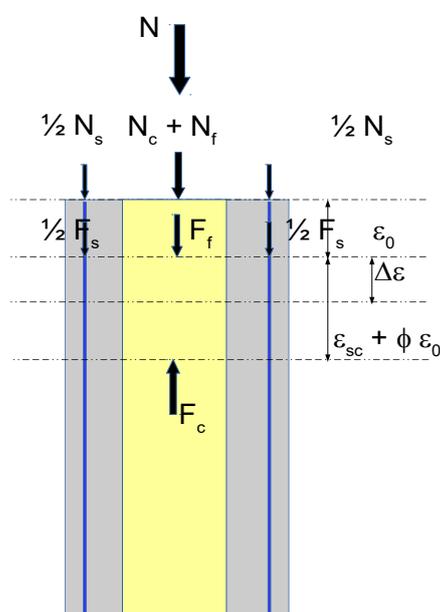


Figure 5: Deformations due to shrinkage and creep and the compensating forces for the vault composed of concrete, steel and Fusées.

The specific deformation $\Delta\varepsilon_x$ and the internal force F_x for the concrete, fusées and reinforcement follows from:

$$\Delta_c = \frac{\varepsilon_{sc} + \phi \varepsilon_0 - F_c (1 + k \phi)}{A_c E_c A_c} \quad F_c = \frac{E_c A_c}{(1 + k \phi)} \times [\varepsilon_{sc} + \phi \varepsilon_0 - F_s / E_s A_s]$$

$$\Delta_f = F_f / E_f A_f; \quad F_f = F_s E_f A_f / E_s A_s$$

$$\Delta_s = F_s / E_s A_s \quad F_s = \frac{[\varepsilon_{sc} + \phi \varepsilon_0] \times E_c A_c / (1 + k \phi)}{1 + [A_f E_f + E_c A_c / (1 + k \phi)] / E_s A_s}$$

Table 4 shows the stresses and forces due to the time dependent deformations for the permanent load, calculated for a specific deformation of the concrete due to shrinkage $\varepsilon_{sc} = 0.4 \times 10^{-3}$ and a creep coefficient $\phi = 3$. The concrete is tensioned, probably the

concrete will be cracked. Due to the cracks the stiffness of the vault will be much smaller than assumed before.

	Normal force	Stress: $\sigma_x = N_x / A_x$
concrete	$-N_c + F_c = -23,0 + 107,9 = + 84,9$ kN	$\sigma_c = + 84900/54700 = + 1,55$ MPa
fusées	$-N_f - F_f = - 8,2 - 93,0 = - 101,2$ kN	$\sigma_f = - 101200/24200 = - 4,2$ MPa
reinforcement	$-N_s - F_s = - 1,3 - 14,9 = - 16,2$ kN	$\sigma_s = - 16200 / 314 = - 51,6$ MPa

Table 4: Stresses and normal forces due to the permanent load for time t.

ULTIMATE STATE

Nowadays structures are designed in the ultimate state to resist design loads, including the safety factors. For the given vault, described previously, the maximal design load: $q_d = 1,2 \times 2,2 + 1,5 \times 0,5 = 3,4$ kN/m. Due to the permanent load and asymmetrical live load the vault is subjected to a bending moment $M_d = 1,5 \times 1,62 = 2,43$ kNm and normal force $N_d = 1,2 \times 32,7 + 1,5 \times 3,7 = 44,8$ kN. For the ultimate state the stiffness is defined with a MN- κ -diagram [5] for the ultimate design load: $N_d = 44,8$ kN, see figure 6. For $M_d = 2,43$ kNm the stiffness $EI = 0,32 \times 10^{12}$ Nmm².



Figure 6: MN- κ diagram, ultimate state for a normal force $N_d = 44,8$ kN.

The buckling force: $N_{cr} = \pi^2 \times 0,32 \times 10^{12} / (1,04 \times 7200)^2 = 56,3 \times 10^3$ N. The ratio buckling force with respect to the normal force is very small: $n = N_{cr} / N_d = 56,3 / 44,8 = 1,3$. Due to the second order the bending moment increases much: $M_d = 2,43 \times 1,3 / (1,3 - 1) = 10,5$ kNm. This bending moment, including the second order, is larger than the ultimate bending moment $M_u = 4,9$ kNm, so the structure is unsafe and has to be strengthened. Possibly hangers between the ties and vault can reduce the effect of the second order. Especially for renovations this can be very cost-effective. The potentiality of the hangers to reduce the effect of the second order will be studied for the described vault.

TIES AND HANGERS

Three or more hangers, connecting the tie with the vault, can reduce the buckling length substantially, provided the slender hangers do not buckle. Palkowski [6] researched for bridges the increase of critical buckling load in case all hangers are tensioned continuously due to the load acting on the deck. For a structure with three hangers the buckling length follows from: $l_{buc} = \psi s = [1 - \cos \phi]^{1/2} \times s \geq 1/2 s$. For an arch or vault with

$f/a = 1/4$ and $\cos \phi = 0,8944$: $\psi = (1-0,8944)^{1/2} = 0,32$. Due to the hangers the factor ψ is smaller than $1/2$, then the buckling length $l_{buc} = 1/2 s$ is decisive.

The hangers of a bridge with the deck hanging on the arches, are tensioned continuously. However the hangers of a vault, supporting the ties, are not tensioned continuously. Possibly some hangers are compressed if the vault is loaded asymmetrically. Slender hangers cannot resist compressive forces, so the buckling of the vault is only restricted by the tensioned hangers. Consequently the critical buckling length is not reduced much [2]. Curving the ties upward, by shortening the hangers, will tension all hangers and reduce the buckling length of a vault substantially. However a convex tie will decrease the lever arm and increase the thrust, so the camber must be small, just enough to tension the hangers continuously. For the described vault the effect of the convex tie will be shown.

Assume the coordinates of the tie are halfway the span and at a quarter of the span respectively $c \times f$ and $3/4 c \times f$. Due to the curvature of the tie, the rise of the vault decreases with $f \times (1-c)$. For a vault subjected to an equally distributed load q the thrust increases with a factor $1/(1-c)$: $H = 1/2 q a \times (a/f)/(1-c)$. The force S , acting at the hangers, follows from the equilibrium of the bending moments for the tie halfway the span and at a quarter of the span: $S = H \times c \times f/a$. For the vault the bending moments are for $x = 0$ and $x = 1/2 a$ equal to zero. So the forces S do not increase the bending moment.

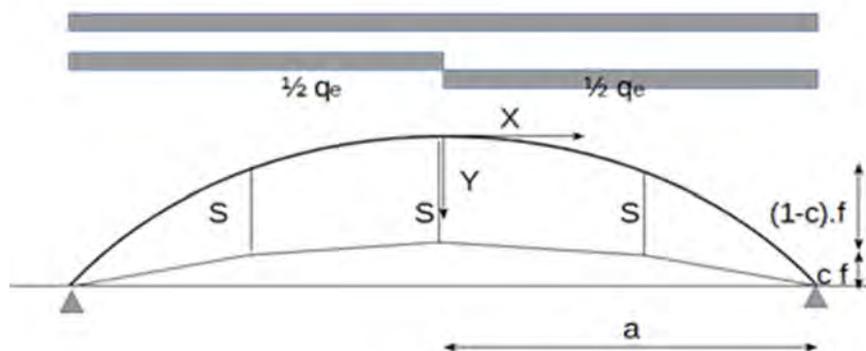


Figure 7: Vault with convex tie subjected to a symmetrical and anti-metrical load

An asymmetrical load q_e acting at half of the vault can be splitted into a symmetrical equally distributed load $1/2 q_e$ and an anti-metrical load $1/2 q_e$, see figure 7. The thrust H due to the anti-metrical load $1/2 q_e$ is zero, so the force S is not effected by anti-metrical load. For $x = 1/2 a$ the bending moment is still equal to: $M_{x=a/2} = q_e \times a^2/16$.

		Sym.		perm. + live load	Asym.	
		perm. load	live load		live load	perm. + live load
shear force, $x = 1/2 a$	V	8,8 kN	1,9 kN	10,7 kN	1,0 kN	9,8 kN
thrust:	H	33,4 kN	7,6 kN	41,0 kN	3,8 kN	37,2 kN
hanger	S	0,4 kN	0,1 kN	0,5 kN	0,1 kN	0,5 kN
normal force:	N	34,5 kN	7,8 kN	42,3 kN	3,9 kN	38,4 kN

Table 5: Resulting forces for the vault with convex tie with $c = 0,05$.

Table 5 shows the results for a vault with convex ties and $c = 0,05$ for $x = \frac{1}{2} a$. Comparing the results of table 2 and table 5 shows that the normal loads do not increase much due to the convex tie.

Due to the permanent load and asymmetrical live load the vault is subjected to a normal force and bending moment of respectively $N_d = 1,2 \times 34,5 + 1,5 \times 3,9 = 47,3$ kN and $M_d = 1,5 \times 1,62 = 2,43$ kNm.

For a buckling length $l_c = \frac{1}{2} \times 1,04 \times 7,2$ m the buckling force $N_{cr} = 225,3 \times 10^3$ N. The ratio buckling force with respect to the normal force $n = N_{cr}/N_d = 225,3/47,3 = 4,8$. Due to the second order the bending moment is increased slightly: $M_d = 2,43 \times 4,8 / (4,8 - 1) = 3,1$ kNm. This moment is smaller than the ultimate bending moment: $M_u = 4,2$ kNm. This vault with convex tie can transfer the ultimate design loads safely.

CONCLUSIONS

The time dependent deformations can reduce the stiffness of Fusée Céramique vaults composed of fusées, reinforcement and concrete much. Possibly slender vaults are not safe concerning the buckling risk and have to be strengthened. Shortening the hangers will curve the ties upward. The convex ties will tension the hangers continuously. Tensioned hangers reduce the buckling length of the vault substantially. However shortening the hangers will increase the normal forces, so it is advisable to curve the ties slightly, just enough to tension the hangers continuously.

Possibly the described method to strengthen the Fusée Céramique vaults can be helpfully to preserve these slender vaults for the coming generations. Furthermore this method can be also used to design arches and cylindrical vaults efficiently, to save materials, to reduce the embodied energy and to decrease the emissions of greenhouse gasses.

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DEVELOPMENT OF AMMONIUM OXALATE TREATMENT FOR SITE CONDITIONS - INITIAL RESULTS

Tabitha Dreyfuss¹

KEYWORDS

Limestone, Consolidation, Oxalate, *In Situ* Treatment

ABSTRACT

This paper presents an overview of the first phase of post-doctoral research work being carried out on the consolidation of a soft and porous limestone using ammonium oxalate. Although oxalates are primarily considered to serve a protective role, the function being currently researched is consolidation of salt-infested stone, susceptible to salt damage. This research work follows previous doctoral work which systematically looked at ammonium oxalate treatment to Globigerina Limestone and progressed systematically from the laboratory to the field. In the laboratory, individual salts - sodium chloride, sodium sulfate and sodium nitrate - were artificially introduced to previously desalinated quarry stone and the oxalate treatment was then applied by poultice. This was followed by a second phase, where identically contaminated quarry sample sets were treated and exposed to external urban conditions, to weather naturally for one year. During this second phase, a parallel study was carried out on the weathered stones of one exposed wall of the historical building chosen to house the exposed laboratory samples. This sequence allowed for the evaluation of the effects of the different factors, one variable at a time. The conclusions and recommendations for further research from the doctoral work formed the basis for this post-doctoral research project. This includes the study of the same oxalate treatment in the presence of naturally-occurring salt mixtures in historical buildings. Three location typologies were identified, being coastal, rural and urban sites, as representative of the expected predominantly occurring chloride, nitrate and sulfate soluble salt types respectively. Additionally, a calcium carbonate dust additive was considered in the modified treatment procedure, which also saw the change from poultice application to brush application of the oxalate. In this paper, the focus is on the first evaluation, by DRMS, of the treated areas in the first site being studied – a fortification wall situated on the shoreline on the Mediterranean Island of Malta. The success of the consolidating treatment was thus confirmed, in the form of an increase in drilling resistance, the magnitude of which was found to be directly related to the application method/presence of additive, an encouraging verification of the performance of the treatment in a real situation. By means of these findings, it has been established that ammonium oxalate treatment for the conservation of salt-contaminated historic porous limestone is possible, and thus this research is planned to continue for another two years, to develop its relevance to practice.

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INTRODUCTION – DOCTORAL RESEARCH WORK

The research which led to the current postdoctoral work was carried out at doctoral level and aimed at investigating the efficacy of ammonium oxalate treatment on highly porous (up to 40%) Globigerina Limestone [1]. This work was based upon previous work with ammonium oxalate treatment which started in Italy in the early 1980s and is based on the chemical reaction of ammonium oxalate with calcium carbonate to form the more durable – especially to acidic environments - calcium oxalate [2, 3]. This research was followed by testing on local limestone in Malta [4, 5, 6, 7, 8]. Other studies also extended the research to *in situ* monuments, and included marble besides limestone [9, 10, 11], while other research on ammonium oxalate diffusion is also being carried out [12].

The doctoral study [1] was structured in three phases: laboratory treated samples in Phase 1, identical samples exposed to natural site conditions for one year in Phase 2, and *in situ* wall samples in Phase 3. This study therefore progressed from a laboratory based, controlled environment, to uncontrolled site conditions. Laboratory samples included salt-free samples and samples artificially contaminated with sodium chloride, sodium sulfate and sodium nitrate respectively. Phase 2 included quarry samples and stone artificially weathered with the same salts as those utilised in Phase 1. Phase 3 wall samples consisted of naturally weathered stone of the same type.

Treatment was applied using a 5% ammonium oxalate monohydrate cellulose pulp poultice. Testing was carried out throughout the three phases, and included visual observations, colorimetric analyses, adhesion (tape) tests, Drilling Resistance Measurement System (DRMS) testing, X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM with EDS), acid resistance tests, salt crystallisation tests, salt mobility testing, open porosity and pore size distribution measurements and water absorption tests by capillarity. Results showed that whewellite was formed in all treated samples, even in the presence of the soluble salts, and no deleterious by-products were detected which was in keeping with research being carried out by others [13]. Treatment also resulted in aesthetic improvement and surface consolidation while still retaining the water transport properties, albeit these being slightly reduced. The form (crystal orientation) and depths of whewellite formed, which overall occurred at a depth of 0.7mm to 1.6mm, were found to be related to the soluble salt types present during treatment [15].

Natural weathering of treated stones resulted in limited differential deterioration after one year of site exposure. In this current stage of the research, the addition of a calcium carbonate (limestone) dust has been included to potentially counteract this type of surface deterioration, by providing an increased surface area for reaction with ammonium oxalate [6] which could assist in distributing the resulting calcium oxalate more evenly and potentially mitigating future differential deterioration [1].

POSTDOCTORAL RESEARCH PROGRAMME

Conclusions from the doctoral research described above led to the development of a programme for continued research. This was aimed at extending and developing the research on ammonium oxalate treatment to onsite scenarios so as to evaluate and potentially enable *in situ* conservation. The presence of naturally occurring salt mixtures was the next step that prompted the testing of three distinct sites, where one of the three salt types considered individually at doctoral stage would be expected to be predominantly present, due to the site's location. Historical buildings were examined in coastal areas, rural areas and

urban areas where chlorides, nitrates and sulfates respectively would probably be predominant in an otherwise varied salt mixture.

Different modes of application of the treatment were also incorporated in the study, where both the already studied poulticing method, as well as application by brush, would be examined. Besides being more practical on site, brush application would allow for the addition of a powder (calcium carbonate dust) as per recommendations resulting from the doctoral research outcomes [1]; in this way, the resulting suspension could be applied directly to the stone's surface rather than through the poulticing medium which could possibly selectively remove the dust.

SITE SELECTION

The first site selected was Saint Sebastian Bastion, part of the fortifications of Marsamxett Harbour, Valletta, Malta and located directly on the coast of the Mediterranean Sea, 35m from the shoreline. In addition to the proximity to the sea, the restoration of this Bastion is envisaged in the near future, making it an ideal study area where the future interventions may benefit from the results obtained in this research.



Figure 1: Basemap showing area studied and its proximity to the sea (<http://geoserver.pa.org.mt>).



Figure 2: Rectified photography of Saint Sebastian Bastion, Valletta, showing area considered, (Restoration Directorate, Malta).

WORKING METHODOLOGY

Two treatment methods were simultaneously (within a period of 1 hour) applied *in situ* in different areas, at approximately 7 m above street level. The mean ambient temperature during treatment was 26°C and the mean Relative Humidity was 72%.

The first application consisted, as per the usual established methodology, of a 5% ammonium oxalate monohydrate solution applied in a cellulose pulp (300µm) uncovered poultice left in place for 24 hours. Following treatment, the still-damp poultice was manually removed and the excess pulp brushed off with a dry, soft nylon brush. The second application method was by brushing and included a 5% ammonium oxalate monohydrate solution together with 5% (in the ammonium oxalate solution) of graded limestone dust (passing 600µm sieve). The weight of ammonium oxalate used per square metre in the two treatment types was calculated. This was found to be 4 times greater in the poultice application than that in the brush application. In both cases, after treatment, the stone was left to air dry for 3 days at ambient conditions (22-40°C temperature and 34-89% Relative Humidity) prior to the commencement of testing.

Besides these two treatments, an additional two applications were carried out with water only i.e. in which no ammonium oxalate was added. These served as controls, being one containing a cellulose poultice and the other a limestone dust suspension in water applied by brush. In this way, any effects brought about by the application method but independently of the ammonium oxalate could be discerned.

Selected tests were subsequently carried out directly on site, while cores 20mm (diameter) x 30mm (deep) were extracted 1 week post treatment for laboratory testing.

THE TESTING PROGRAMME

The chosen tests within the postdoctoral work are in part carried out on site, and these include colorimetry, Drilling Resistance Measurements (DRMS) [15] and the contact

sponge test [16], and in part laboratory-based and carried out on the extracted cores, including ion chromatography, X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM & EDS), helium pycnometry and Mercury Intrusion Porosimetry (MIP).

This selection allows for a comprehensive range of data to be obtained at an early stage after treatment. These tests will give information on the aesthetical changes induced by the treatment, through colorimetry, any consolidating effects achieved and the depth to which this was reached, both of these through DRMS, and also data on the water transport properties after treatment through the contact sponge test. The subsequent laboratory-based tests allow for further in-depth analysis into the salt mixtures present on site through ion chromatography, whether any adverse by-products are formed by the treatment through XRD, the surface topography brought about by the treatment through SEM and any effects on the porosity and pore size distributions through helium pycnometry and MIP.

The first results from the DRMS testing are discussed hereunder. DRMS measurements were carried out using a 5mm diamond-end drill bit at a penetration rate of 20mm/min and 300 revs/sec.

DRMS RESULTS AND DISCUSSION FROM SITE 1

Drilling resistance measurements were first carried out on the untreated stone, where the initial 1.10mm were found to register a value of 3.0N, approximately 2.0N less than that recorded in unweathered stone elsewhere (which ranged from 4.77N to 5.11N) [1, 17]. This difference is thought to be the result of naturally occurring inhomogeneities within the stone itself, as well as natural weathering within the stone's surface occurring over the course of time. Following the surface applications, an increase in drilling resistance within the outer 1.10mm of stone was recorded for all interventions, (Figure 3).

The stone treated with the blank poultice recorded an increase of approximately 1.0N; this could be explained as due in part to calcite dissolution and re-deposition at the surface [18] as well as to salt mobilization to the surface through the poulticing mechanism [19]. Treatment with the ammonium oxalate poultice gave a further increased drilling resistance within the stone's first 1.10mm, with a peak drilling resistance of 7.75N occurring at a depth of 0.6mm. This can be explained as the result of the increased hardness of the calcium carbonate converted to calcium oxalate, over and above the increased hardness contributed by calcite mobilization and the salts mobilized to the surface [20].

For the brush and limestone dust applications, an increase in the first 1.00mm was also recorded for both the blank application (from 3.0N to 5.70N) as well as that including ammonium oxalate (from 3.0N to 4.49N with a peak of 4.76N at a depth of 0.8mm). With this application, salt mobilization was not observed in SEM examinations [19] and therefore this phenomenon is not thought to contribute to the increased drilling resistances here.

With the addition of ammonium oxalate to the brush and limestone dust application, there was unexpectedly no further increase in drilling resistance and this is possibly related to the reduced reaction time for calcium oxalate formation with brush application as well as to the lower amounts of ammonium oxalate solution involved in this method of application, although further research is required. The increased values are therefore considered to be predominantly due to the carbonate dust itself rather than to the resulting calcium oxalate. In addition to physically occupying the space available in the crevices present on the surface of the weathered stones resulting in "filling", the actual adhesion and cohesion of the calcite dust to the weathered stone is probably also accompanied by calcite dissolution, mobilisation and re-deposition to form a more compact surface, whilst also "binding" in some of the applied stone dust. This would give rise to a greater value of drilling resistance

when compared to unfilled pores and spaces in the untreated stone surface. Further research is under way.

Even though the two treatments both involving brush and limestone dust application result in increased hardness, implying a perceived consolidating effect, the actual long-term adhesion and cohesion is an important factor to consider. The addition of ammonium oxalate in this treatment type was seen under SEM examinations to bridge crystals together and to the parent material underneath giving rise to predicted “long-term” treatment [19]. The amount of adhesion and cohesion that would occur following calcite dissolution, mobilisation and re-deposition alone requires further research, in particular on quarry, untreated samples.

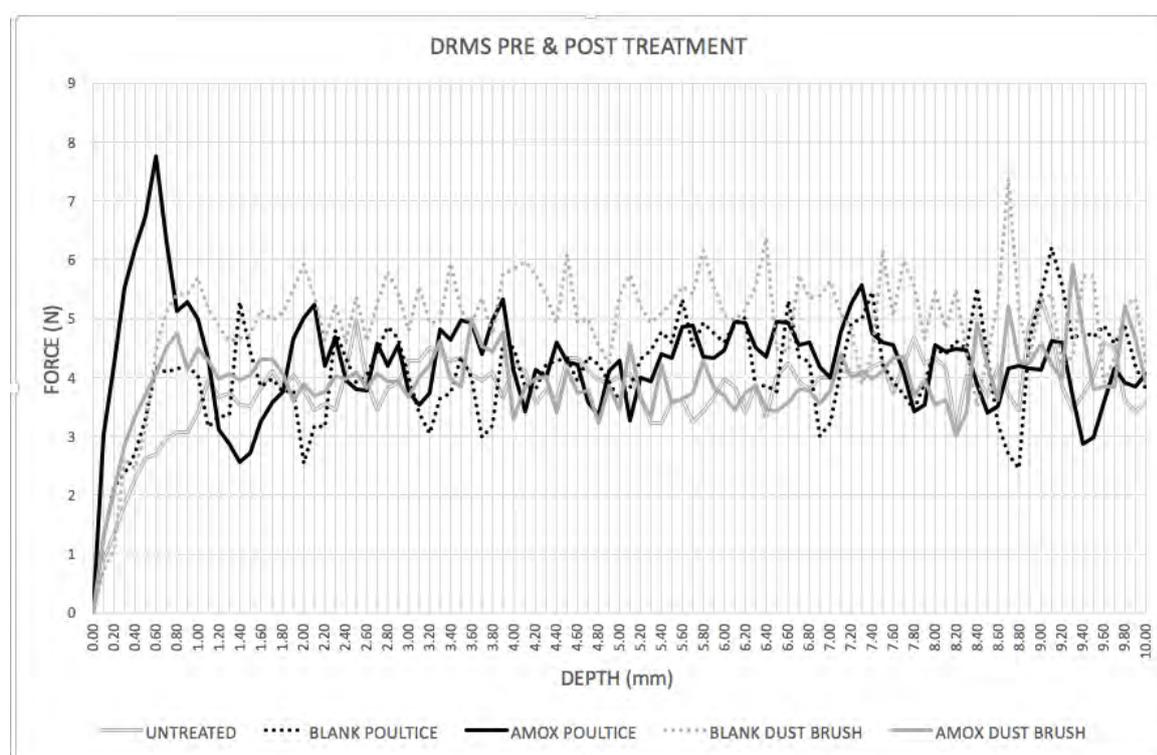


Figure 3: DRMS results from Saint Sebastian Bastion, Valletta.

CONCLUSIONS – RELEVANCE TO PRACTICE

The results obtained from the DRMS measurements show that poultice treatment with ammonium oxalate increases the surface drilling resistance to a greater extent than both types of brush application with limestone dust additive – with and without ammonium oxalate. The increased amount of consolidant product available in the poultice application together with the poultice mechanism itself probably accounts for a significant part of this difference. The increased hardness obtained with the poultice treatment may suggest this application method to be preferable to application by brush. However, when considering consolidation, it is important to avoid “excessive” surface consolidation which can lead to a surface crust with a greater drilling resistance than the underlying stone. Additionally, the water transport properties in the treated region should always be retained. The formation of any secondary by-products when treatment is applied in the presence of different individual salts and different salt mixtures requires verification through ion chromatography and X-Ray Diffraction, which is ongoing.

The absence of a crust forming through both brush applications suggests that this application method is worth considering. The increased hardness in the absence of ammonium oxalate brush application requires further research. It is worth noting here that the 6 graphs represented in Figure 3 correspond to different stone blocks on site and therefore the natural variations from block to block may account, at least in part, for this discrepancy. The values obtained for the drilling resistance with both brush applications are close to those obtained elsewhere for unweathered quarry stone. Therefore, application by brush may be both more practical on site as well as result in drilling resistances that are more acceptable. Furthermore, this application method has the added advantage of seemingly not mobilizing salts present within the stone [19]. Continued research is ongoing.

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LIGHTWEIGHT VAULTING SYSTEMS IN THE EARLY 19TH CENTURY, FROM NAPLES TO EUROPE. KNOWLEDGE FOR CONSERVATION OF AN ADAPTIVE BUILT HERITAGE

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KEYWORDS

Historical Construction Techniques, Vaulting, Adaptability, Vulnerability, Conservation

ABSTRACT

In the Kingdom of Naples, as well as in Europe, the early 19th century was a period of deep experimentations in relation to innovative lightweight ‘mixed’ vaulting systems. The strong interlace between scientific culture and empirical knowledge, together with a renovated *constructive* Neoclassicism, represented crucial aspects for the definition and diffusion of building systems which were alternative to a *heavy* constructive practice, well established and much better-known. The technical competence which was developed in those years was extraordinary and demonstrated the capacity of architects and engineers to learn from the past and to propose innovating and unusual building vaults. They are structures made up of lightweight materials such as wood, concrete with light and volcanic aggregates, bricks laid lengthwise and cylindrical hollow clay bricks. An interesting aspect is related to the widespread diffusion of this technical competence, from Naples to European countries such as France and Germany.

This ongoing PhD research explores the level of progress which the 19th century building yard proves in the evolution of lightweight construction techniques – with particular reference to vaulting systems – by evaluating the adaptability and vulnerability as well as the resilience capacity compared with extreme events such as earthquakes. This research – by starting from an historical study that inevitably interlaces direct surveys – comes to envision the conservation project by encouraging further reflection about issues related to vulnerability and adaptability of these constructive systems.

Our main goal is to devise an exhaustive framework of knowledge, which is necessary for defining possible intervention approaches for these particularly vulnerable systems. In fact, the lacking knowledge of historical construction techniques can cause wrong and damaging restoration projects. It is necessary, instead, to find methods for a sustainable restoration, by using ‘compatible’ materials and adaptive techniques and by safeguarding the monumental value. The current state of the art for these construction systems requires further in depth-analysis and new practical applications aiming at supporting an aware project of restoration.

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INTRODUCTION

The Early 19th century represents a moment of remarkable liveliness and experimentation in Italy as well as in Europe, with interesting implications on the construction yard of the period: the scientific advancements of the 18th century in the field of Statics provide a potential breeding ground for the following researches, by paving the way to a new manner of architectural conception, clearly in opposition to the predominant intuitive approach [1].

In comparison to the 18th century treatises, a significant improvement in the method is evident: the attention is not more focused only on the stereotomy but also on the materials properties. In the 19th century, in fact, there was a renovated interest towards this theme and the ‘tangible’ parts of the buildings. This period’s treatises clearly testifies such a trend: by analysing both the works by French architects – such as Rondelet, Borgnis, Sganzin – and by Italian ones – as Cavalieri San Bertolo, Valadier, de Cesare – it is possible to deduce the constructive techniques and the materials which were used for the realization of vaulting in this period. They are lightweight structures made up of materials such as wood, concrete with light and volcanic aggregates, bricks laid lengthwise and cylindrical hollow clay bricks.

Simultaneously it should be emphasised a renovated interest – starting from the 18th century and partially justified by the discovery of the archaeological towns of Pompei and Ercolano – for the ancient constructive techniques and in particular for the Roman-Byzantine ones. Numerous journeys carried out by French, German and English architects in Italy within the Grand Tour paved the way for a reinterpretation of the ancient constructive systems, which were reproduced and sometimes emulated by the European technicians in the most important architectures of the period.

Moreover, the strong political and cultural relationships between regions only apparently far apart – such as France and the Kingdom of Naples, later of the Two Sicilies – facilitated the circulation and sharing of scientific and technical knowledge with undeniable results in the architectural projects. The establishment in Naples of the *Scuola d’applicazione di Ponti e Strade* (1811) – on the French model of the *École d’application des Ponts et Chaussées* – strongly contributed to the training of professionals which were constantly up-to-date and open to the dialogue with the French and European scholars [2].

Contrary to the 18th and the previous centuries which have been studied by many research teams from the construction techniques point of view [3], the 19th century, with a few exceptions [4], has still not been investigated sufficiently. The research works on contexts which are different culturally and geographically, by analyzing the relationships between the scientific knowledge of academia and the empirical ones of the local construction cultures. Moreover, the thesis aims at understanding the basic rationales behind the spread of lightweight vaulting systems by paying particular attention to the sharing of knowledge, the scientific expertises together with the technical competences.

The contexts that this work investigates, in fact – although far apart and for reasons completely different – show and testify the spread of lightweight constructive systems, sometimes very original, but in each case relating to the requirement to unload the ceilings. Starting from the Contado of Molise (nowadays Molise), a little region of the Central-Southern Italy, which was hit in 1805 by a violent earthquake, this ongoing research presents a rich records of lightweight construction techniques spread in Naples – the political and cultural Capital city of the Kingdom – and in some European countries, such as France and Germany.

BETWEEN ART AND SCIENCE. THE SPREAD OF LIGHTWEIGHT VAULTS FROM SOUTH ITALY TO EUROPE

Contado di Molise (Italy)

On July 26, 1805 a violent earthquake damaged a large area of the South Italy, in particular the ‘Contado of Molise’, one of the more underdeveloped region in the Kingdom of Naples. The earthquake destroyed completely the majority of the identity buildings of the urban centres, by imposing reconstruction or restoration in fewer cases [5]. Starting from 1806 – in spite of the lack of a rebuilding programme – a lot of construction yards linked to the ecclesiastical and civil architectures were opened. The analysis of the projects and in particular of the bills of quantities allows to define the main construction techniques which were used to build the new vaults. They are made up of several materials such as wood, concrete with aggregates together with both full and hollow bricks.

A variety of systems were employed, testifying the richness of the vernacular constructive tradition due to economical reasons and the availability of the materials in the area. Moreover, it should be borne in mind the need to realise lightweight vaults that were able not to weigh down on the weak structures in elevation and to avoid collapses because of the horizontal loads in the event of further earthquakes. All the technicians working on the damaged architectures were master builders and only after the Second Restoration in 1815 engineers which came from the Neapolitan *Scuola d’applicazione di Ponti e Strade*. The relationships between these two professional-classes, which respectively embodied cultures rested on an empirical and scientific approach, became stronger in this period. It produced a fruitful dialogue and an interlace of expertises which are clearly deductible by the used technical solutions, which are often mixed, between tradition and innovation.



Figure 1: Italy, Baranello (Campobasso). St. Michele Arcangelo church. The extrados of the vault in the central nave: the image shows the wooden structure and the concrete made up of gypsum and lime (L. Romano 2016).

Besides the known and wooden vaulting – so-called «incannucciata» – widespread in the Neapolitan area as well as in other contexts of the Southern Italy (Abruzzo, Campania), this ongoing research deepens the use of a variation of the traditional wooden vault, which is made stiffer thanks to the presence of a concrete casting in lime and gypsum on the extrados, namely *a colo di gesso*. The use of this constructive system has been proved through direct surveys and archival documents: it was commonly employed for several churches in Molise, such as the Cathedral of Campobasso, the St. Michele church of Baranello together with the St. Croce church of Vinchiaturò. The structure of the vault is made up of few beams, so-called *filagne* together with horizontally little poles, wooden straws and a concrete layer of 6 centimetres. In the archival documentation these vaults are defined «strong but lightweight and usable to walk above» in spite of their vulnerability in case of construction errors. The system, moreover, is partially suspended to the roof, through little wooden poles, known as *rielle* [6].

Despite some critical issues, it should be emphasised that the lightness of this constructive system was one of the reason justifying its use in the architectures of Molise; moreover, the presence of a layer of lime and gypsum on the intrados and extrados of the vault legitimizes the greater stiffness compared to the classical wooden vaults. In addition, it protects against deterioration of the wood.

This technique was proposed by Leonardo Massimiliano De Vegni, the author of an interesting essay published in an architectural journal in 1788 [7]: he showed various methods aiming at increasing the duration of the wooden structures by plastering with gypsum and by covering with lime the vaults as previously suggested by Sebastiano Serlio in his treatise of Architecture.

Another material – available in situ and used both for the realization of structures in elevation and vaulting – was the *cimento*, defined as «lightweight and porous tuff, namely concrete of water» [8]. After the earthquake, several vaults were built by using this material, which belongs to the family of travertine; this type of structure, moreover, withstands the humidity and the meteoric infiltrations. As the volcanic aggregates – although of a greater weight – the *cimento* is a natural stone particularly lightweight and, therefore, very convenient for the construction of concrete vaults. This technique can be considered as a legacy of the roman *opus caementicium*: it was used in many churches of Molise such as Frosolone and Bojano as well as described by Giuseppe Valadier in his treatise, by testifying the strong spread of the system in the Central and Southern Italy [9].

It should be emphasised that master builders, and engineers later on – taking into account the availability of the materials in the areas – chose different constructive techniques for the realizations of the vaults of the ecclesiastical and civil architecture. In some projects – such as in the Mother church of Castropignano (Campobasso) – were used the bricks laid lengthwise while in others – like in Collegio Sannitico of Campobasso – the hollow clay pots, locally known as *pignatielli*. This testifies the great variety of the constructive technologies that, despite their difference, are all lightweight and better adaptive to possible future earthquakes.

Naples

Lightweight vaults spread out not only in Molise but also in Naples, the political and cultural Capital city of the Kingdom, as well as cornerstone of the scientific debate in the Southern Italy. In this case, however, it was not an earthquake to impose the use of lightweight materials but the awareness – following the advancements of the Science of Construction – of the need to reduce as more as possible the horizontal loads and the

pressures from the vaults to the masonries. In fact, in the case of vaults not excessively loaded or addressed to withstand only their own weight, it is preferable using full or hollow bricks, pumices or wood. This trend is confirmed by the most known architects of the early 19th century such as Valadier, Cavalieri San Bertolo, de Cesare and others. They dedicated entire sections of their treatises to the different materials which can be used for the realization of vaults.

In Naples and in the neighbouring towns, this research reveals a prevailing use of lightweight construction techniques which were alternative to a ‘heavy’ building praxis, characterized by the presence of the Neapolitan yellow tuff. The analysis of the bills of quantities related to the project of reconstruction or restoration of the Neapolitan Royal Palaces – mainly the Royal Palace and the Capodimonte Realm – highlights the usage of a great variety of materials, from the pumice of Vesuvius and Lipari to the bricks laid lengthwise. Although this technique was common in the Northern Italy and in Sicily also in the previous centuries, it was firstly used in Naples for the vaults of the Royal Palaces in the early 19th century. According to the archival documentation, these vaults were realized by a Sicilian master builder, a *damusellaro*, the only technician able to build this type of vault. Beyond the strong influence of France – where this technique started spreading from the second half of the 18th century as testified by the Count d’Espie’s essays [10] – the influence of the Sicilian architecture was also predominant. This last one was, in turn, strongly related to the Spanish one. The *tabicadas* vaults, in fact, represent a constructive system which was largely used in the Iberian Peninsula with continuity in use down to our days [11].

In addition to the vaults in bricks laid lengthwise, in the Neapolitan case it is possible to observe the use of hollow clay pots both as lightening and with a structural role – e.g., in the Royal Palace and in the Mother Church of Mondragone (Caserta) – as well as the pumice, used both for the concrete and masonry vaulting. In this respect, the reconstruction of the concrete dome of St. Croce church in Torre del Greco (Naples) and the construction of the monumental main staircase in the Royal Palace of Naples represent very interesting examples. For the latter, the architect Gaetano Genovese – after considering all the possible usable solutions and materials – opted for the pumice of Lipari island, which is more lightweight than the Vesuvian one and, moreover, workable as ashlar [12]. The choice of this different material, therefore, testifies the rich variety of the constructive systems of this period and represents, as in the case of the Molise vaults in *cimenti*, an interesting reinterpretation of the roman legacy.

Europe: France and Germany

In the Kingdom of Naples, later of the Two Sicilies, as well as in Europe, the scientific advancement of the early 19th century, together with the great interest for the classical architecture, led to the upswing and reinterpretation of the ancient constructive systems, such as the Byzantine hollow clay pots ceilings. As underlined above, the rediscover of the ancient culture, in fact, did not only concern the formal aspects of the architecture, but also the constructive ones. The Roman-Byzantine technique, in particular, starting from the second half of the 18th century generated a strong interest by scholars of antiquity, as architects and art historians. Although it was already in use during previous centuries, chiefly as lightening [13], only in the 19th century this technique spreads out with structural purpose, both in Italy and Europe.

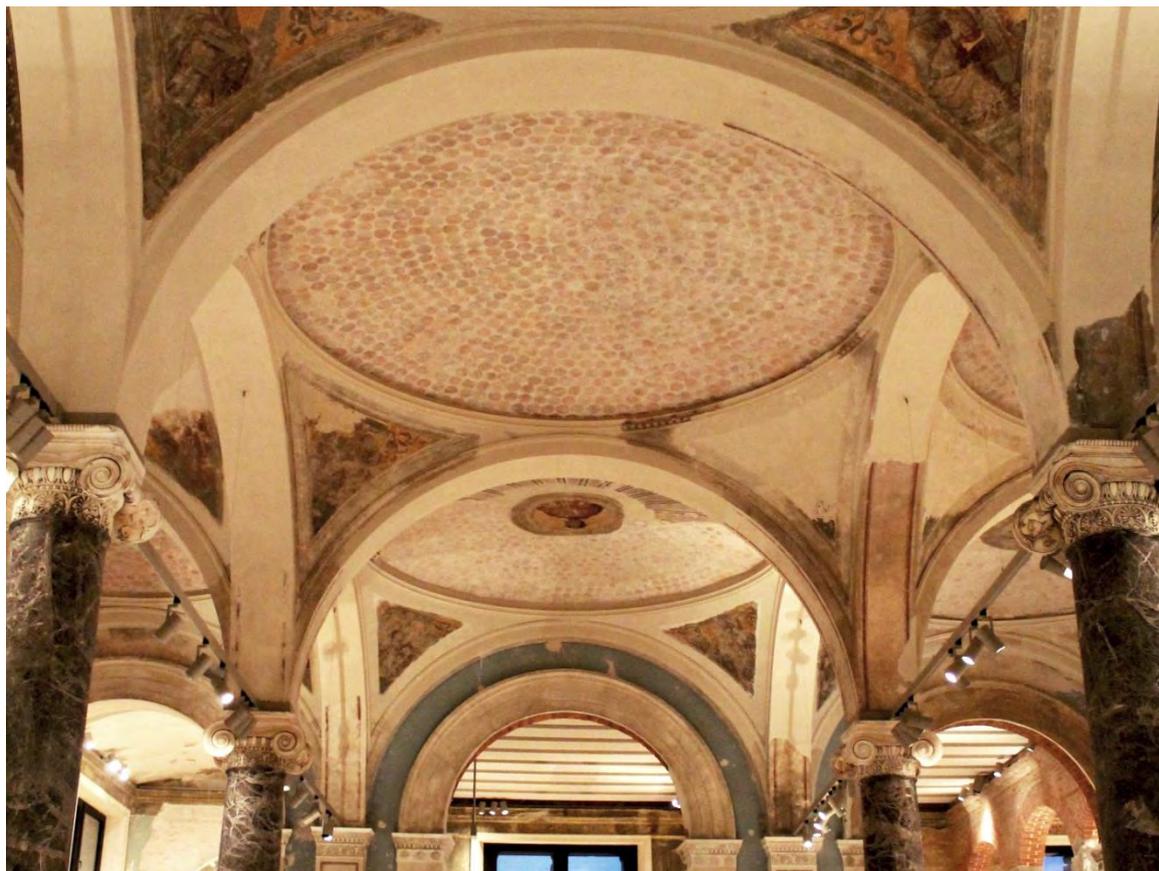


Figure 2: Germany, Berlin: the Neues Museum. Clay pots vaults designed by Friedrich August Stüler in the 19th century (L. Romano 2015).

Italian documents from the late 18th century provide interesting information about the using of clay pots in the Byzantine architecture of Ravenna. However they do not reveal the use of this type of vault in the coeval Italian architecture, unlike France where clay pots ceilings were tested from the half of the Age of Enlightenment [14].

A similar diffusion of this technique – that first of all assumes a reinterpretation of the constructive system according to the needs of the period – is confirmed by many contemporary essays such as the *Historical Dictionary of Architecture* by Quatremère de Quincy [15] and the treatise by Charles Louis Gustave Eck (1840) [16], entirely devoted to architectures with clay pots ceilings and steel. This work is particularly interesting because it deals with an innovative constructive system by giving a lot of examples of buildings where the constructive technique was used. The author dates the first experimentations to the unsuccessful works carried out by the architects Bernardini and Lassurance in 1720 and later by Victor Louis who in 1786 realized the vaults of the French Theatre in Paris.

It is noteworthy that, unlike Italy where a similar technique spread at a later time, in France the use of clay pots is always combined to iron chains able to increase the strength of the ceilings and to cover large spaces.

The same constructive technique is used – also in this case with iron parts – both by Leo von Klenze in the project of the Ermitage in St. Petersburg [17] and by F. A. Stüler in the Neues Museum of Berlin [18]. Both the architects travelled in Italy and visited Roman and Byzantine architectures. The resurgence of this ancient system, however, was filtered by a moment of strong reinterpretation and adaptation to the planning requirements.

The Neues Museum, for example, in addition to problems relating to foundations, needed a plan to compartmentalize the building to prevent fire from spreading. Therefore, the lack of clay pot ceilings in Europe is linked to their strong fire-retardant properties as well as to the substantial lightness and to the simplicity of realization. Unlike the Italian contexts – where, in spite of the scientific advancements, the planning was still partially related to an empirical approach – a more scientific methodology can be noticed in France and Germany: a clear example is provided by the project of the vaults in the Neues Museum and by the contemporary studies on their resistance [19].

VULNERABILITY AND CONSERVATION OF A FRAGILE HERITAGE: FUTURE DEVELOPMENTS

Although the contexts that this work investigates are very different and far apart within them, the particular historical moment together with the strong cultural contaminations allow to justify partially the affinities and the analogies in the results.

All these structures – in spite of their spread in Italy and in various European contexts – are still relatively unknown both in academic and in work field. The lack of knowledge about their constructive techniques can cause damaging interventions which are not in line with the needs of the old structures. To avoid such mistakes, it is necessary to make in-depth analysis on traditional building materials as well as on their properties and degradation, by defining a complex reference framework of knowledge.

In relation to the seismic area of Molise, vernacular constructions allow us to consider how knowledge can be gained from the experience of people living in earthquake regions. Inhabitants of seismic areas were often able, even if not always, to adapt their constructions to the situations, such as after the 1805 earthquake. In relation to the vaulting systems, the main goal is to reduce vulnerability and to increase resistance by making them more ductile than stiffer. For example, the vaults realized by wood and gypsum should be carefully studied in order to close-off the truss from the vaulted systems and, therefore, to avoid instabilities or collapses caused by possible movements of the roof. Moreover, it should be evaluated the use of Fiber Reinforced Polymers (FRP) for the consolidation project, not always compatible with the old materials and above all reversible, in spite of their durability.

The same considerations could be suitable also for the other types of lightweight vaults. The concrete structures and the vaults made up of bricks laid lengthwise should be deepened in relation to the use of wooden and steel chains as well as of other vaults of reinforcement placed at the extrados. An interesting project of restoration – which however embodied a particular approach – has been carried out by David Chipperfield in the last years on the Neues Museum of Berlin. He decided to complete the clay pots ceilings partially or totally collapsed during the Second World War with the same material – the new clay pots has been realized specifically for the Museum – with the goal of safeguarding the historical image of the place [20].

In conclusion, a successful and respectful restoration project must take into account the potential causes that determined the damage, and adapt the available techniques to the old structures. The use of compatible and renewable materials within a well-considered approach is necessary to achieve a durable and sustainable intervention, bearing in mind the lessons which is possible learning from the past.

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RETROFITTING HISTORICAL BUILDINGS: A PROBABILISTIC ASSESSMENT OF INTERIOR INSULATION MEASURES AND THE HYGROTHERMAL RISKS

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KEYWORDS

Building Retrofit, Interior Insulation, Probabilistic Assessment, Damage Prediction

ABSTRACT

To improve the thermal performance of historic buildings, interior insulation is often the only feasible post-insulation technique. However, applying interior insulation might increase the risk of hygrothermal damage, such as frost damage and decay of embedded wooden beam ends. Hence, a reliable assessment of these hygrothermal risks is crucial in order not to compromise the building's service life. Since many influencing parameters are inherently uncertain (e.g. material properties, construction geometry, interior and exterior climate), a deterministic assessment may lead to unreliable predictions. Therefore, this study applies a probabilistic assessment: a hygrothermal simulation environment is coupled to a Monte Carlo design approach, to take into account these uncertainties. Three vapour tight interior insulation systems are studied, as well as a capillary active insulation system. To compare the hygrothermal performance of these different insulation systems, the temperature, relative humidity and moisture content profiles of the different wall assemblies are analysed. Additionally, the risk on frost damage and decay of embedded wooden beam ends is estimated. Overall, the capillary active insulation system is more adequate for masonry walls that are prone to frost damage or have wooden beam ends embedded. Furthermore, larger insulation thicknesses result in a higher wood decay risk.

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INTRODUCTION

To improve the thermal performance of historical buildings, interior insulation is often the only feasible post-insulation technique. However, applying interior insulation might increase the risk of hygrothermal damage, such as frost damage and decay of embedded wooden beam ends. Because improving the energy efficiency of a historical building must not compromise the building's service life, a reliable assessment of these hygrothermal risks is crucial. Given that many influencing parameters are generally inherently uncertain (e.g. material properties, construction geometry, interior and exterior climate), a deterministic assessment may lead to unreliable predictions of design impact. Therefore, this study applies a probabilistic assessment and design method to incorporate these uncertainties and to come to a more global evaluation of the hygrothermal risks.

METHODOLOGY

A probabilistic assessment is performed for a massive brick wall renovated with different interior insulation systems. Different wall thicknesses are considered, as well as different interior and exterior conditions. Four insulation systems are studied: (1) extruded polystyrene (XPS), (2) mineral wool with a vapour barrier, (3) calcium silicate, adhered to the brick wall with a 4 mm glue mortar, and (4) mineral wool with a smart vapour retarder. As an interior finishing layer, a 10 mm gypsum board is used, only the capillary active system (4) is rendered with a 10 mm plaster layer. For each insulation system, eight insulation thicknesses are considered: 1, 2, 4, 6, 10, 15, 20 and 30 cm. Hence, 33 options are analysed (4 interior insulation systems, with 8 possible thicknesses + uninsulated reference wall). This study limits to a 1D cross section of the wall, so no construction details such as corners or embedded wooden beam ends are modelled. Furthermore, the masonry wall is simplified to a single isotropic brick layer; no mortar joints are modelled.

Probabilistic assessment

The hygrothermal performance is studied by use of DELPHIN 5.8 [1]. This simulation environment is coupled to a Monte Carlo design approach via MATLAB, which enables taking into account all uncertain variables and insulation systems. For this purpose, a simplified version of the probabilistic design methodology of Van Gelder et al. [2] is used; the input parameters are sampled several times according to their probability distribution, using a maximin Latin Hypercube multi-layered sampling scheme that allows subjecting all design options to the same uncertainties. Hence, the design options' output distributions and their hygrothermal performance can reliably be compared.

The wall characteristics and boundary conditions that are expected to influence the hygrothermal risks significantly are considered probabilistic and are shown in Table 1. To deal with variability in climatic conditions, three different exterior climates are included. Uniform distributions of the wall orientation, the solar absorption and the amount of wind-driven rain that reaches the wall are considered. Furthermore, a normal distribution of the exterior convective heat transfer coefficient is assumed, which depends on the sampled climate. The Lewis relation relates the heat transfer coefficient to the exterior moisture transfer coefficient. Finally, as the properties of historical brick façades vary widely, three different brick types are included (Table 2), with a uniform distribution of the brick wall thickness. The interior conditions are defined by the European standard on numerical simulations EN15026 [3], where the interior temperature and relative humidity depend on the daily average exterior temperature. Two different humidity loads, a low occupancy and

a high occupancy load, are prescribed. Both are considered to account for variability in the interior conditions as well.

Input parameter	Input distribution
Meteorological climate data	D(Essen, Bremerhaven, Munich)
Wall orientation [degree from north]	U(0, 360)
Solar absorption [-]	U(0.4, 0.8)
Scale factor catch ratio WDR [-]	U(0, 1.5)
Convective heat transfer coefficient [W/m ² K]	Essen N(7.3411, 2.1135) Bremerhaven N(11.6693, 3.1689) München N(7.2235, 1.7694)
Brick layer thickness [m]	U(0.15, 0.5)
Brick material	D(Brick 1, Brick 2, Brick 3)

Explanation of symbols used: $U(a, b)$: uniform distribution between a and b ; $D(a, b)$: discrete uniform distribution with options a and b ; $N(\mu, \sigma)$: normal distribution with mean value μ and standard deviation σ .

Table 1: Probabilistic parameters and distributions.

Material property	Brick 1	Brick 2	Brick 3	XPS	CaSi	Glue mortar
Capillary absorption [kg/m ² s ^{0.5}]	0.125	0.46	0.04	8e ⁻⁶	1.11	0.008
Dry vapour resistance factor [-]	24.8	14.3	45.1	150	3.85	38.45
Capillary moisture content [kg/m ³]	130	206.7	101	≈ 0	830	255
Saturated moisture content [kg/m ³]	209	323	253	950	900	261.1

Table 2: Material properties.

Hygrothermal risks and performances

To analyse the impact of the interior insulation on the hygrothermal performance, the temperature, relative humidity and moisture content in the wall are analysed. To exclude potential influence of starting conditions, the simulations are started on September 1st and data from the first four months is not used. After this initialization period, the simulations run for another three years. During the last year, the temperature, relative humidity and moisture profiles of the wall assemblies are monitored. Furthermore, two performance indicators are defined: frost damage and decay of embedded wooden beam ends. The frost damage risk is evaluated by the number of moist freeze-thaw cycles at 0.5 cm from the exterior surface. A moist freeze-thaw cycle is a freeze-thaw cycle that concurs with a moisture content above the critical saturation degree for which damage occurs. In this study, a critical saturation degree of 25% is assumed. The wood decay risk is evaluated at 5 cm from the inner brick surface. Since currently no reliable wood decay model is at hand, this risk is assessed as the number of hours that the relative humidity exceeds the critical relative humidity for wood decay. A relative humidity of 95% is assumed critical. Note that no actual wooden beam ends were modelled, as this is a 1D study; hence, this performance indicator only gives a rough indication of the wood decay risk.

RESULTS

This paper only discusses the results of the XPS and capillary active CaSi insulation systems, as the results for the two mineral wool insulation systems (with a vapour barrier or a smart vapour retarder) were found similar to the results of the XPS insulation system. As a reference, also the results of the uninsulated wall are shown. Beforehand, the temperature (T), relative humidity (RH) and moisture content (MC) profiles of one of the samples are discussed in detail. For this sample, the Bremerhaven climate and a 32 cm thick wall of brick type 3 are used; the orientation is 350 degrees from north, the solar absorption

is 0.63 and the WDR scale factor is 0.46. The profile plots show the monthly average profiles in January, April, July and October, for the reference wall and both insulation systems with thicknesses 2, 4, 6, 15 and 30 cm. Afterwards, the findings from these profiles are compared to the probability distributions of the considered performance indicators.

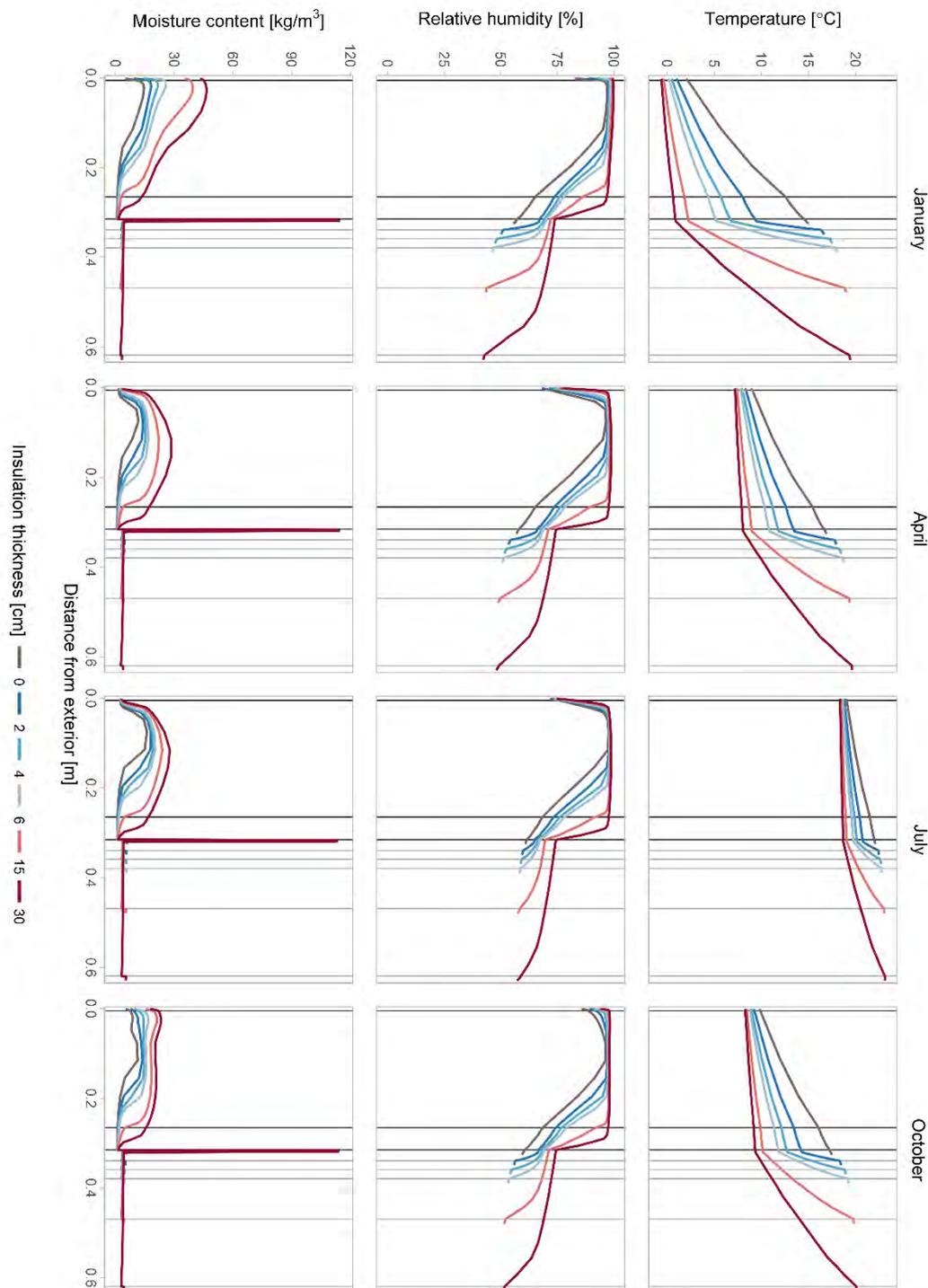


Figure 1: The average temperature, relative humidity and moisture profiles during January, April, July and October for one sample of calcium silicate insulation with thickness 2, 4, 6, 15 and 30 cm. The profiles of the reference wall are indicated are grey.

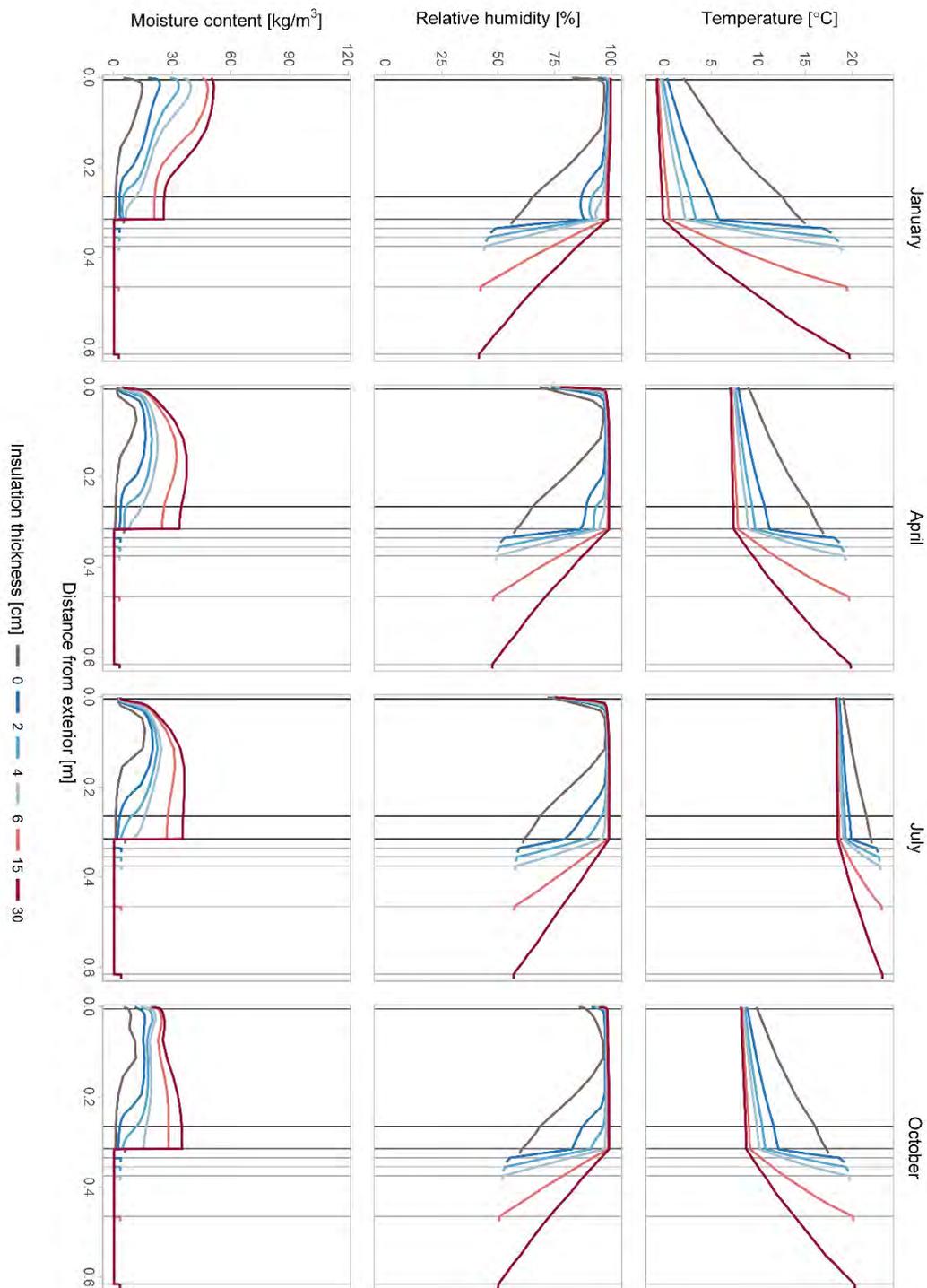


Figure 2: The average temperature, relative humidity and moisture profiles during January, April, July and October for one sample of XPS insulation with thickness 2, 4, 6, 15 and 30 cm. The profiles of the reference wall are indicated in grey.

Temperature, relative humidity and moisture content profiles

The T, RH and MC profiles are shown in Figure 1 and Figure 2, for the capillary active and vapour tight XPS insulation respectively. The different insulation thicknesses are plotted in colour, the uninsulated reference wall is plotted in grey on both graphs. It is

apparent that the RH and MC profiles at the inner part of the brick wall are higher in case of a vapour tight insulation. For the capillary active insulation system, the RH and MC are more in line with the findings for the reference wall. This can be accredited to the high vapour permeability of CaSi, which allows the wall to dry out inwards [4]. Consequently, embedded wooden ends show less decay risk when a capillary active insulation system is applied. Nevertheless, a considerable rise in RH and MC is seen for larger CaSi insulation thicknesses. This suggests that the decreasing vapour permeability due to an increasing insulation thickness has a significant impact on the drying potential of the wall, resulting in a higher RH and MC in the masonry. Figure 2 shows a similar tendency for the vapour tight insulation system, although less pronounced; since the high vapour resistance of 1 cm XPS already reduces the drying potential substantially, a further decrease in vapour permeability has a smaller relative impact. Furthermore, the RH and MC are found to decrease if the vapour resistance of the masonry wall is lowered to a value more in line with a brick-mortar composition ($\mu = 5$) [5], while keeping the other input parameters fixed. This resulted in a significant lower wood decay risk for the reference wall and the capillary active insulation system, while the effect in case of a vapour tight insulation system was much smaller.

Regarding the moist-freeze thaw cycles, Figure 1 clearly shows that, in case of a capillary active insulation, the MC at the outer part of the wall only differs notably from the reference wall for larger insulation thickness. This effect, in combination with a lower exterior surface temperature, results in an increased number of moist freeze-thaw cycles for larger insulation thicknesses. In case of a vapour tight insulation system, on the other hand, a significant increase in MC is seen as soon as 1 cm of insulation is applied. Additionally, a masonry wall retrofitted with a vapour tight system generally has a higher MC at the outer part than when a capillary active insulation is applied, due to the decreased drying potential. Hence, the critical saturated moisture content for frost damage will be exceeded more often. As a consequence, a vapour tight insulation results in a higher number of moist freeze-thaw cycles.

Wood decay

Figure 3a shows the dotplot of the number of hours that the relative humidity at the wooden beam ends exceeds 95%. The frequency of each indicator value is represented by the dot's size; the bigger the dot, the more often the value occurs. Additionally, the grey lines connect the samples with the same boundary conditions. Note that for all design options, including the reference wall, the critical relative humidity can be exceeded during the entire year as well as never. This plot confirms the findings from the T, RH and MC profiles: the wood decay risk increases as the insulation thickness increases. In case of the XPS insulation, the increase is largest for the first centimetres of insulation, after which it appears to stabilise. Furthermore, as the vapour tight insulation system causes a higher MC and RH at the inner part of the brick wall, the wood decay risk is significantly higher compared to the capillary active system, for all insulation thicknesses.

Frost damage

Figure 3b shows the boxplot of the number of moist freeze-thaw cycles, as a function of the dry thermal resistance of the corresponding insulation system (R_{dry}). Additionally, the black line shows the 75th percentile. In case of a vapour tight insulation system, a strong increase in number of moist freeze-thaw cycles is seen, from 1 cm insulation onwards. For the capillary active insulation system, the increase in moist freeze-thaw cycles is much less

pronounced and appears only after a few centimetres of insulation. This is in line with the findings from the T, RH and MC profiles. Note that for all insulation systems and thicknesses, the median is zero moist freeze-thaw cycles.

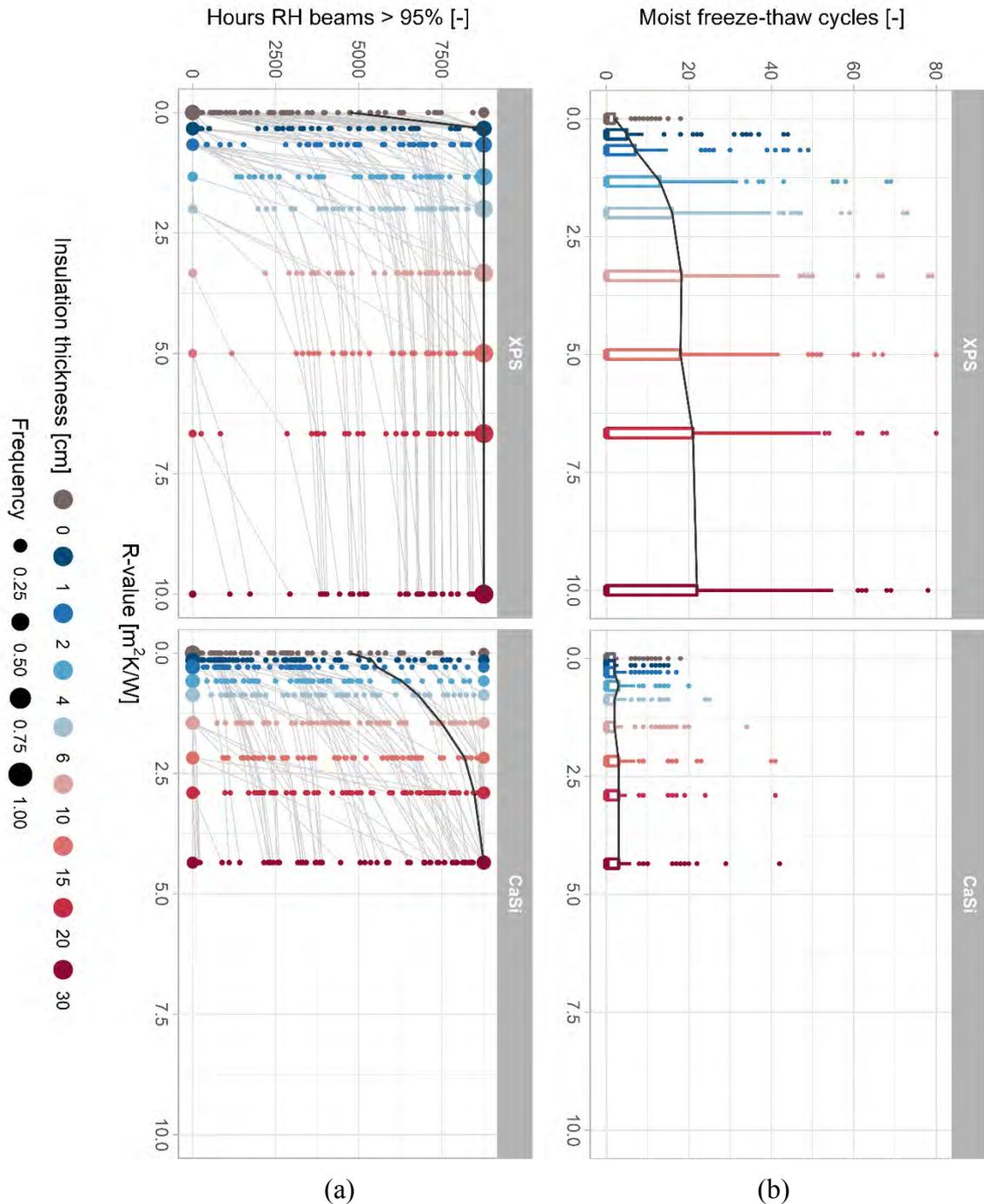


Figure 3: (a) Dotplot with frequencies of the number of hours that the relative humidity in the masonry, at 5 cm from the interior brick surface, exceeds 95%, and (b) boxplot of the number of moist freeze-thaw cycles ($w > 0.25w_{sat}$), both as a function of the dry thermal resistance of the insulation systems.

DISCUSSION AND CONCLUSION

In this paper, a probabilistic approach is applied to assess the hygrothermal performance of different interior insulation systems. Vapour tight insulation systems were found to have a higher masonry moisture content and relative humidity, which lead to a larger decay risk for wooden beam ends and an increased number of moist freeze-thaw cycles. In case of a capillary active insulation system, the results were more in line with the uninsulated reference wall. Nevertheless, a significant increase in wood decay risk was found for larger CaSi thicknesses; as the insulation thickness increases, its vapour resistance becomes more notable. This effect was less pronounced for the vapour tight insulation system.

Some remarks need to be considered, though. First of all, a realistic input is of vital importance, as the output is determined by the input. Hence, caution is required when applying the current observations while dealing with other boundary conditions. Furthermore, the current study contains some simplifications and assumptions. To start, no wooden beam ends were modelled, thus excluding potential air rotations around the beam ends which might result in a different moisture distribution. Secondly, the masonry was assumed a single isotropic brick layer and the brick properties were considered representative for the masonry. However, results showed that a higher vapour permeability resulted in a significantly lower RH and MC, and consequently a lower wood decay risk. This stresses the importance of a correct characterisation of masonry walls. In order to obtain reliable results regarding the applicability of interior insulation, the influence of the masonry vapour permeability requires further investigation. To end, it should be noted that the used performance indicators do not give a quantitative analysis of the risk; this would require more accurate damage prediction models, which are currently not available.

ACKNOWLEDGEMENTS

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URBAN MICROCLIMATE: NATURAL VENTILATION AND OPEN SPACE IN THE HISTORIC CITY. SUMMARY OF CRITICAL EVALUATION ON THE ITALIAN AND INTERNATIONAL RESEARCH

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KEYWORDS

Natural Ventilation, Historic City, Integrated Conservation

ABSTRACT²

Analysing the city as a 'relations system', a reality, paraphrasing Edgar Morin [1], not only physical but also geo-psycho-bio-human in which humans must relate the manifestation of their own necessities and freedoms to the responsibilities related to them, one wonders what are the system inputs and outputs [2] that determine the processes and changes, conditions of comfort and discomfort - starting from a necessarily interscalar evaluation - of the city as a complex 'urban room'.

The difficulties concerning the ability to evaluate a multitude of contributing factors and the translation of these values into useful information on a practical level for crisis situations improvement (bearing in mind that knowledge of the factors, specifically the ventilation) vary, depending on the scale of the investigation and on the level of detail to achieve.

The natural ventilation is one of these factors that is often not calculated for its complexity and inconstancy; instead, natural ventilation results in positive effects on the extent of the heat island which differs in relation to the wind speed and the characteristics of the building's fabric. [4].

Remote sensing techniques and cartographic photointerpretation, according to Gis logic, computational simulation, the use of scale or empirical models or the realization of *in situ* measuring campaigns allows us to acquire data at various scales.

Nevertheless, it is necessary to apply simplifications and-or limitations of the investigation field, both deriving from instrumental or functional requirements, especially by relating to complex fabrics such as those historic. This begs the question: how much said simplifications influence the responsiveness of the model to the real data?

For this reason, part of my research has focused on the critical reading of professional literatures, interpreting some of the most important definitions with a wide design approach and considering what are the inputs and outputs of which knowledge is essential to locate a 'correct model' of air circulation, as synergistic product among various contrib-

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² The abstract reported here recalls some lines of the article: Turchetti, G. (2016). Microclima urbano: ventilazione naturale e ridefinizione dello spazio della città storica. In Talia M. (ed.), *Un nuovo ciclo della pianificazione urbanistica tra tattica e strategia / A new cycle of Urban Planning between Tactic and Strategy*, Planum Publisher, Roma-Milano.

uting factors. The main goal is to define a methodological analysis that aims to systematize the positive elements and minimize the problems of these methodologies, providing an expeditious support tool, that helps in the context analysis and in the definition of the first project phase, in view of a microclimatic improvement of the open space and even indirectly of the indoor ones of the 'città storica' for an 'integrated conservation'.

INTRODUCTION

The natural ventilation study pertained to and still today is mainly about confined environments where the phenomenon is more easily controllable and manageable. This is the realm in which they have developed the first and main theories about the comfort³ for environments built around man, initially 'ideal'⁴ environments and then increasingly interdependent from the context, due to significant contributions, since the early fifties, from the Victor brothers and Aladar Olgyay and Baruch Givoni, and from the first adaptive theories introduced by Humphrey and Nicols since the seventies.

The single edifice is read as an obstacle placed in the open area and directly exposed to an undisturbed air flow, thus allowing to understand individual phenomena (shadow and wind wake, stagnation points, etc ...), that if analysed in an urban fabric would pile up and overlap in an extremely more complex way.

The increase in levels of urbanization and of the connected problems, however, has moved the axis of research and experimentation more and more to the urban organism scale with the definition of new assessment models of the ventilative phenomenon. These models are capable of analysing the airflows in the presence of a much more articulate 'weave', constituting the "urban fabric" and aiming at assessing the environmental factors, to paraphrase a famous line of St. Los [5], in relation to the technological system, climatic environment, distributive and figurative and also in relation to the architectural structure of the city.

NATURAL AND URBAN OPEN SPACE VENTILATION: STATE OF THE ART AND PONDERING POINTS.

Natural ventilation, as some studies show -including [4,6,7]- is the cause of positive effects on the size of the island that differ in terms of wind speed and building fabric characteristics, an aspect that strongly affects the definition of intensity and air masses direction. The wind speed threshold value beyond which the heat island dissipation effect is obtained, is also dependent on the extent of the urban agglomeration and also proportional to the number of inhabitants. Potential or negative effects on the urban fabric ventilation are mostly read with different eyes from those of the architect who will speak on space materiality. Still, today, you feel the lack of a support tool that helps architects or engineers in the defining the urban scale of the problem. Although the urban climatology

³ The first ones were the studies conducted by the American ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (formed by the merger in 1959 of the American Society of Heating and Air-Conditioning Engineers ASHAE, founded in 1894, and The American Society of refrigeration Engineers ASRE, founded in 1904) (www.ashrae.org) with contributions by the Danish P.O. Fanger that processes, as a result of a climatic chamber experimentation, the evaluation indexes of the wellness of the individual (PMV - predicted mean vote- and PPD -predicted percent dissatisfied-) taking into account subjective and indoor environmental variables.

⁴ The first assessments of the environmental conditions of indoor spaces, dating back to the first twenty years of the twentieth century, narrowed the problem only to the internal parameters of temperature, humidity and air velocity, without considering any contribution of external factors on the studied environment.

theme is covering over the last 10-20 years a leading role in research, also architectural, on solutions on environmental adjustment/mitigation (just think of the line of research of new low-emission materials and/or permeable and the theme the design or redesign of the urban green space or green infrastructure), the study of the air masses movement and the contribution that can provide for the mitigation of urban open space “takes the backseat” and it doesn’t touch, if not in an extremely marginal way, the architecture field.

In the urban field, the degrees of difficulty in understanding the ventilative flow and other factors related to environmental issues (already known in the indoor field) exponentially increase and it is evident the necessity not to use evaluation parameters calibrated on 'absolute values' but 'related' to the single entities involved⁵. At this scale, where single canyons constitute the walls of the urban room and where coverage is characterized by the closest layers of the atmosphere -the so-called canopy and boundary layer-, it prevails the line of research that exploits the knowledge on the progress of urban scale flows for the design or the redesign of the built plant. In particular the interaction between the single building or group of buildings with the urban area in which it is comprised. Significant was, at this juncture, the contribution of the Urbavent project (2001-2003) [8] that has its roots in the previous Naturvent project of the late nineties. The project has addressed the issue of strengthening of natural ventilation as a tool for the reduction of energy consumption for buildings located in urban areas, including the significant effect of the increase in the urbanization level of the European territory – estimated by now at about 75% with a ten-year increase of 3% - which is mainly due to the reduction of the flows potential in relation to the increase of the barrier elements and of the problems connected to the surface roughness of the urban space. In the context of this project, interesting studies have been conducted on the ventilative factor in the city of Athens that led to the definition of the wind strength theoretical calculation model in an urban canyon, embedded in an instrument called by the same name of the project: Urbvent. The proposed analysis methodology in the existing (but spatially limited) urban context has allowed to identify specific problems of this complex scenario and sought to respond to the lack of support tools that would help architects and engineers interpret the ventilative phenomenon during the design.

So far, we remain within the sphere of the single building or building front, stressing the predominance of the built space over the open one, which, although being co-participant in the definition of urban organism as the location of the active flows of city life, it remains a theme into the background⁶.

From the early years of the 21st century to the present time, much has changed in the field of research and experimentation on the theme, thanks mainly to the evolution of

⁵ Especially in the last fifteen years, studies are being developed that seek to evaluate whether and how to use, modify the 'traditional' comfort indexes or define new ones to be applied in the outdoor field: from the PMV and PPD indices, to PET and UTCI, specifically designated for the Mediterranean climate (MOCI). [9]

⁶ Though it concerns a parallel field to the one discussed here, a short point should be made with reference to experiments and projects that concern the open space of the city by assessing the indirect use of ventilation as a source for energy production for the consumption reduction. We think, for example, about the theme of the introduction of micro-wind and windmill systems in existing fabrics: from the Abres à vent-New Wind by Jérôme Michaud-Larivière project, to the Vibro-Wind project proposed by Cornell University. But we also remember the experimentation conducted at the Universal Exhibition in Seville in 1992 where 12 wind towers were placed in the open space between the various pavilions, resuming the 1992 Arab tradition or the towers designed in Madrid and Shanghai by the Urban Ecosystem.

techniques and technologies that have allowed us to achieve unprecedented results in such a short time.

Remote sensing techniques, for example, which are "mainly based on the combination of (statistical) image classification and the visual interpretation of Very High-Resolution satellite imagery" [10], enable us today to get an overview of the urban ecosystem in its entirety. For example, think of the Urban Atlas of the European Environment Agency (EEA), which is part of the GMES/Copernicus monitoring services. The Atlas provides a useful database for understanding the characteristics of the urban body, including some environmental factors, of nearly 700 major EU cities [11], providing useful information for decision-making on issues related to climate change. Undoubtedly, this data is essential to understand and locate the most vulnerable areas of each city and to define an action strategy that is as close as possible to the real needs and peculiarities of the site. [12].

But, whilst it is recognized the paramount importance of these data for the activation of strategies and plans at the meso-scale and local scale, the accuracy of the data provided by these tools, linked in particular to spectral and spatial resolution of the sensor [13], does not allow us to analyse it in further detail. Once located the macro area of intervention, other tools must be entrusted to fully understand the multiplicity of competing factors in the environmental definition of the examined area.

If we focus on the specific ventilation theme, on traditional instruments, from measurement campaigns on-the-spot to the use of empirical or wind chamber⁷ scale models, they are now complemented by computational tools based on microscopic analysis models, also known as CFD (computed fluid dynamics), also integrated in some software that allows a holistic reading of the various competing factors in the definition of comfort, or rather urban discomfort. These tools help to discretize the actual figure by comparing it to ever smaller and more precise geometric meshes [15], offering an almost 'immediate' reading of various climatic factors, some of which are difficult to instrumentally measure. Conversely, these tools need a simplification of the morphological and structural data of the software itself and have a response time that directly increases in proportion to the increment in the survey area and the complexity of the fabric that is to be analysed.

It is therefore reasonable to ask how much the limitations of the computational model affect the correspondence of simulated data with the actual one. A few researches, albeit significant in the international landscape, seek to analyse the reliability of the simulated value compared to the real one, with particular attention to the evaluation of the ventilative factor. The wind speed value provided by the virtual model is in many cases divergent from the actual data and, specifically, mostly underestimated in the city historic center fabrics and overstated in the 19th/20th century expansion areas [16,17].

This demonstrates that fluid-dynamic computing tools need to be integrated with the most traditional in situ measurement systems, if only for validating the model in view of its use to prefigure future interventions scenarios.

The theme is more cogent if we focus on historic and consolidated fabrics, characterized by a high morphological and morphometric complexity.

So, the important issue of urban space has to be analysed: so far, in this short dissertation about the city, we defined it as that part of new or existing urban fabric that is subject to substantial redefinition. This is because most research and experimentation, if not almost all, focus on this part of the fabric by neglecting or treating only marginally the his-

⁷ The wind chamber flow simulation allows us to choose the desired definition, depending on the scale of the model, but does not allow us to evaluate the thermal inputs resulting from the superficial surface characteristics. [14].

toric city⁸, namely that part of town characterized by urban fabrics that, of medieval origin or of 19th/20th century expansion, must be protected for its historic and cultural value.

For example, the empirical models, which usually synthesize the aspect ratio of an urban area, from those of Ellefsen to those of T.K. Oke [18-20], are based on overseas urban realities (large Megalopolis characterized by mainly rectilinear canyons, large variance of the altimetric built factor, the building density extending vertically rather than horizontally, etc ...) that exemplify a reality far distant from the European model, and specifically Italian, of the city.

In the Italian landscape, apart from some studies in which the environmental conditions between new cities and historic ones are compared or some interesting experiments conducted on consolidated fabrics, such as those proposed in the REBUS® project - acronym RENovation of Public Buildings and Urban Spaces promoted by the Emilia Romagna Region - or in the Manual for the Reduction of the Heat Island Phenomena promoted by the Veneto Region [21], or hints on the importance of the ventilative factor at the guidelines level, but specific to the historic building rather than to the public space⁹, Ventilation in the open space of the historic city is not subject to a specific analysis. Yet it is all the historic fabric of most cities to be most vulnerable to climate change and to suffer from rising temperatures. Undoubtedly, the degree of freedom of intervention in these areas is greatly reduced, but it is also worth investigating the ventilative phenomenon, along with the most commonly studied factors, and understanding whether and how ventilation can positively contribute to the environmental improvement of consolidated and historically protected spaces, also with 'minimal intervention'.

THE IMPORTANCE OF A QUICK EVALUATION: CRITICAL CONSIDERATIONS AND PRESENTATION OF THE RESEARCH WORK.

From this summary of the state of the art on the research subject, just briefly presented here, it is clear that we must start from the basics and recalibrate the analysis tools that are usually conformed to other city models, in order to understand the ventilative problem in complex fabrics, such as those historic.

The aforementioned problems, pertaining the scale of investigation and the instrumentation to adjust to it, are exacerbated by analysing the *città storica* so defined, and there is the need to re-read what literature has bequeathed and evaluate what changes to make, so that, both in the learning phase and in the evaluation phase, we have the necessary tools to propose intervention scenarios closer to the reality of such spaces.

Fundamental issues emerge, so closely related to each other, and which have been the starting point of my research.

The sampled reality is the one that defines the historic fabric of the city of Rome.

They started from the understanding of the environmental characteristics of the Capital through the collection of major climate studies, from the early studies of Colacino and

⁸Today, it is no longer a historic center, but a historic city as well as "those urban settlement structures that constitute cultural unity or the original and authentic part of settlements and witness the character of a vibrant urban culture [...]" (Commissione Franceschini 1964 - Dichiarazione XL) extended to all the fabrics typical of medieval *facies* but also to the eight-twentieth-century expansion that have a strong identity value.

⁹ Such as the Energy Reconstruction Guidelines for Historical Heritage elaborated under the A.T.T.E.S.S. project.

Lavagnini to the latest bulletins provided by the CRA-CMA¹⁰ or recent university researches, such as those of the Department of Civil, Constructional and Environmental Engineering or the Department of Astronautics, Electrical and Power Engineering (La Sapienza, University of Rome), just to name a few.

At the same time, the analysis of the specific morphological characteristics, and above all the morphometric characteristics of the city, has been investigated to recalibrate its parameters.

At this most theoretical stage, a field experiment has been carried out, envisioning an on-site measurement campaign, on selected areas among those that have the highest degree of vulnerability in the historic fabric [22]. These data, directed at the pedestrian level, were coupled with the direct data collected by the weather station that could best describe the influence of the urban plant on the anemometric characteristics: the Collegio Romano Station¹¹.

This collected database has allowed to validate the simulated data, this time specific for the Capital fabric, an extremely important step for the next phase of the intervention.

On an experimental model, defined especially for this research, possible intervention scenarios were tested, focusing on project planning above all on those aspects of the urban plant that can most influence the ventilatory factor, water above all, with the aim of mitigating the unfavorable environmental conditions recorded. The final point of the research is through a trial and error process that is based on a continuous validation of the data, the definition of a methodology for quick study that can systematize the various tools used in order to obtain a fast planning response. A methodology that proves itself flexible (adaptable to the heterogeneity of the facts), iterable (easily repeatable on different cases), implemented over time and which can respond to the lack in the technical, procedural and regulatory field.

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¹⁰ Meteorology of Rome by Beltrano M.C. Published by the CRA-CMA (Research Unit for Climatology and Meteorology applied to Agriculture).

¹¹ Weather observations Collegio Romano CREA-CMA (Research Unit for Climatology and Meteorology applied to Agriculture - formerly UCEA) Piazza del Collegio Romano, Rome. It is worth pointing out that the data provided by a meteorological station located within the urban fabric compared to those provided by extra-urban meteorological stations - which are usually located in airport areas as they record inflections of environmental factors that accurately describe the climatic conditions of the urban plant - are more precise.

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SAFETY ASSESSMENT OF MASONRY STRUCTURES USING ORDINAL OPTIMIZATION

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KEYWORDS

Order Statistics, Ordinal Optimization, Safety Assessment, Masonry Structures.

ABSTRACT

The safety assessment of historical masonry structures is still a controversial matter nowadays. When the collapse includes sliding, the Standard Limit Analysis theorems are no longer valid and the load factor of the onset of collapse is not necessarily unique. Hence many researchers have been looking for the solution of the onset of collapse for which the load factor is minimal. This is a very hard problem, presented in its simplest formulation as a Linear Complementarity Problem. Its computational complexity is NP-hard and no method guarantees to provide a solution, if any, or proves there is no solution at all.

In previous essays, a probabilistic Non-Standard Limit Analysis based method was proposed. The problem was presented as a Unilateral Contact Problem, formulated as a Complementarity Problem and solved through Sequential Linear Programming with random starting points. The implemented method was a Monte Carlo type method. The results match, within reason, with the load tests carried on some physical models. Nevertheless the goodness-of-fit tests do not allow these results to be considered as extracted from any known probability distribution and hence to use statistical shortcuts.

By adopting the previous approach the problem becomes tractable but still very expensive from a computational point of view.

The purpose of this study is to determine the minimum number of simulations that are necessary to obtain technically acceptable results.

The method described can be applied to other engineering problems in which it is necessary to find the characteristic value of a specific property while the distribution of this property is unknown.

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INTRODUCTION

To evaluate the safety of all types of structures it is necessary to use parameters whose values are not fixed. These parameters, that might correspond to loads (forces and displacements), geometrical properties (cross-sections, eccentricities) and material properties (strength and stiffness) can be treated as random variables using probabilistic methods for safety assessment.

Some of these values vary according to the fluctuations in the physical properties of the materials. This variability is accentuated in the case of historical masonry structures, which makes the use of the methods mentioned above particularly suitable. Therefore, for unreinforced masonry, probabilistic methods, such as those mentioned in Schueremans [1], are here proposed.

Suitable methods exist to perform these calculations in cases where the variation fits a known distribution, but in those cases where the distribution is unknown, or simply this type of hypothesis cannot be assumed, general simulation methods, such as the Monte Carlo simulation, can be used.

The Monte Carlo simulation is a method of general purpose with extremely simple implementation. It is used in a large number of scientific and technical fields, and is often applied as a last option to obtain an approximation to the optimal value of very difficult problems of global optimization. It is especially useful for this type of problem, as its characteristics make ineffective other more specific methods.

However, in spite of its generality, its use is limited by the large number of repetitions required to obtain sufficiently precise values, especially in the case of using it as a method of approximation to a global optimum. For this reason, many methods have been proposed to reduce the number of repetitions or simply to determine the minimum number needed to obtain a certain level of precision.

The present paper will try to determine what is the minimum number of repetitions of a crude Monte Carlo simulation when applied to the resolution of a very difficult specific problem: the value of the load that causes the collapse by sliding in a dry masonry wall.

There are many methods for checking the stability of this type of structure, such as Limit Analysis, but when the collapse includes sliding, the Standard Limit Analysis theorems are no longer valid and the load factor of the onset of collapse is not necessarily unique. Hence many researchers have been looking for the solution of the onset of collapse for which the load factor is minimal. This is a very hard problem, presented in its simplest mathematical formulation as a Linear Complementarity Problem. Its computational complexity is NP-hard and no method guarantees to provide a solution, if any, or proves there is no solution at all.

In the following lines a Monte Carlo simulation is proposed to obtain a reasonable approximation to the minimum expected value of the load that will cause the sliding collapse in a dry masonry wall and, more importantly, to obtain a distribution of the possible solutions and to be able to compare them with the distribution of the experimental results previously obtained on this type of walls.

At the end of 2013 a series of thirty-three load tests were performed on a dry masonry wall at the Building Structures Department Laboratory, ETSAM, Technical University of Madrid. The actions were self-weight and a horizontal pulling load [2]. The objective was to obtain a sufficient number of slip-slip tests in order to perform a statistical study of the results and compare them with those of some commonly used numerical methods. The results showed a wide dispersion (Fig. 1) that could not be explained by the dispersion in the properties of the constituent materials of the wall. Although all of these results remained

within the range of possible Non-Standard Limit Analysis solutions, not all were equally probable. It then seemed appropriate to implement a method that would allow better results for this type of problems.

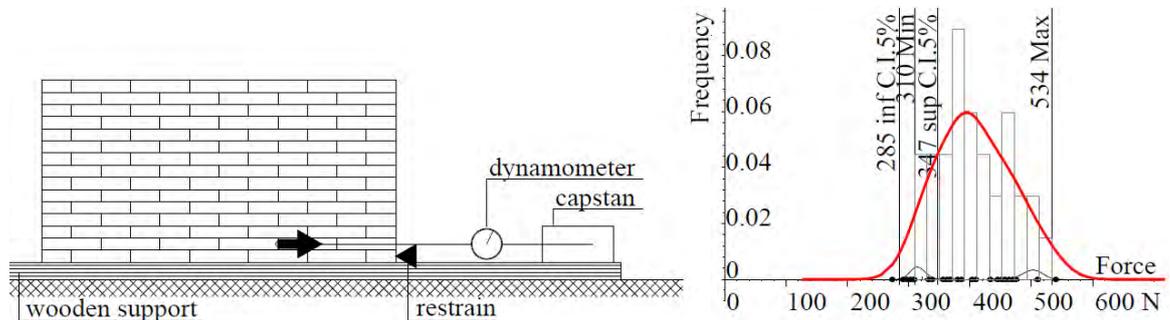


Figure 1: Load test scheme and results.

A probabilistic Non-Standard Limit Analysis based method was proposed. The problem was presented as a Unilateral Contact Problem, formulated as a Complementarity Problem [3] and solved through Sequential Linear Programming with random starting points. As stated in previous papers [4] the calculation of all extreme onset of collapse solutions was equivalent to the calculation of all possible combinations of the points of application of the contact forces at the contact surfaces.

The implemented method was a Monte Carlo type method [5] that consists on:

- 1) Randomly determining the application points of the contact force.
- 2) Calculating the maximum value of the point load that causes the onset of collapse by sliding.
- 3) Checking that the solution is one of onset of collapse.
- 4) Rejecting solutions that do not meet the required conditions.
- 5) With the accepted solutions, and maintaining the same values for those restraints that have reached their limit value, calculating the minimum value of the point load that produces the onset of collapse.

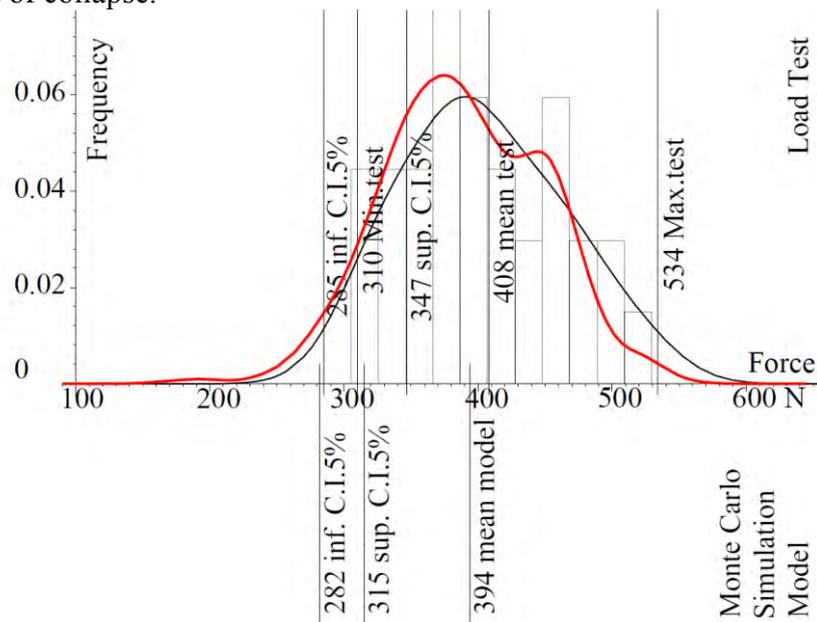


Figure 2: Comparison of experimental results (thin black line and upper labels) and those of Monte Carlo simulation (thick red line and lower labels)

The process should be repeated as many times as necessary to reach a number of load values enough to perform a statistical analysis.

The theoretical basis of this method and its implementation are specified in [6] and summarized in figure 2.

Using the described approach the problem becomes tractable but still very expensive from a computational point of view. In a Monte Carlo simulation the number of necessary iterations to obtain the desired precision remains unresolved.

On the other hand, some difficult engineering problems can be processed using a general method called Ordinal Optimization [7]. This methodology was developed in the early 90's to solve problems inherent to Discrete Event Systems. It was later extended to continuous variable problems, and even to constrained optimization problems.

The two fundamental ideas of Ordinal Optimization are:

- 1) Not trying to get the best (or worse) but something good (or bad) enough.
- 2) Getting the order is much easier than getting the value.

Both "goal softening" and "ordinal comparison" concepts apply to our problem. There is no need for an additional explanation about goal softening since in engineering applied to resistance problems, it is not the minimum absolute what is sought, but a characteristic value (the 5% percentile). "Ordinal comparison" and "percentile" are very close concepts.

Thus, once it has been established that a material resistance value of 5% percentile is being sought, it seems natural to apply the concepts of Ordinal Optimization. For this purpose, a branch of Nonparametric Statistics called Order Statistics is proposed in this study.

PROPOSED METHOD

The application of a binomial (Bernoulli) distribution is specially interesting for evaluating the minimum number of solutions necessary to obtain the lower bound of the desired percentile with a given confidence level. The formulas, as stated in [8], can be applied directly, but as they are very simple they will be deduced for the following example.

Let A be a set of elements of which a percentage $p = 5\%$ have the desired property (in this case being in the 5% of those with the lowest value). The highest value element of this percentage p will be the corresponding percentile p . As stated in (1), if an element is randomly extracted only one time, the probability of being within the percentage p will be 5%, and that of not being within it will be 95%. If the operation is repeated N times then P_{fN} (the probability of not being within) will be 0.95^N . Hence, after N extractions probability $P_{s \geq 1}$ that at least once an element belonging to 5% of the minors has been obtained will be $1 - P_{fN}$.

$$\begin{aligned}
 (1) \quad & p = 5\% = 0.05 \\
 & n=1 \rightarrow P_{s1} = p = 0.05 \\
 & n=1 \rightarrow P_{f1} = 1 - p = 0.95 \\
 & \dots \\
 & n=N \rightarrow P_{fN} = (1 - p)^N = 0.95^N \\
 & n=N \rightarrow P_{s \geq 1} = 1 - (1 - p)^N = 1 - 0.95^N
 \end{aligned}$$

If we call the probability of obtaining at least one hit $P_{\geq 1}$ Confidence Level C and p the percentile corresponding to the percentage p of the lowest values under study, the lowest element obtained will be less than or equal to the percentile p , and therefore a lower bound to p . Let C be the pursued Confidence Level / 100 and p the pursued percentile / 100. The minimum number of necessary evaluations N is given by (3) which is obtained by operating formula (2).

$$(2) \quad C = 1 - (1 - p)^N$$

$$(3) \quad N = \frac{\ln(1 - C)}{\ln(1 - p)}$$

$$(4) \quad p = 1 - (1 - C)^{\frac{1}{N}}$$

Formula (4) is equivalent and delivers the lowest percentile that can be obtained of a given Confidence Level C and a number of simulations N .

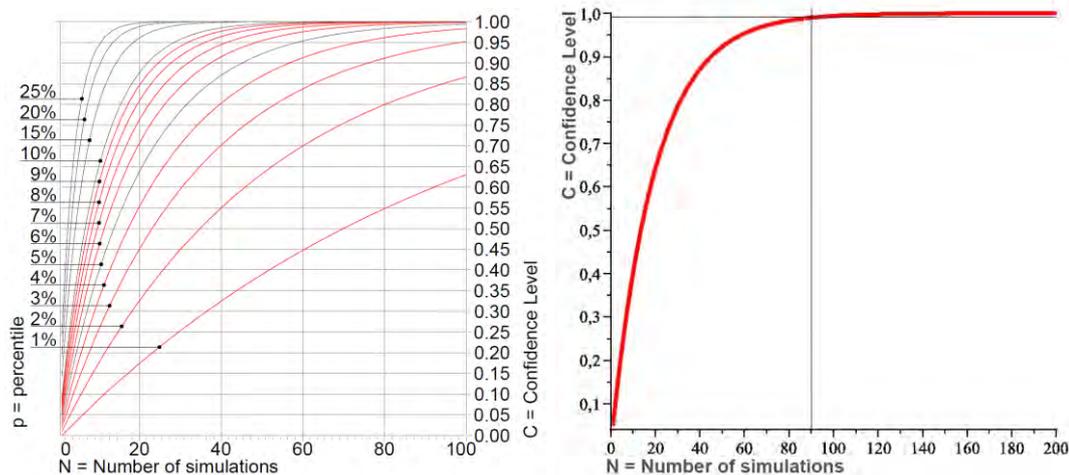


Figure 3: Left: graph N, C for different percentile values p . Right: graph N, C for percentile $p = 5\%$, indicating the case corresponding to $N = 90$.

DISCUSSION

Figure 3-left shows the formula (2) for different values of p . Note that as the percentile value decreases, the N value needed to obtain the same Confidence Level C value increases.

Figure 3-right shows, for a broader range of values of N , the case study corresponding to a specific characteristic value –that is, the 5% percentile. Note that at first the Confidence Level increases very rapidly with the number N , but as simulations advance a greater increase of N is required to achieve a small increase of the Confidence Level.

The application of formulas (2, 3, 4) allows us to find the minimum number of evaluations - either a load test or a numerical simulation - necessary to obtain a characteristic value with predetermined p, N , but provides no information about the distribution of the results obtained by each method.

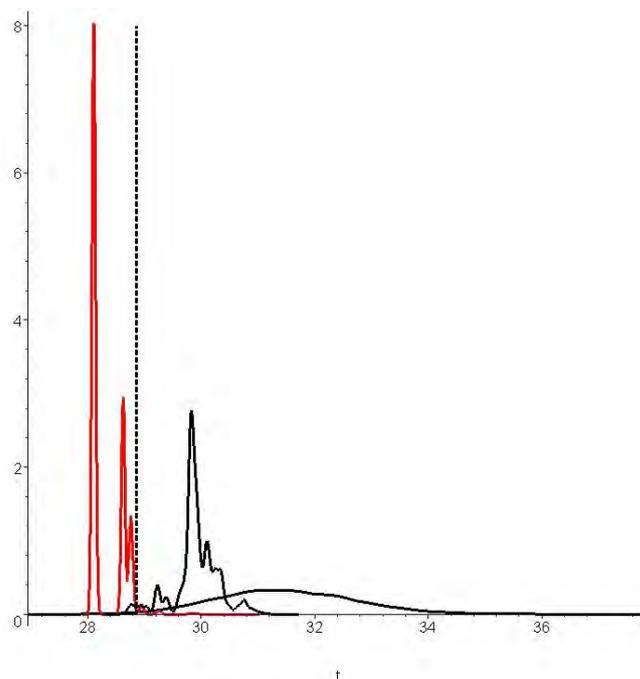


Figure 4: Comparison of the minimum results obtained through Ordinal Optimization (in red) and the 5% percentile of the Monte Carlo simulation and the load tests (in black).

More information can be obtained if the analysis is limited to this case study. Figure 4 shows a comparison of the results corresponding to the minimum obtained from Ordinal Optimization with a 5% percentile for Monte Carlo Simulation and Load Tests for the present case. The graphs correspond to the Gaussian kernel density estimation [9] using the Silverman rule for bandwidth. The sharpest black peak represents the 1000 simulations made by the method of Monte Carlo, while the lower black curve represents the 33 load tests. The graph in red corresponds to 100,000 evaluations using the Bootstrap [10] of the Ordinal Optimization with $N = 90$. It should be noted that the latter consists of finding 100,000 times the minimum value of a sample of 90 values extracted randomly from the 1000 results obtained by the Monte Carlo method. As predicted by the Order Statistics, these minimum values should be in 99% of cases ($C = 99\%$) a lower bound for the 5% percentile of Monte Carlo simulation. The black dashed line represents both the 99% percentile for the minimum values of the Ordinal Optimization and the 5% percentile values for the Monte Carlo simulation.

Finally, it is interesting to compare these results with those that would be obtained by applying the formula (5) suggested by Broding [11] for the Monte Carlo Method, which corresponds to (3) and that, converted to the notation used here, would read:

$$(5) \quad N \geq \frac{-\ln(1-C)}{p}$$

Substituting the values, we obtain that $N = 93$, which is a very similar value to the one predicted.

CONCLUSION

In conclusion, the application of Order Statistics allows finding the minimum number of randomly obtained solutions that is necessary to obtain the characteristic value of the resistance with the desired Confidence Level.

This number is surprisingly limited for the usual cases. In this case study, applying Ordinal Optimization criteria to a Monte Carlo simulation with values of $C=99\%$, $p=5\%$, only 90 randomly obtained solutions are necessary. The lowest of them will be lesser or equal to the 5% percentile corresponding to the Monte Carlo method with $N \infty$.

The method described is applicable to any other engineering problem, where a characteristic value or any other percentile of a property under study is required. In these cases the minimum number of iterations required (calculations, tests...) can be obtained simply by applying the formulas (2, 3 or 4).

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LITERATURE REVIEW ON THE ASSESSMENT OF MASONRY PROPERTIES BY TESTS ON CORE SAMPLES

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KEYWORDS

Core, Unreinforced masonry (URM), Mechanical properties, Slightly-destructive tests, In-situ tests

ABSTRACT

Starting point in this research is to find a quick and non-destructive method to characterize the mechanical properties of existing masonry. Tests on cylindrical cores have been recently introduced as a novel in-situ testing method to identify the properties of existing clay brick masonry. Currently, some researchers reported promising results, showing that the adopted methodology causes minor damage to the structures and it allows a direct estimation of the mechanical properties.

To evaluate the mechanical properties of masonry, cores extracted perpendicular to the surface of a wall are subjected to the splitting tests, by which the compressive and shear properties of the masonry can be estimated. In the first case, previous studies adopted different core configurations (i.e. size and joint pattern) subjected to compressive load. In the second case, cores with only a single bed joint were used. In the literature, the cores were tested in a way that the bed joint was rotated with respect to its original position. Consequently, a mixed compression–shear stress state is induced at the centre of the mortar joint.

As far as the research methodology is concerned, a review of the literature is required. In the first part of this paper, the authors give an overview of available literature regarding compression tests and splitting tests on masonry cores. The correlation established in the literature between the mechanical properties obtained from tests on masonry cores and those standard tests on the companion samples are outlined in this paper. Afterwards, a summary of the adopted methods and drawn conclusions are presented. Eventually, on the basis of these literature findings, a research project has been set-up at Delft University of Technology, aiming to establish a quick and non-destructive method to assess the masonry properties. The applicability of the core testing method is investigated for the brick masonry consisting of clay solid brick and general purpose mortar. The preliminary results of the tests on the clay brick masonry replicated in laboratory are reported in this paper.

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INTRODUCTION

Material characterization of existing unreinforced masonry (URM) can be pursued either by performing destructive tests (DT) in laboratory on the extracted samples or by performing slightly-destructive tests (SDT) in-situ. Although the laboratory tests have the advantage of directly providing properties, such as strength, stiffness and stress-strain relationship, these tests are invasive, costly and present technical challenges, when applied for in-situ assessment of mechanical properties. Consequently they can be performed in limited cases. On the contrary, in-situ tests have the advantage of being slightly-destructive and require less time. However, reliability of these test methods is still under investigation.

In alternative to the standardized in-situ techniques, such as double-flat jack [1] and shove tests [2], new slightly-destructive tests on masonry cores are currently under investigation by various researchers [3-9]. These methods aim to determine the compressive and shear properties of the masonry through splitting tests on cores. Similar to other SDT, this methodology seems promising because it allows a direct evaluation of mechanical properties and sampling induces limited damage to the structure. The test allows evaluating the compression and shear properties of masonry.

With the aim of establishing a quickly and slightly-destructively method for the material characterization of masonry, a literature review is presented in this paper concerning the tests on masonry cores. A comparative study of previous research findings is performed with attention to the correlation between the mechanical properties obtained by the tests on the cores and companion destructive tests. As a result, a testing procedure is defined that is being adopted by the authors.

LITERATURE REVIEW

Compression tests on cores

The great potential of using small diameter cores for assessing the compression properties of clay brick masonry has recently been shown by some researchers [3-7]. These researchers adopted companion compression tests on the masonry wallets or stacked-bonded prism to validate the testing method. The correlation between the results of tests on cores and companion samples for the compressive strength and the Young's modulus were investigated.

The International Union of Railway (UIC) [10] proposed a method to perform compression tests on cores with 150 mm in diameter, including two mortar bed joints and a head joint in the centre of the section. The UIC standard suggests conducting a minimum number of three compression tests on each kind of masonry, and preferably six tests if possible. The applicability of using 150 mm and 100 mm diameter cores were investigated for the clay brick masonry in the previous studies [3-7], even though further investigations are still essential in this field.

Brencich et al. [3], Ispir et al. [4] and Pelà et al. [5] adopted the same core geometry as proposed by the UIC. Moreover, Pelà et al. introduced another type of 150 mm in diameter core consisting of only two bed joints. Sassoni et al. [6-7] studied the suitability of using 100 mm diameter cores, which were easier to extract from walls than the ones with 150 mm in diameter. They adopted two types of cores in their studies. The first type included a central bed joint, and the second type included one central bed joint and one head joint.

Figure 1 shows the ratio between the compressive strength obtained from performing tests on the masonry cores and those of companion destructive tests reported in the literature [3-7]. This ratio varies between 0.6 and 1.8 in different studies.

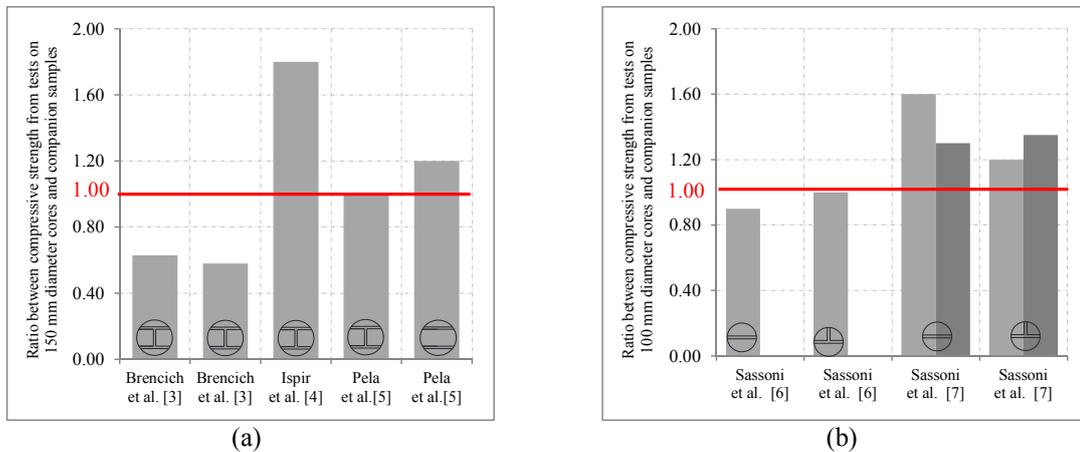


Figure 1: Ratio between the compressive strength of cores and those of companion samples: (a) tests on cores with 150 mm in diameter; (b) tests on cores with 100 mm in diameter.

A ratio between results of tests on masonry cores and those of the companion samples was reported less than 1 by Brencich et al. [3]. This ratio deviates from the values reported in other studies. As reported by Brencich et al. [3] a concave metal was used during loading as recommended by the UIC. One reason for this outlier ratio might be explained by the stress concentration produced by imperfect contact between the steel cradles and the specimen. Instead of using steel cradles, Pelà et al. [5] and Sassoni et al. [6-7] suggested performing tests on the cores with casted high-strength mortar on their top and bottom. An acceptable correspondence between the results of core samples and companion samples were reported by them. The masonry cores completed with high-strength mortar to resemble the situation in a real wall, where the confinement effect is experienced. In addition, an optimum bond between the specimen and the high-strength mortar can be expected. Consequently, performing test on the masonry cores with casted high-strength mortar on their top and bottom is suggested.

A very high ratio of 1.8 was reported by Ispir et al. [4] between the compressive strength of core samples and those of companion samples. Since limited information was provided by them, no conclusions can be drawn. Accordingly, the results of the studies carried out by Brencich et al. [3] and Ispir et al. [4] are excluded from the current study, since the authors of the current study are uncertain about the reliability of those testing procedure.

Core geometries, both with head joint and without head joint, were investigated by Pelà et al. [5] and Sassoni et al. [6-7] to study influence of the vertical joint on the test results. From their studies, it was concluded that the collapse mechanisms in the masonry cores without head joint deviates from those of masonry companion samples subjected to compressive tests. However, numerical modelling is essential to further study the influence of head joint. It might be expected that in the absence of head joint, the compressive strength of masonry can be overestimated, particularly, in the case of masonry with weak mortar and strong brick. Therefore, to gain deeper insight into the behaviour of masonry, cores with head joint are preferable to cores without head joint.

It is worth noting that a stack-bonded prism without head joint was adopted as companion sample by Pelà et al. [5]. Thus, it might be expected that the obtained results from

companion samples are more comparable with those of cores without head joint. Consequently, it is suggested to adopt masonry wallets as a companion sample.

Comparing the results obtained by Pelà et al. [5] and Sassoni et al. [6-7] from tests on cores with different diameters, it can be concluded that both 100 mm and 150 mm diameter cores are able to adequately represent the compressive strength of masonry.

The ratio between the Young's modulus obtained from performing tests on the masonry cores and those of companion destructive tests reported in the literature is shown in Figure 2. The applicability of tests on core samples to evaluate the Young's modulus was investigated in the literature only for cores with 150 mm in diameter. This ratio varies between 0.3 and 1.3 in different studies. As mentioned earlier, the outlier results provided by Brencich et al. [3] and Ispir et al. [4] are excluded in this study. As shown in Figure 2, an acceptable correspondence was reported by Pelà et al. [5] for both types of cores (with and without head joint).

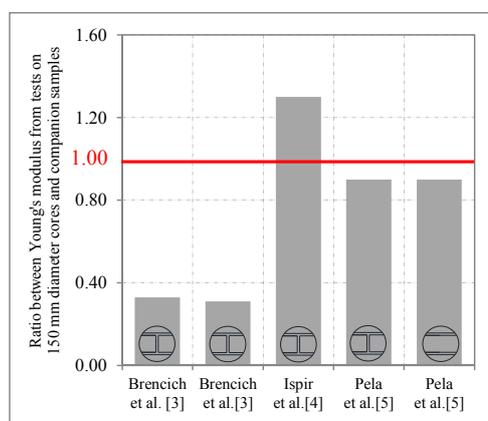


Figure 2: Ratios between the Young's modulus of cores and those of companion samples for cores with 150 mm in diameter.

Splitting tests on cores for the determination of shear properties

Performing splitting tests on masonry cores was firstly introduced by Benedetti et al. [11], to investigate the properties of mortar. Subsequently, this type of test was improved as a technique to study the shear properties of mortar interface. However, very limited information was reported in the literature about the evaluation of shear properties of masonry by using this technique [8-9].

In order to determine the shear properties of the brick-mortar interface, cores with only a single bed joint were subjected to splitting tests while they were inclined with respect to horizontal reference. A mixed compression–shear stress state was induced at the centre of the mortar joint. Then, the shear stress and compression stress states could be derived, respectively, by projecting the failure stress in the parallel and orthogonal directions with respect to the rotated mortar layer. By employing Coulomb friction criterion the initial shear strength and coefficient of friction was determined.

Apart from splitting tests on the masonry cores, Mazzotti et al. [8] and Pelà et al. [9] conducted shear-compression tests on the companion samples. The masonry wallets and masonry triplets were adopted as companion samples by Mazzotti et al. [8] and Pelà et al. [9], respectively. Tests on the companion samples were performed according to relevant standards [12-13]. As shown in Figure 3, an acceptable correspondence between the results obtained from splitting tests on cores and from standard shear tests on the compan-

ion samples was observed. The applicability of cores with 100 mm and 90 mm in diameter was investigated in their research.

Different modes of failure were reported in the previous studies. The inclination angle of the mortar layer was found as a decisive factor in formation of the mode of failure. The observed different modes of failure at different mortar layer inclinations were reported as follows: (a) splitting of the cores, (b) mix of splitting and sliding along the mortar-brick interface and (c) sliding along the mortar-brick interface. For the masonry cores tested according to an inclination of 40°, 45° and 50°, the predominant observed failure mode was sliding along the brick-mortar interface. While the masonry cores that were tested at mortar layer inclinations of less than 40° and higher than 60° showed splitting and brick wedge detachment, respectively. Therefore, those results obtained from performing tests on masonry cores at mortar layer inclination between 40° and 50° were used to determine the shear properties, since sliding along the brick-mortar interface was dominant failure mode.

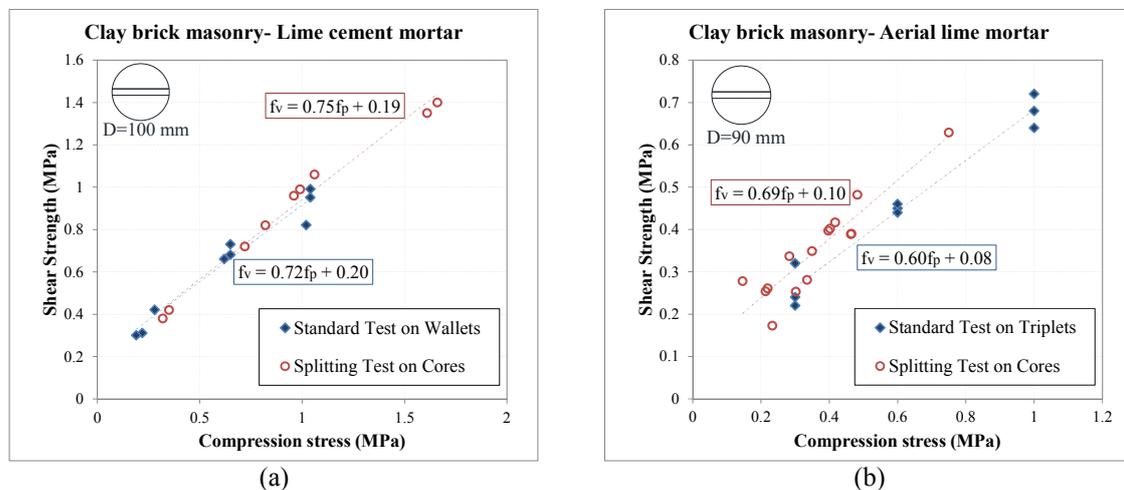


Figure 3: Comparison between the results obtained from standard shear tests on the companion samples and splitting tests on the masonry cores with: (a) 100 mm in diameter [8]; (b) 90 mm in diameter [9].

EXPERIMENTAL PROGRAM

Quick and less-destructive characterization of the mechanical properties of masonry is the ambitious target of the authors. Accordingly, a testing program was defined at Delft university of technology (TU Delft) aiming at investigating the applicability of new proposed slightly-destructive tests on the masonry cores and standardized in-situ techniques (i.e. double flat jack tests and shove tests) to obtain the mechanical properties of masonry. Moreover, the applicability of non-destructive tests such as Schmidt hammer test and ultrasonic tests are being investigated in the scope of the mentioned program. However, the current paper only deals with the testing program dedicated to perform tests on the masonry cores.

The lack of testing procedure to characterize the masonry properties by performing tests on the cores is evident in the literature. In order to pursue the correlation between the results of tests on masonry cores and companion samples, a summary of the adopted methods and drawn conclusions presented in the previous sections are compiled to define and develop a testing program.

Pursuing the correlation objectives, experiments on masonry cores and companion samples are being performed on the clay brick masonry specimens replicated at TU Delft laboratory. If possible, adopting a dry-extraction procedure is recommended, which could

not affect the integrity of the mortar. Tests on the masonry cores are being performed according to the testing program briefed in this section.

The accuracy of the obtained properties from tests on cores can be confirmed by comparing them with the properties obtained from performing standard tests on the companion samples. The compression tests on the masonry wallets are carried out according to the standard EN 1052-1 [14], and shear-compression tests on triplets are performed following the standard EN1052-3 [12] prescriptions.

Compression tests

The applicability of 100 mm diameter cores with one central bed joint and one head joint as well as 150 mm diameter cores with two bed joints and one central head joint are being investigated within this study. Two samples for each type of core were tested. The extracted samples were completed with high-strength mortar in order to ensure that the loaded faces of the specimen were levelled to each other. The compression load was applied by a hydraulic jack operated in displacement-control, using the displacement of the jack as control variable. The sample was instrumented by linear variable differential transformers (LVDT), allowed measuring deformations along the vertical axis of symmetry, horizontal axis of symmetry and the transversal expansion. To evaluate the compression properties of masonry cores, the applied compression stress can be evaluated either referring to the horizontal cross-section of the specimen or to the cross-section of the regularization cap, as suggested by Pelà et al. [5]. In Figure 4, $f_{m,c1}$ and $E_{m,c1}$ refer to the compressive strength and the Young's modulus obtained considering the cross-section of the cores and $f_{m,c2}$ and $E_{m,c2}$ are calculated considering the cross-section of the regularization cap. The ratio between compression properties of core samples and masonry wallets (companion samples) in terms of compressive strength and Young's modulus is shown in Figure 4. As it can be seen, this ratio for the compressive strength varies between 0.69 and 1.00; and for the Young's modulus varies between 0.44 and 0.82. As mentioned earlier, to this point only four core specimens were tested, while more tests are being performed.

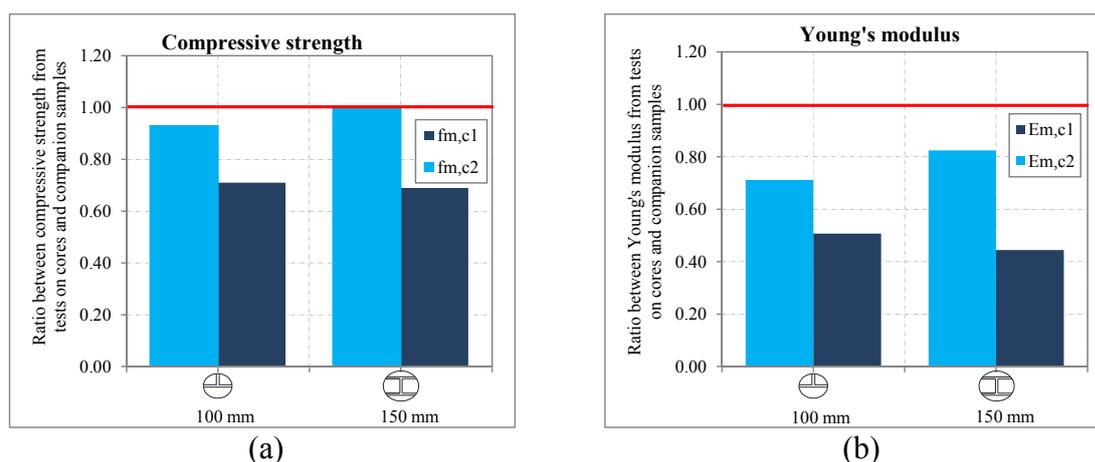


Figure 4: Ratio between the compressive strength of cores and those of companion samples: (a) compressive strength; (b) Young's modulus.

Splitting test

As investigated in previous studies, masonry cores subjected to splitting load were able to reproduce the masonry shear properties in terms of initial shear strength and coefficient of friction. As a result, in the current research program masonry cores with one

central bed joint are being subjected to the splitting tests with mortar layer inclinations of 40° , 45° and 50° with respect to its original position. The splitting load is applied by a hydraulic jack operated in displacement-control, using the displacement of the jack as control variable. Two wood strips are inserted between the loading platens and the sample. The relative sliding displacement between the two bricks is measured using one LVDT on each face. Figure 5(a) shows the results of splitting tests on the samples for the three different inclinations. During the tests on cores two failure mechanisms were observed: sliding at the interface and splitting of the brick near the constraints (SL+SP) or sliding along the mortar-brick interface (SL). Comparing the shear properties obtained from tests on the cores and standard test on triplet, see Figure 5(b), an acceptable agreement in terms of initial shear strength is established. However, the coefficient of friction evaluated with the core tests is 20% higher than the one estimated with the triplet tests. More tests are still being performed, therefore, the obtained results should be considered as preliminary.

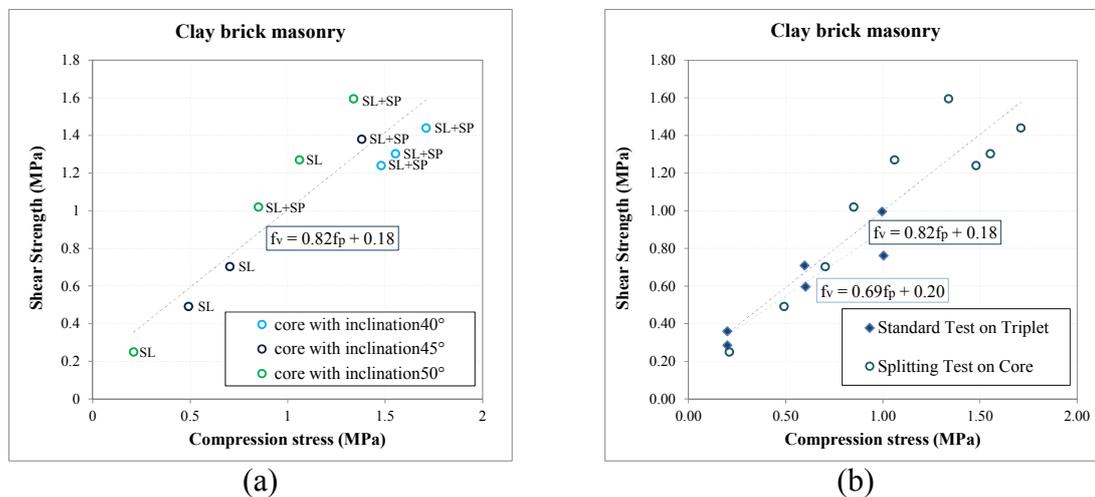


Figure 5: Splitting tests on the core samples: (a) indicating the observed failure mode; (b) comparison between results of cores and those results obtained from standard tests on triplets.

CONCLUDING REMARKS AND FUTURE WORK

The suitability of using cores to assess the compression and shear properties of masonry was investigated by few authors. It was concluded that tests on the masonry cores seem promising, since an acceptable correspondence between test results was reported in the literature.

The ambitious target set by the authors of this paper is to supersede the standard destructive tests with a quick and slightly-destructive method. Following the purpose of this research, a testing program was developed at TU Delft. The efficiency of tests on cores to evaluate the compression and shear properties of masonry is being investigated in this program. The compression and splitting tests on the masonry cores are conducted based on the procedure described in this paper; and standard tests are performed in agreement with relevant standards. Finally, a comparison between the compression properties (both compressive strength and the Young's modulus) and the shear properties (both initial shear strength and coefficient of friction) is reported. The ratio between the results of cores and those of companion samples for the compressive strength varies between 0.69 and 1.00; and for the Young's modulus varies between 0.44 and 0.82. By comparing the shear properties obtained from tests on the cores and those of standard tests on triplet, an

acceptable agreement in terms of initial shear strength is established. However, the coefficient of friction evaluated with the core tests is 20% higher than the one estimated with the triplet tests. It is worth noting that the obtained results should be considered as preliminary, due to the limited number of the samples tested. To draw a final conclusion, more tests are still being performed on the masonry cores.

ACKNOWLEDGMENT

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COMPUTATIONAL MODELING OF THE CYCLIC PUSHOVER TEST ON A CALCIUM SILICATE ELEMENT MASONRY ASSEMBLAGE

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KEYWORDS

Calcium Silicate Elements, Masonry, Finite Element Modelling

ABSTRACT

Induced seismicity in the Groningen region of the Netherlands has led to a large scale testing campaign on Calcium silicate element masonry structures at Delft University of Technology. An overview of the finite element analysis (FEA) using an implicit solver, on the full scale quasi-static cyclic pushover test performed on a two-storey calcium silicate element masonry assemblage is presented in this paper. Tests have been performed in the experimental campaign at material, component, and structural level, of which the material tests like bond wrench tests, compression tests and shear tests are also briefed in this paper.

The pushover case study has been modelled using a total strain based rotating crack modelling approach for the Calcium silicate masonry and a discrete cracking / coulomb friction model along the connections in the assemblage. The material parameters used in the FEA for the pushover case study are obtained from the aforementioned material level tests. In this study, monotonic analyses are performed along both directions of the cyclic loading and the loading protocol is simulated using a displacement controlled approach. Comparisons are made with the experiment in terms of force-displacement curve, crack pattern and drift ratios.

The use of an implicit solver for quasi-brittle materials comes with convergence issues, and these have been elucidated in this study. If material parameters calibrated on the basis of the material tests are used, a significant overestimation of the capacity in both loading direction of the test is found. Therefore, there is need for better correlation between material level tests and the behavior observed at the structural level to understand the true behavior of the masonry. The computed maximum displacements have been severely under predicted in both directions reiterating the need for most robust solution procedures to realize global softening behavior in masonry structures.

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INTRODUCTION

Calcium-silicate blocks (also known as ‘elements’ or ‘CASIELS’) have been in use in the Netherlands since the 1970’s. A steady increase in size from traditional brick format (in Dutch ‘waalformaat’) in the early 1960’s [1], towards large elements can be observed in Dutch construction practice since the early 1960’s [1]. Although the blocks in the 1970’s had smaller sizes, the need for speed and efficiency in construction practices have led to elements (CASIELS) that are now roughly 90 x 65 x 10 cm³. The calcium silicate (CS) elements are generally used only as internal leaf, finished on the interior side with plaster and on the exterior side with insulation, a cavity and finally a baked clay brick as external (aesthetic) leaf. These elements, to this date, are frequently applied for the construction of terraced houses in the Netherlands including the seismic region of Groningen.

Thus, a research campaign (also extended to tests on Calcium silicate elements masonry) was performed at TU Delft to address the seismic situation in Groningen at material, component and building level. The material tests and the quasi-static cyclic pushover test are briefed upon in the next two sections of this article followed by the finite element modelling of the pushover test. The macro modelling approach, combined with non-linear interfaces at connections, is used in this study owing to the size of the structure being analyzed. Subsequently, the results and conclusions drawn are presented.

MATERIAL TESTS ON CALCIUM SILICATE ELEMENT MASONRY

As far as the properties of calcium silicate (CS) element masonry at material level are concerned, strength, stiffness and softening properties for compression, bending and shear are the matter of importance. These tests provide valuable information to define the input parameters as well as the constitutive material law for nonlinear finite element analyses. Consequently, a series of tests was performed to fully characterize the mechanical properties. The obtained material properties are listed in Table 1.

Material property	Unit	Average	Std. dev.
Compressive strength of masonry perpendicular to the bed joints	MPa	13.93	1.03
Compressive strength of masonry parallel to the bed joints	MPa	9.42	1.63
Elastic modulus of masonry in the direction perpendicular to bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	MPa	8801	958
Elastic modulus of masonry in the direction parallel to the bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	MPa	7400	929
Out-of-plane masonry flexural strength parallel with the bed joint	MPa	0.58	0.08
Out-of-plane masonry flexural strength perpendicular to the bed joint	MPa	0.73	0.03
Flexural bond strength	MPa	0.56	0.12
Masonry initial shear strength of masonry interface	MPa	0.83	-
Masonry shear friction coefficient of masonry interface	-	1.48	-

Table 1: Material properties of replicated calcium silicate element masonry.

The orthotropic behavior of masonry in compression was investigated by performing compression tests on masonry wallets both in the direction perpendicular and parallel to the bed joint following EN 1052-1 [5]. The CS element masonry showed an orthotropic

behavior meaning that its compressive strength and elastic modulus are higher in the direction perpendicular to the bed joint. The orthogonality ratio for the compressive strength and the Young's modulus was found equal to 1.5 and 1.2, respectively.

An adopted displacement-control procedure allowed studying the post-peak behavior under compression. However, differently than other masonry types, the CS element masonry showed a brittle failure without almost any post peak phase. A typical observed crack pattern and stress versus strain curve for the vertical compression tests, where the applied load was perpendicular to the bed joint, are shown in Figure 1.

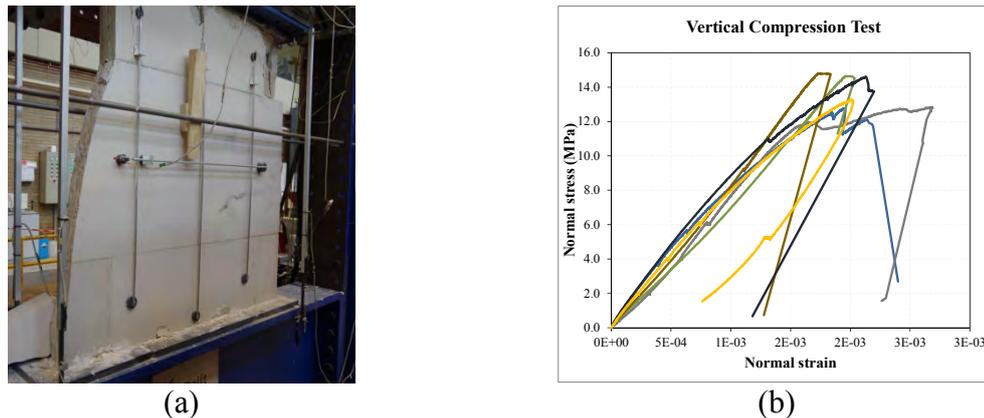


Figure 1: Compression test load was applied perpendicular to the bed joints: (a) typical observed crack pattern; (b) stress-strain curve.

The bending behavior of masonry was determined in agreement with EN 1052-2 [6]. The flexural strength perpendicular to the bed joint was obtained 1.3 times higher than the one which was parallel to the bed joints. The bond wrench test, performed in agreement with EN 1052-5 [7], showed the bond strength value of 0.56 MPa, similar to the flexural strength parallel to the bed joint.

The shear behavior of masonry interface was studied by means of couplets. The shear-compression tests on couplets were performed in agreement with EN 1052-3 [8]. The shear properties were derived following the Coulomb friction criterion. The masonry showed an initial shear strength of 0.83 MPa and a friction coefficient of 1.48.

CYCLIC PUSHOVER TEST ON CA-SI ELEMENT MASONRY ASSEMBLAGE

The two-storey calcium silicate element masonry assemblage with concrete floors has been tested in quasi-static cyclic pushover regime, and is intended to represent a typical Dutch terraced house built between 1960 and 1980. Such a house is characterized by large openings in the facades, slender piers and load bearing cavity walls. Since the test would serve as a benchmark for validation of analytical and numerical models, the built house includes only the load bearing parts of the typical Dutch terraced house. In accordance with the quasi-static pushover test performed on a calcium silicate brick house performed in 2015 [2], this test is steered in a displacement controlled approach where the second floor displacement is controlled using actuators that are hydraulically coupled to the first floor actuators to have an equal force distribution to both floors. That is to say the ratio of forces exerted at the first to second floor is 1:1 ($F_1+F_3 = F_2+F_4$). The scheme of the experiment is shown in Figure 2.

The CS element assemblage has been so designed to investigate the effect of aforementioned slender piers and the presence of large openings in the facades, in combination

with long transversal walls. The standard element size was $897 \times 643 \times 100 \text{ mm}^3$ for the piers and $897 \times 643 \times 120 \text{ mm}^3$ for the transversal walls. A kicker course of CS bricks (in Dutch “*kimlaag*”), glued to the steel foundation at the ground level using sikadur glue and to the floor at the first floor level using a general purpose mortar, was placed under each wall to ensure the construction begins at a uniform level. The piers at the west are wider compared to the ones in the east. Both the top and the first prefabricated concrete floors were supported by the load-bearing transverse walls as well as by the piers. In contrast to traditional brick masonry buildings, the connection between the transversal walls and the piers is not guaranteed by regular running bond; instead the connection was made using steel anchor strips at all bed joints except the ones between the piers and the kicker layers. For detailed overview, refer to [1].

The overall force displacement curve is shown in Figure 2. The thick black line denotes the backbone/envelope curve for the cyclic response.

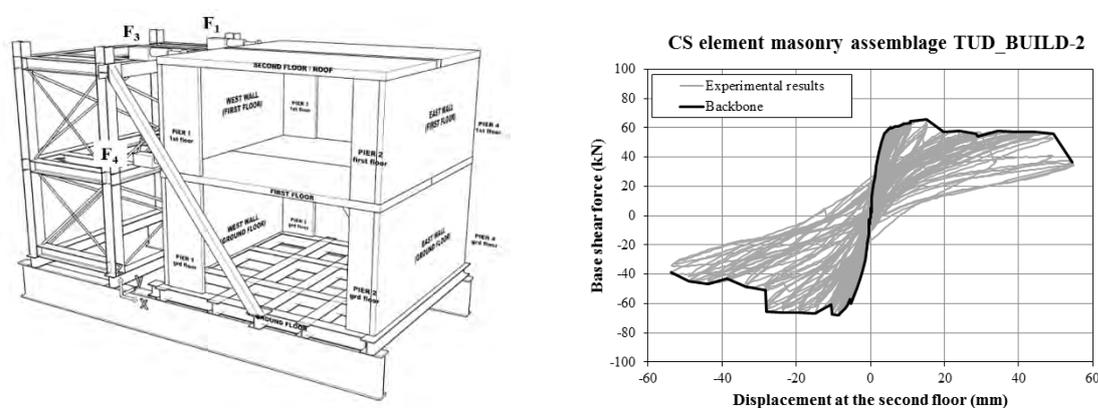


Figure 2: Experimental scheme of the cyclic pushover test on the Ca-Si Masonry assemblage at TU Delft and the capacity curve [1].

The first cracking was observed, in the potentiometers, in the wall-floor connections primarily in the façades but also in the transversal walls. In the pre-peak phase, these cracks were visible to naked eye and this was followed by the rocking of the piers on both storeys, thereby bringing about a reduction in the stiffness of the structure. In the following cycles, the rocking of piers at both storeys continued along with cracking in the transversal walls until the peak load was reached in the positive direction. During the post peak phase, a soft storey mechanism was observed: the rocking becomes highly localized and cracking propagates in the transversal walls. Furthermore, wider piers at ground floor in the façades showed cracking along the joints between the CS elements and splitting cracks, and also an out-of-plane deformation in this phase. The test was continued until collapse of both the wide piers (first on the North side, later on the South side), at an imposed displacement of the top floor equal to 55 mm which translates to a reduction of approximately 45% of the base shear force. The crack patterns at different levels of imposed displacement at the second floor level (d_2) are shown in Figure 3.

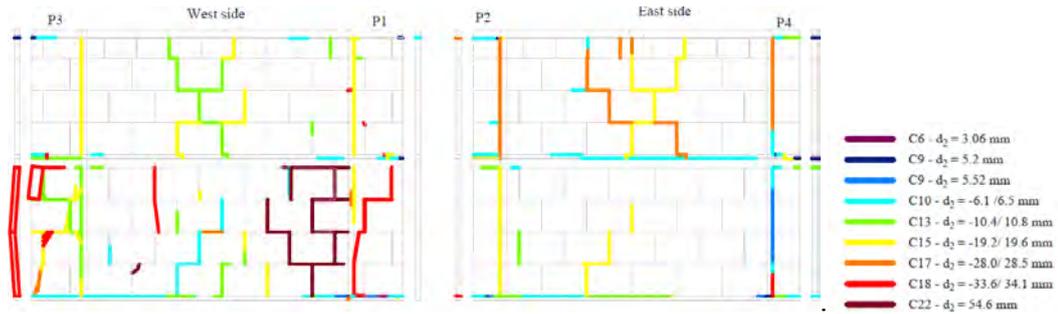


Figure 3: Crack patterns observed during the test for different levels of second floor imposed displacements by visual inspection [1].

FINITE ELEMENT MODEL

This section details the FEM model used for the prediction studies of cyclic pushover test on the CS masonry assemblage. Eight-noded quadrilateral iso-parametric shell elements, 0.2m x 0.2m in size, were used to model the calcium silicate elements in the analysis. The horizontal joints between piers, walls, kicker layers and floors are all represented by quadratic interface elements with discrete cracking and the vertical joints between walls and piers are represented by quadratic interface elements with coulomb friction models.

A total strain based rotating smeared crack model with linear tension softening and parabolic compression softening was used for the constitutive model of the shell continuum elements. A discrete cracking or coulomb friction model with gapping criterion was employed for the interfaces. The tensile strength and fracture energy for Mode-I failure for the shell elements and discrete cracking interfaces, compressive strength and fracture energy in compression for shell elements, and the cohesion and friction properties for the vertical interface are obtained from the bond wrench, compression and shear tests respectively and are summarised in Table 2. Geometric non-linearity is also included.

The loading is applied by means of an auxiliary frame to simulate the application of equal force ratio at the two floor levels by the actuators and the analysis is kept displacement controlled along the centre line of the frame (along its height). Tyings are used to couple the displacements in the direction of loading between the nodes of frame and those of the floors which are at the positions of the actuators. The bottom of the house is kept fully clamped. A detailed overview of the modelling approach with assumptions and material properties is presented in Table 2. 7 integration points are used in the direction of thickness of the shell elements.

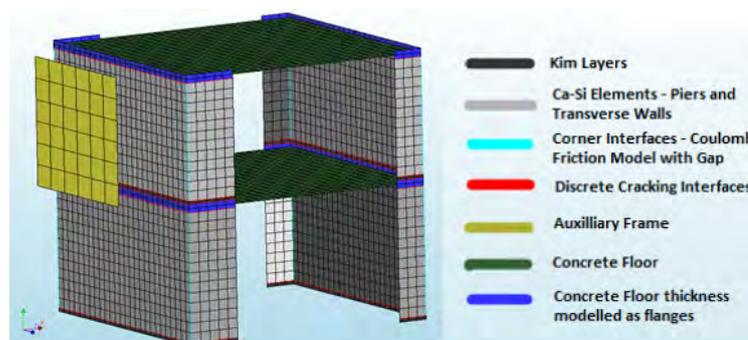


Figure 4: FEM Model of the Ca-Si Masonry assemblage pushover test

Element type	Constitutive model	Material parameters
CS Masonry - Shell elements	Tension softening (linear)	$f_t = 0.4$ MPa, $G_{fl} = 100$ N/m
	Compression softening (parabolic)	$f_c = 10$ MPa, $G_{fc} = 10000$ N/m
Horizontal joints - interfaces	Tension softening (linear)	$f_t = 0.4$ MPa, $G_{fl} = 100$ N/m
Vertical joints - interfaces	Coulomb friction with tension cut-off	Cohesion (c) = 0.68 MPa, friction angle $\phi = 6^\circ$, Cut-off (f_t) = 0.4 MPa

Table 2: Material parameters for the FEA obtained from material level tests

RESULTS & DISCUSSION

The force displacement curves obtained from the numerical simulations of the monotonic pushover in the positive and negative directions are as shown in Figure 5 for properties based on the material level tests. Significant overestimation of the capacity is found and analyses terminate prematurely at lower displacement levels compared to the experiment. The overestimation of capacity stresses the need for variation studies on material parameters and premature termination is due to numerical issues associated with nonlinear finite element analysis of brittle materials with the traditional incremental iterative procedure. Also, extreme localization of damage at certain locations lead to the stiffness of certain elements being reduced to extremely low values (close to zero), consequently resulting in the ill conditioning of the finite element formulation and the premature termination of analysis.

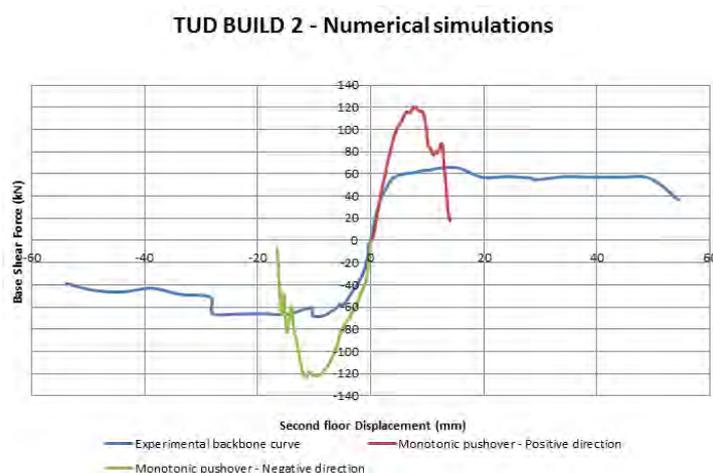


Figure 5: Capacity curve with parameters from material test properties

Parametric studies were performed, by reducing the values of the cohesion (c) and the tensile strength cut-off in coulomb friction interface and of the tensile strength in the discrete interfaces. The capacity curve obtained for $c = 0.3$ MPa and cut-off of 0.1 MPa for coulomb friction interface and tensile strength of 0.05 MPa for discrete cracking is shown in Figure 6. The simulation in positive direction of loading shows good agreement with capacity of experiment, while the negative direction shows a small overestimation. This can be attributed to the fact that the analysis is purely monotonic and the accumulated damage from the cyclic is not truly captured. The use of reduced values induces first cracking along the interface elements along horizontal connections followed by pronounced rocking of the piers and sliding along the vertical joints. Cracking is also ob-

served in the transversal walls, but the cracking pattern is not accurate as the discontinuities between the CS elements, i.e. the head and bed joints, are not modelled in the macro-modelling approach. The soft storey mechanism just begins to appear and the piers show instability in the out of plane direction but the analysis stops prematurely due to the aforementioned reasons. The post peak phase is thus not captured where splitting cracks in ground floor wide piers was observed in the experiment. The evolution of crack patterns and interface relative displacements are shown in Figure 7 and 8.

The parametric study shows the relevance of the calibration of the material parameters. Even when they are obtained from tests at material level, some corrective factor may be needed to be applied in the Finite Element analysis, due to the limitations of the material models and, secondarily, the different behavior that masonry may have at structural level. In any case, it should be remarked, that only one case and a single model have been considered in this study.

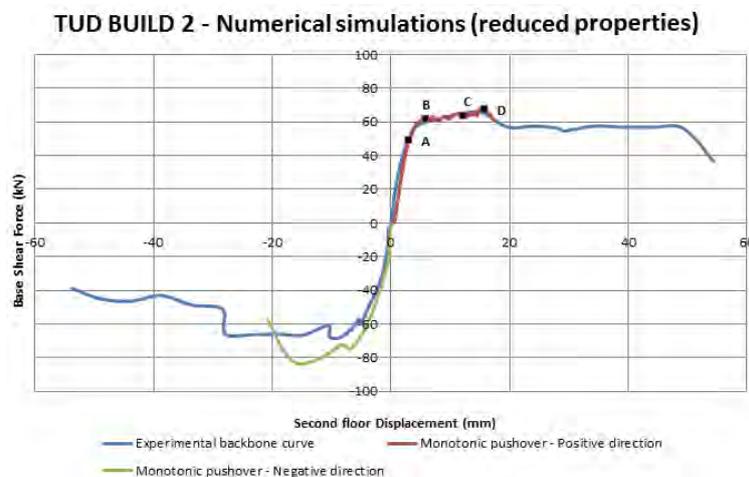


Figure 6: Capacity curve with reduced material parameters

Alternatively, to the standard total strain based rotating smeared crack model, the use of the Engineering masonry model [3], an anisotropic smeared failure model along with a shear failure mechanism based on coulomb friction criterion, may be considered. However, it would probably not lead to significant improvements as the CS element masonry is different from traditional brick masonry and the purpose of the differentiation of failure directions along the head and bed joints, the crux of the model, is lost. The choice of a compromise between a total strain based cracking approach and the provision of interfaces at locations of head and bed joints modelled using the composite interface model [4] is a promising one, but again the model becomes quite complex and it becomes even more unstable from a numerical point of view considering the implicit nature of the solution procedure being adopted. Therefore, this option is left out of the scope of this study, however investigation with an explicit solver is being considered. An alternate total approach, called Sequentially Linear Analysis [3], has been in development over the last decade and is currently being investigated for applications to cyclic loading and extensions to the engineering masonry model.

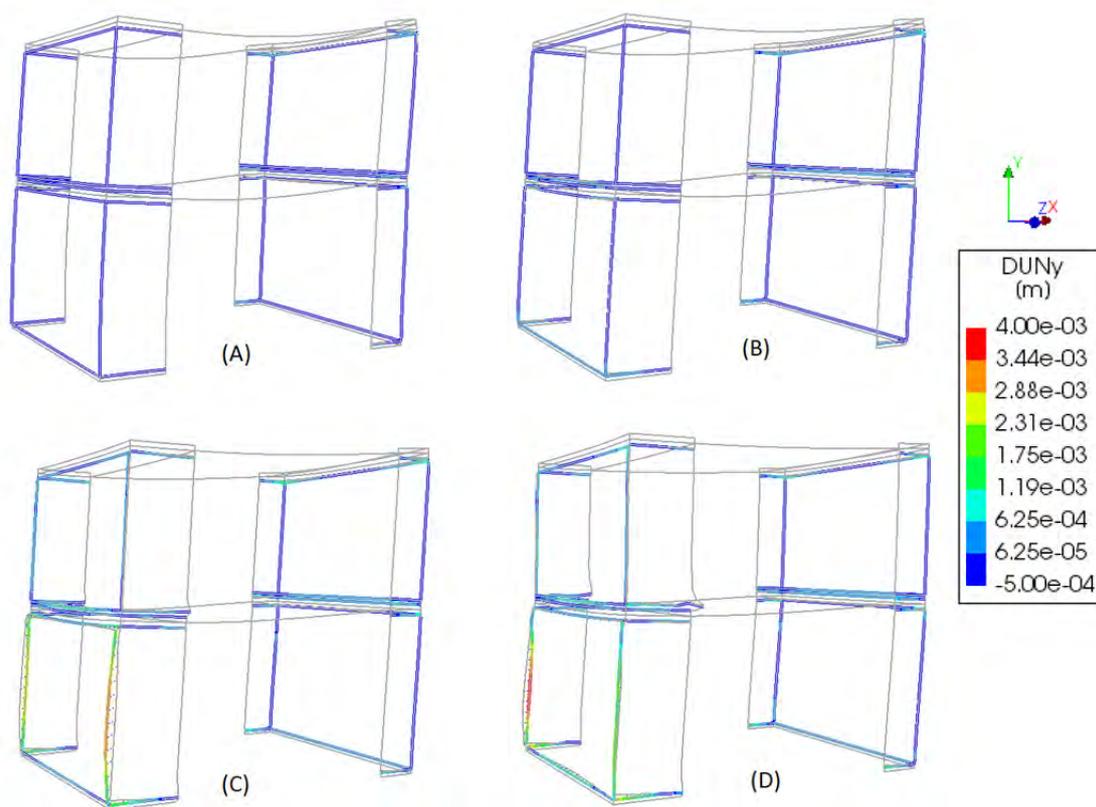


Figure 7: Interface relative normal displacement (at points A, B, C and D on the curve) that shows the rocking behavior and also opening of the vertical interface after initially sliding, - with reduced material properties based on parametric studies (Mesh not shown for clarity)

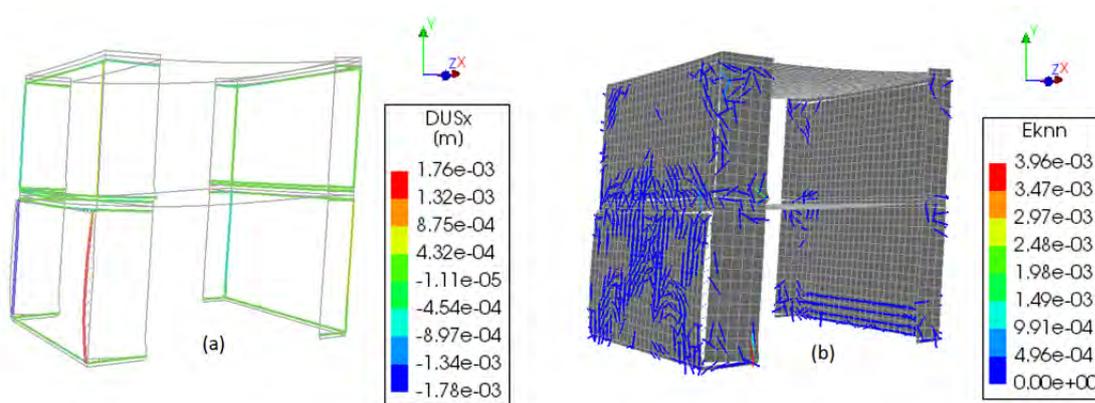


Figure 8: DUSx shows the interface tangential relative displacement at point C of the capacity curve indicating sliding has already happened before C (a) and the crack strains showing cracking pattern for point C of the capacity curve (b)

CONCLUSIONS

This paper presents the finite element analyses of the quasi-static cyclic pushover test of a calcium silicate masonry assemblage. The pushover test has been modelled monotonically in both the pushing directions using a total strain based rotating cracking model for continuum elements representing the calcium silicate elements and a discrete/coulomb friction model for interface elements representing connections. The material parameters are obtained from tests at material level and the model overestimated the capacity in the simulation. A parametric study was performed on the material properties and reduced tensile strength and cohesion values for the interfaces showed good agreement to the experiment. The need for appropriate calibration of material properties while using FEA is thus illustrated. The problems associated with stability of the incremental-iterative procedure, post peak, using an implicit solver have also been elucidated in this study. This reiterates the need for more robust and stable solution procedures for non-linear analysis concerning brittle materials like masonry. Explicit schemes may be used but are computationally very intensive.

ACKNOWLEDGMENTS

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SAFEGUARDING HISTORIC STRUCTURES BY INSTRUMENTED BUILDING MONITORING

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KEYWORDS

Building Monitoring, Historic Structures, Breech Elevated Water Tank, Bebenhausen Abbey, Blauer Turm Bad Wimpfen, Johanniskirche Schwäbisch Gmünd.

ABSTRACT

A regular building inspection allows longevity of structures. There are two basic maintenance programs that may be suitable, differing in interval, cost and benefit. The reactive approach is based on the redundancy of most structural systems. Repair measures take place if a failure of some component is detected. Low inspection costs are favoured over potentially higher rehabilitation expenses and at the price of local damage to the structure or even failure. The preventive approach requires scheduled examination at a medium interval and according mitigation measures, if prospective damage is probable. The incurring inspection costs are accepted in order to reduce material deterioration and prevent extensive repair.

High value targets, such as historic structures, need a more reliable program, as every material loss is final. This can be achieved by predictive preservation, as extension to preventive maintenance. The goal is to carry out additional inspection as needed and prompt, possibly automated reaction. This requires that the structural behavior is known at all times in order to detect any relevant change to the system at the earliest instant. The method of choice is instrumented building monitoring.

In the paper, four different historic structures are presented, where instrumented building monitoring is used to safeguard the structures. The elevated water tank from 1936 at the village Breech was monitored during waterproofing works to prevent thermal cracking of the concrete ceiling. The 14th century summer refectory at Bebenhausen Abbey is continuously monitored to detect an enlargement of the wall tilting and the existing cracking in the arch work. The 13th century castle keep “Blauer Turm” at Bad Wimpfen is monitored for structural change prior to and during conservation. Finally, the also 13th century Johanniskirche church at Schwäbisch Gmünd was monitored to assess the challenging climate conditions and project a preservative climate conditioning.

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BUILDING INSPECTION

Any structure ever built is subject to decay. Its pace of progress inevitably depends on the external influences and the structures resistance to them. Some damage can be well judged by the traditional experience of stonemasons and other hands-on specialists. Scientific certainty, however, can only be achieved by measurements. Against this backdrop, the conservator or researcher has to appreciate that any observed decay can be traced back to some load case the structure was not designed for, be it moisture or additional mechanical load. A building inspection therefore has to look at such effects, if the true cause is to be found rather than suggesting only cosmetic rehabilitation. The external influences may be subdivided into five categories from the perspective of building inspection.

- **Dead loads.** These are all loads that the structure constantly has to bear, primarily the building material's self-weight, but also permanent installations and furnishings, such as pipework and bookshelves. Dead loads may lead to gentle structural decay in combination with susceptible materials, take the evident deflection of historic wooden beams as example. Dead loads are not cause for a regular inspection.
- **Constant loads.** Included in this category are both loads through considered material change, such as creep, the hydration of cementitious materials or groundwater pressure, and loads outside the structure's design, e.g. settling, dust pollution, contamination with noxious substances from traffic and industry, or rising groundwater, especially in combination with de-icing and other salts. Inspection typically takes place upon first observation of damage, which may lead to a subsequent routinely review.
- **Singular loads.** These include all unique events, for example earthquakes, fire and flooding, but also traffic accidents and wilful damage. The effects on the involved structure appear in the entire spectrum of damage between no measurable influences to complete destruction. Most are somewhere in between, which makes this load case especially difficult to assess. If, for instance, a small crack in a concrete beam is detected after a singular event, there is no easy way to judge the extent of damage to the reinforcement. This is where inspection methods come into play. In the given case this could be magnetic stray field testing to detect breaks in the pretensioned steel or ultrasonic testing to estimate the crack depth. Nonetheless, the damage may always be the starting point for future decay, such as corrosion or fatigue.

A special case of singular loads are repair works or strengthening measures to consider change of use or new legal provisions. Such activities can indirectly result in the redistribution of forces in the structure or changes in the structural behaviour under loading, and directly in the exposure to new loads. Inspections certainly have to consider according interventions, as the comparability to prior findings may not be given any more and also new additions will behave in a different way than the old structure and hence be a spark for future damage.

- **Reoccurring loads.** These are loads, which occur on a somewhat regular basis on a longterm basis. Typical examples are frost and snow in moderate climate zones, regular cleaning, or seasonal temperature change. Structures are usually designed for these conditions. If damage appears, it is challenging to trace back to reoccurring loads from a single or even regular inspection, since other influence in most cases conceal the true reason.
- **Frequent loads.** This comprises most live loads, i.e. traffic, daily variation of temperature and relative humidity, or wind and rain. They lead to a great variety of damage and material change, e.g. fatigue, wear, weathering, and swelling and shrinkage. Some of

the most probable damages can be predicted from experience, but their incidence depends on the actual impact level and frequency. Regular inspection is the usual method of choice, see for instance regular bridge inspections.

Structures can long resist the given loads, if they are considered in a suitable manner and the design meets the consequential demands. Nonetheless, not every event and every load combination is foreseeable. In fact, designing a structure to last forever is, most of the time, neither economically, nor ecologically acceptable, necessary or even possible. The identification of undersigned degradation of a structure is the therefore key element for the upkeep of its intended operation. Yet, regardless all effort, the structure will eventually deteriorate, because the probability of detection of a defect at a complex construction is never absolute and remedial measures nearly always either remain a weakness or raise the stresses in some other part.

There are different approaches for structural inspection and according maintenance, differing in the inspection interval and acceptable damage (Table 1). Despite other occasional proclamations, it is not possible to generally praise or condemn any strategy. For example, the demands for temporary shelter, a highway bridge and a historic cathedral are completely different. The most suitable one is a trade-off between the object's pursued service life, along with its conservation value, and the inspection effort and repair costs. The reactive approach sees inspection as a singular event only upon visual observation of damage or after incidences that are likely to have caused damage. It relies on the redundancy of structural systems, where the failure of one component can be compensated temporarily or permanently by some other part. In the preventive approach, the construction is revisited on a regular basis. Existing damage is actively looked for, possibly with the aid of non-destructive test methods. The predictive approach, finally, chooses to prevent damage before it occurs or before it becomes visible. The strategy is somewhat elaborate, but preserves the structure's condition the best possible.

	Maintenance	Inspection	Damage
Level 1	Reactive	Singular	Obvious
Level 2	Preventive	Repeated	Detectable
Level 3	Predictive	Continuous	Invisible

Table 1: Maintenance levels.

The preservation of historic structures requires particular care regarding inspection and maintenance. Any damage is undesirable, since the loss of material is final and many parts irreplaceable. Fortunately, the nowadays existing historic objects are in essence most likely well-built - they would otherwise not have survived. Yet, modern anthropogenic influences, such as acid rain, air pollution, climate change in general, or simply increased frequency of visit or use, pose a greater threat to conservation than ever. The continuous inspection of historic objects is therefore a fundamental requirement, if they are to be sustained for future generations. The method of choice in this case is instrumented building monitoring.

BUILDING MONITORING

Manual building inspections always draw a picture of the examined object at a certain point in time. Though they may be very accurate, largely unrecognized are daily variations in the data. Although some parameters can be noted during inspection, like the average temperature or the precipitation conditions, they can only show a small slice of entire scope.

The installation of a building monitoring system, which continuously records the structural behaviour and the loads, overcomes this time gap at the price of limitation of measurement points. The goal is to permanently assess the structure's condition, its material and parts, to be able to immediately react to change, plan rehabilitation measures and estimate the residual lifespan.

The detection of damage with a building monitoring system strongly depends on the selection of the right sensors under the given circumstances, their placement and their amount. It is often not enough to simply put a temperature data logger somewhere seemingly reasonable. Significant information can only be obtained, if several aspects are considered and the right questions are asked. Some examples are given for each step, certainly without claiming completeness.

- The primary question always asks for the reason of the inquired monitoring. What is the goal? Is there an acute problem? Is the usage of the object changing or does it need optimization? Or is the goal to prevent future damage?
- The second step in the design of a building monitoring should ask for the condition of the structure. Which materials is it built of and what is this material typically vulnerable for? Are there known damage or critical areas? How old is the structure? Has there previous been repair work? Which are the relevant loads? How is the structure accessible?
- In a third step, the relevant measurement parameters have to be established. There are five basic categories that describe the most common features (Figure 1), given below.
 - Geometry. This includes all basic geometrical changes, such as strain, displacement, and inclination.
 - Known deficits. Comprised in this category are the explicit condition monitoring of apparent weaknesses, such as cracks, salt efflorescence, and wear.
 - Loads. The category contains the external influences given in the first section. Included are for example mechanical forces, wind, temperature, humidity and moisture, solar radiation, atmospheric pollutants, and so on.
 - Material behaviour. Measurements in this category regard the reaction of the building or decorative material to the loads. Examples are creep, corrosion, swelling and shrinkage, and water and salt movement.
 - Structural behaviour. Apart from local findings, it is often extremely helpful to regard the big picture, that is, the overall structural performance. Comprised are for instance force and temperature distribution or vibrations.
- The fourth step requires the technical selection of the most suitable sensors. The choice must respect the technical boundaries. What is the expected measurement range and can it be covered with this sensor? What resolution is sensible and can be achieved? Does the sensor have a hysteresis or a temperature dependence? Is the system designed to work under the given environmental conditions? Is the sensor stable over extended periods of time? Does it need repeated service?
- Step five requires the planning of a suitable measurement configuration. How many sensors are necessary for the task? Where do they have to be placed? Should the measurements be continuous, time or event based?
- The most appropriate measurement system has to be selected in the next step. Is a wireless or wired measurement system better for the intended use? Can cables be installed without impairing the sight and may they be fixed to the surface? Is the system remotely accessible for maintainable and changes to the measurement routine? Is the data stored

locally or is it send to a server via Ethernet or mobile internet? Are alarms required when measurement values exceed limits? What happens if the systems fails?

- The seventh step concerns the operation. Can the accumulating data be reduced and how can it be stored? Is there a possibility to verify data, e.g. in terms of sensor redundancy? In which way is the data analysed and can this be automated? Who has access to the data and how are reports generated?
- Finally, the eighth step deals with the data interpretation. What is the meaning of the collected data for the structure? What can be done to change the measured behaviour? And beyond time series, can the data be used as input for modelling or active influence to the building?

With all steps appropriately considered, it is possible to create a building monitoring, which benefits the structure the most.

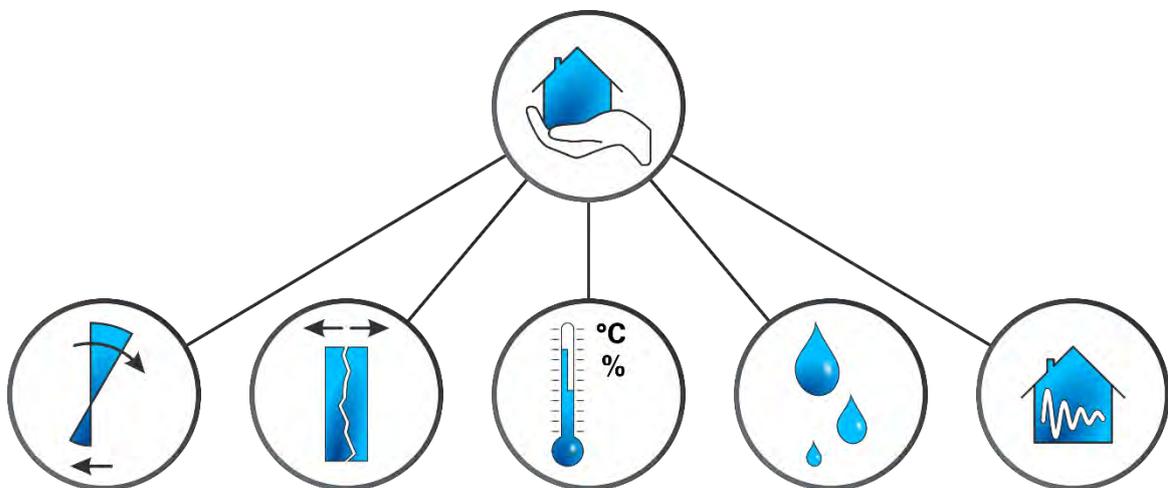


Figure 1. Monitoring categories. From left to right: geometry, known deficits, loads, material behaviour and structural behaviour.

SOME EXAMPLES

Monitoring in the context of historic structures differs from other fields of application by the requirements of conservation and often the focus on both monitoring slow processes and achieving lasting results. The four examples (Figure 2) given in the following show some tasks and recently applied monitoring methods.

Designing a safe climate for the Johanniskirche church

The Johanniskirche church at Schwäbisch Gmünd was built in the 13th century in late Romanesque style (Figure 2, top left). The interior presents splendid painting artwork from 1870, directly painted on the sandstone masonry walls and the wooden ceiling. The church is used as museum and concert location. The motivation for the installation of a monitoring system was the poor state of the wall paintings. Strong condensation led to detachment of paint layers, especially the gold plating, and discoloration along the pathways of the dripping water, culminating in puddles on the floor. Additionally, salts (mainly sodium sulphate) were found in the plinth of the walls. The wooden ceiling grapples with mould growth.

With the aim of preserving the paintings, it was decided that the interior climate would have to be optimized with regard to water condensation on the walls. The two possibilities

to reduce condensate occurrence are directly through active dehumidification and indirectly by heating to increase the vapour capacity of the air. Both approaches inherit certain hazards to the structure. Dehumidification, be it directly or indirectly, leads to a greater moisture gradient within the walls, which increases the amount of transported salt. Heating might also lead to salt crystallization and fosters mould growth.

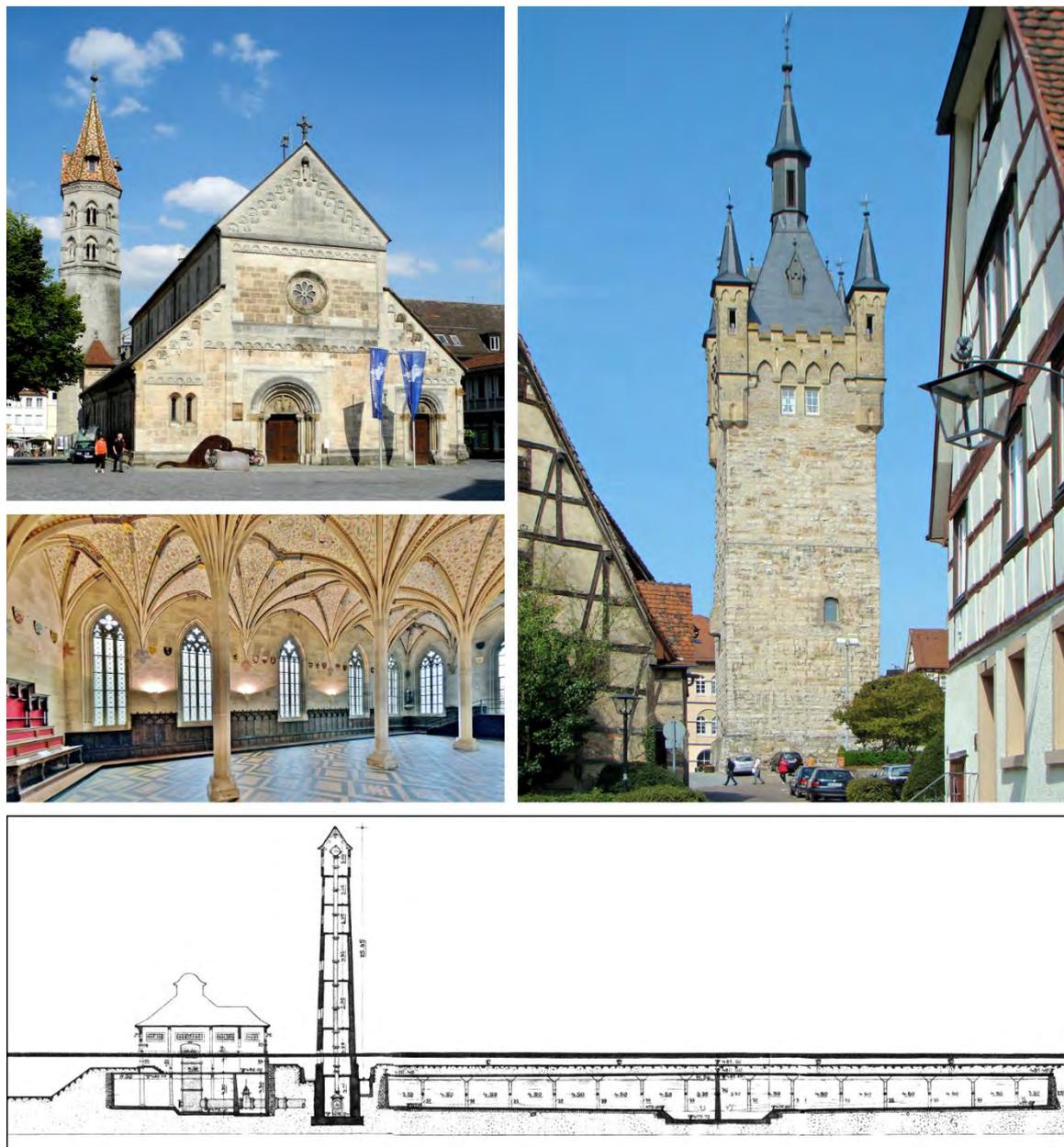


Figure 2. Top left: 13th century Johanniskirche church at Schwäbisch Gmünd. Wikimedia Commons, “Schwäbisch Gmünd – Johanniskirche ab 1225, Westfassade”, Franzfoto, CC-BY-SA 3.0, cropped from original. Mid left: 14th century summer refectory at the Bebenhausen Abbey. Wikimedia Commons, “Kloster Bebenhausen”, Holger Uwe Schmitt, CC-BY-SA 4.0. Right: 13th century castle keep “Blauer Turm” at Bad Wimpfen. Wikimedia Commons, “Blauer Turm in Bad Wimpfen”, Peter Schmelzle, CC-BY-SA 3.0, cropped from original. Bottom: Section of the 1936 elevated water tank at Breech.

To understand the reasons for the condensation and specify the conditions when it occurs, 13 climate sensors for measuring temperature and relative humidity were installed in

the church. The sensors were clustered for the data interpretation according to their catchment area. A wireless measurement system with remote access was chosen to avoid wiring across the artwork and to be able to control actuators if necessary.

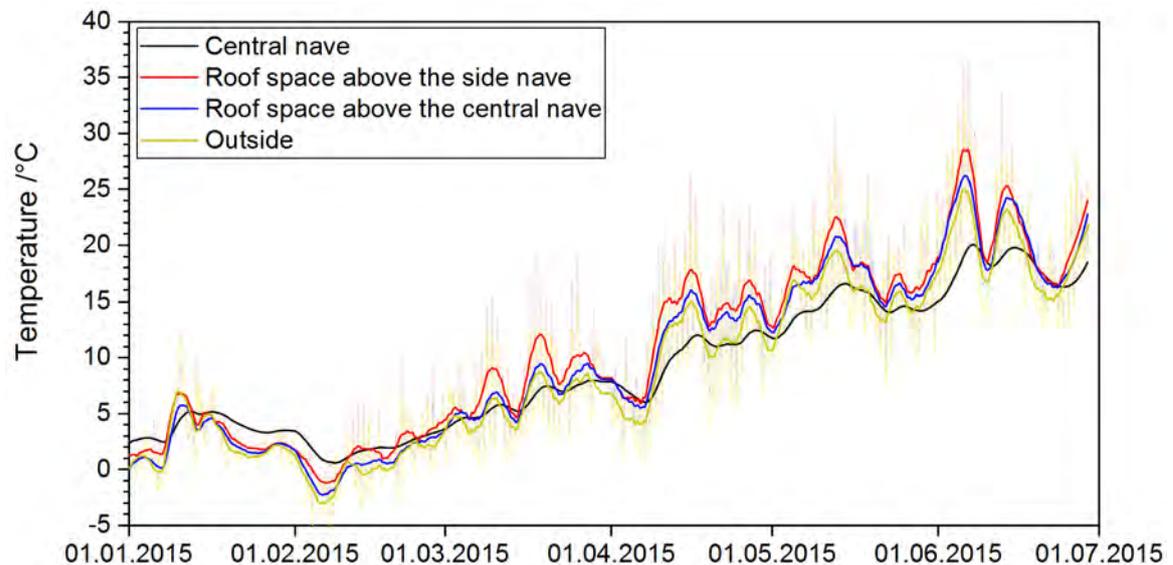


Figure 3: Temperature monitoring at the Johanniskirche church. Shown are the weekly average (solid lines) and original data (transparent lines) for the defined sensors clusters.

The monitoring started in 2014 and is still active. Figure 3 shows the temperature development in the course of half a year for the different sensors clusters. Condensate occurs, when the dew point on the walls falls below the dew point of the air. This is especially the case, when warm air enters the church and cools down, which increases the relative humidity. While the airspace within the church can follow a steep temperature rise to a certain extent, the walls cannot. The water then precipitates on the wall surface. The effect is known as “summer condensation” and can be approximately determined from the figure, where the outside temperature rises above the temperature of the central nave. At the Johanniskirche church, an excessive air exchange rate promotes the problem. A detailed treatment of the project can be found in [1].

Different mitigation measures were considered and tested out of a range of possibilities. The most promising one provided an automated window control, based on a real-time evaluation of the interior and exterior dew point calculation for the different sensor clusters. The windows were opened, when the absolute humidity of the exterior air was calculated to be well below the one inside the church, i.e. when the moisture introduced with the outside air would not lead to a condensation on the walls. This gentle approach requires a minimum of energy and avoids technical measures. The success was noticeable in reduced condensate, but not completely satisfying, because the uncontrolled air exchange via constructional leaks was greater than could be realized with the given windows. A possibility would be to technically increase the air exchange. However, the conditions for natural dry ventilation are sparse, especially in spring, when most of the condensate occurs. Mobile condensation dehumidifiers would be another possibility. They are, however, limited in their use at low temperatures, as found inside the church. Peaks in the relative humidity could be buffered by cautious, temporary heating of the air. The results in the given case would have to be carefully evaluated against the backdrop of the high, uncontrolled air exchange rate and the imminent worsening of mould growth or salt efflorescence.

Monitoring structural change at the Bebenhausen Abbey

The Bebenhausen Abbey is a former Cistercian monastery from the 12th century. A richly ornamented Gothic summer refectory was built in the 14th century (Figure 2, mid left). It is open for public visit. During 2016, minor debris was noticed on the refectory's floor. A successive inspection of the complex dome structure revealed massive cracks with widths up to more than the centimetre size. The involved engineering consultants found the reason in the tilting refectory wall. In fact, the toppling is rather slow, with an advance of about 10 mm per century at the top.

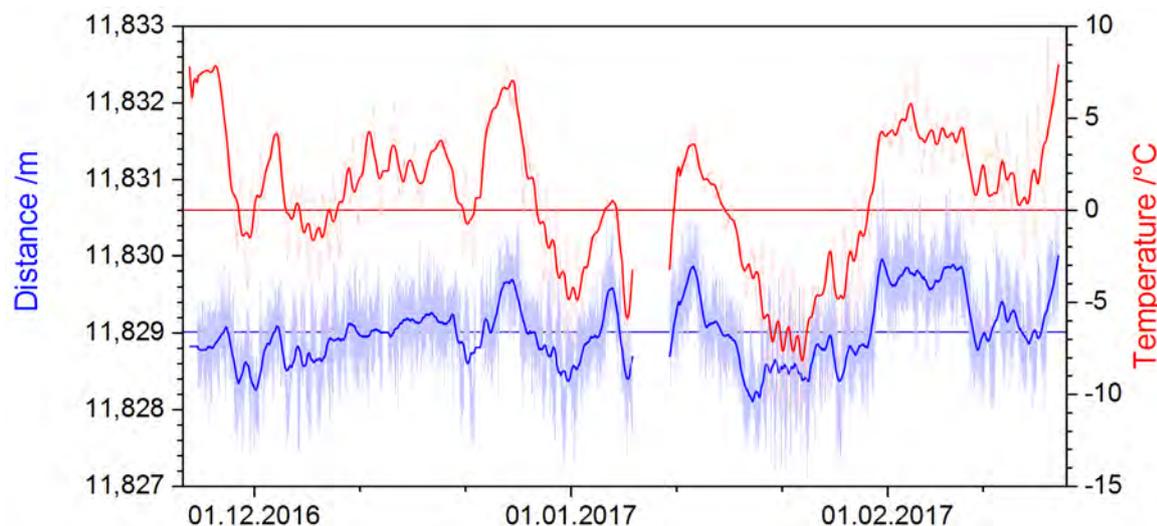


Figure 4: Distance monitoring at the Bebenhausen Abbey. Shown are the two day average (solid lines) and original data (transparent lines) of the laser (blue) and temperature (red) measurement. Indicated with horizontal lines are the average distance and the freezing point. In mid-January, at -10°C , the system failed, because the Ethernet connection was operating outside the specified limits. A switch cabinet heater solved the problem, as can be seen at the end of January.

For safety reasons, as the room is used for concerts, and considering that the building is constructed in a seismic area, it was decided to install a monitoring system. The task was to capture any increase in the tilt. The designed system included a laser distance measurement in the attic above the summer refectory between the two side walls. Laser sensors were chosen for their high resolution and reproducibility despite the measurement span of about 12 meters and their low influence from temperature. A wired system was chosen to satisfy the sensor's power consumption and installed in 2016. The data is transmitted to the MPA servers via mobile internet.

Until now, the measured distances (Figure 4) generally correlate very well with the temperature. Some anomalies can be noted, e.g. during the first week of the measurements and at the very low temperatures at the end of January. The exact structural response of the complex construction is difficult to assess at this state, because only few data is available.

Monitoring the structural integrity of the Blue Tower

The historic tower “Blauer Turm” (German for “Blue Tower”) at Bad Wimpfen was constructed in the 13th century as castle keep (Figure 2, right). Since then, it has changed its appearance several times. The last major modification was the addition of four turrets. Along with a number of fires, uncontrolled water introduction and (nowadays) questionable repair measures, this has led to severe vertical cracking all over the tower. As a first emergency measure, a corset of timber and steel was installed, to beware the tower from potential collapse.

A monitoring system was then to be installed to keep the tower’s integrity under surveillance and send alerts if necessary. The selected system design considered a range of different sensors with an intended overlap of their guarded parameters in order to have a good redundancy and to be able to verify or discard apparent outliers in the data. Amongst others and additional to a range of climate sensors, the system comprised a circumferential monitoring of the tower width at mid-height using laser sensors, an instrumentation for the tower inclination in all directions and a monitoring of the forces within the protective corset.

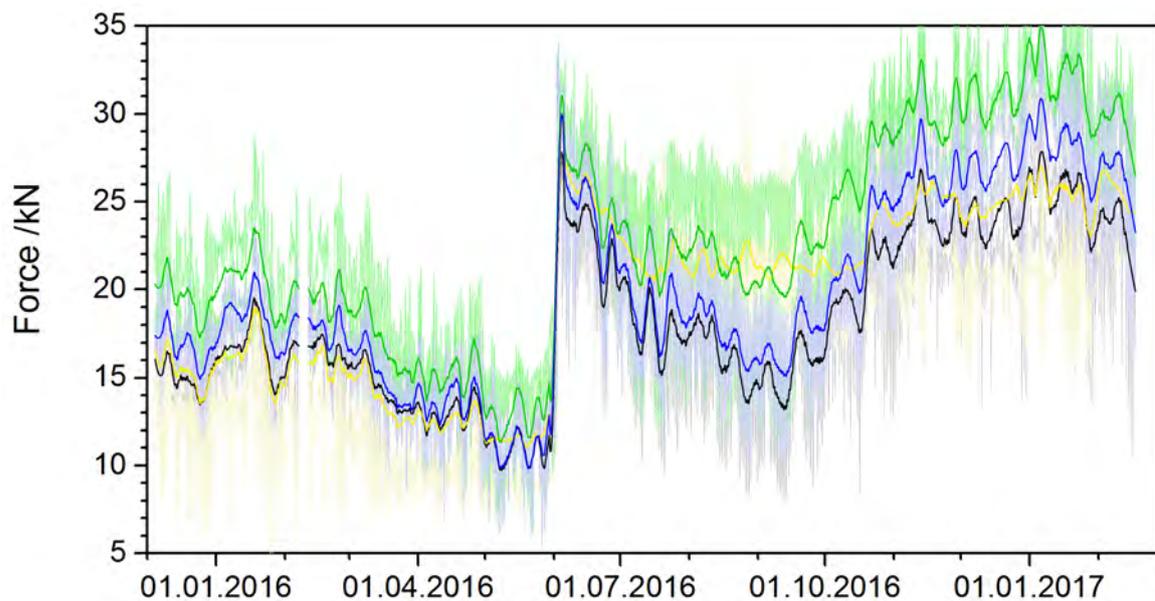


Figure 5: Measured forces in the threaded rods. Shown are the weekly average (solid lines) and original data (transparent lines) for each corner. Southwest – black, southeast – yellow, northeast – green, northwest – blue.

Presented in Figure 5 are the measured forces in the threaded rods, which tension the horizontal steel bracing at the corners. After an initial tensioning to an intended 20 kN, the forces slowly decreased with increasing temperature and with the drying timber framing. Based on the measurement data, the threaded rods were retightened in mid-summer of 2016 to ensure continued operability of the corset. The observable daily and seasonal variations are quite large. This is due to the different thermal capacity of the tower, built from sandstone, and the steel bracing. During warm days or even direct sunlight, the steel heats up, leading to a thermal expansion of about 2 mm. The masonry walls on the other hand have a slow thermal response, from which follows a difference in expansion, which yields the observed decline of the forces.

Monitoring temperature during construction work at a water tank

The elevated water tank at Breech was constructed in 1936 (Figure 2, bottom). During the construction work for a new waterproofing in 2016, the protective soil had to be removed. In consequence, the top of the tank was exposed to direct sunlight. In the past there were known damages, i.e. cracking, from other tanks as a result of the thermal expansion of large roofs of 50 m. The client wanted to prevent cracking through a temperature monitoring with an connected alarming system. After reaching a defined threshold level of 22,5 °C (Figure 6), he was able to react by successive water cooling of the exposed top. The monitoring and the alarming worked very well and the new waterproofing was installed without any reported damages.

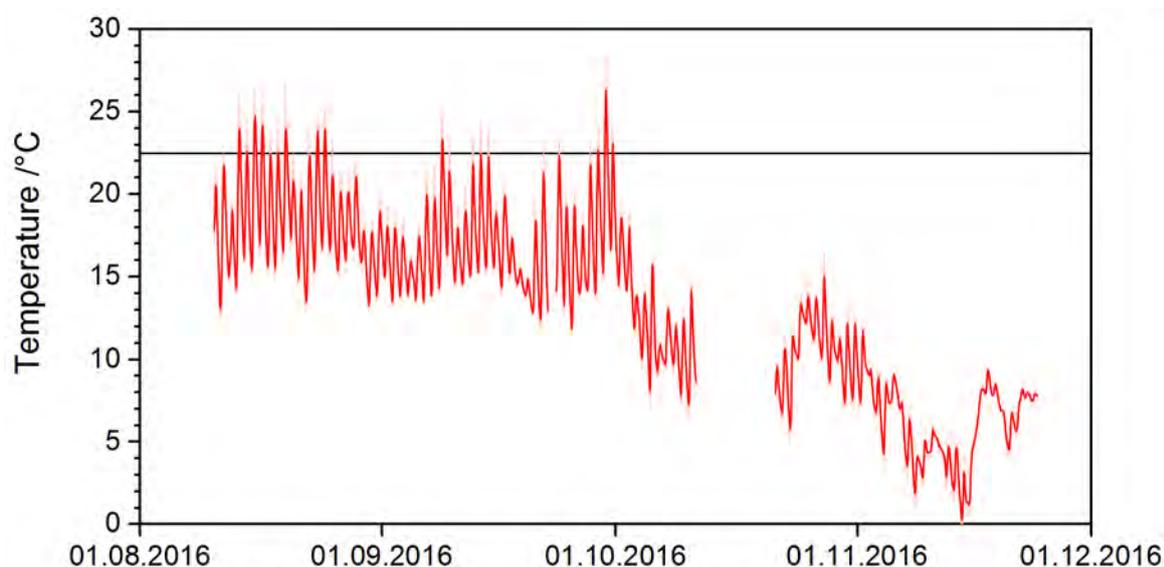


Figure 6: Temperature development in the ceiling of the water tank. Shown are the average temperature (solid line) and separate sensor data (transparent lines). The data gap in October is due to a cut through the data line during the ongoing works.

CONCLUSIONS

Instrumented monitoring is an extremely helpful tool if the state of a structure has to be continuously assessed or damage causes are to be found. It is utmost important to keep the ever-changing load conditions in mind, may it be mechanical actions, temperature, moisture, or any other action, something that can hardly be achieved by singular or even periodic inspection. The given examples show some of the manifold possibilities of monitoring application at historic structures.

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HYGROTHERMAL BEHAVIOUR OF BUILDING COMPONENTS IN CONTEXT WITH THE ROOM USAGE OF A HISTORIC RESIDENTIAL BUILDING IN JEDDAH, KSA

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KEYWORDS

Coral Stone, Hygrothermal Simulation, Thermal Comfort, Historic Building

ABSTRACT

Before the invention of air conditioning systems historic buildings were able to provide a comfortable indoor climate without using a mechanical air conditioning system for almost every day and night time. Was there a significant interaction between building geometry, construction, material and climate?

Jeddah is the second biggest town in the Kingdom of Saudi Arabia. El-Balad, its historic city center, has been on the list of world heritage since 2014. It is located on the west coast of the red sea. The coastal weather is very hot and humid. Typical three to six story high buildings are made of the regional material coral stone; the openings in the façade are filled with wooden shutters.

Al-Nawar House, a typical, in its origin approximately 300 years old example of a residential building type, was undertaken a conventional way of building survey. The results were drawings, material and damage mappings, documentation of the building's history and the user's daily routine of living in that house.

How can we prove the thermally comfortable functionality of a room with no active air conditioning system in such a hot and humid outdoor climate zone? Which data has to be collected in addition to a conventional way of building survey?

According to several sources for modelling the indoor climate the indoor air temperature and humidity profiles were calculated. In a second step a one-dimensional hygrothermal simulation of an outer wall was performed with the software WUFI pro. The interaction between materiality, climate, user behaviour and thermal comfort can be surveyed in the analysis of the building component's temperature and humidity profile.

This research project is part of the author's doctoral thesis at Vienna University of Technology with the working title: Climatic and Building Physical Influences on the Morphology of a Residential Building Type in Jeddah, KSA.

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INTRODUCTION

In historic architecture the choice for a building material mostly depends on its availability. But was this decision also influenced by the capability of a material to improve the thermal comfort in a building? How can be reconstructed the comfortable use of a room in a historic and abandoned building?

This paper describes a method and parameters to calculate and simulate the indoor climate of a room according to its construction materials and ventilation system.

Situation of Jeddah and Al-Nawar House

Jeddah is located in Saudi Arabia at the east coast of the Red Sea, about 90 km west from Mekka. Al-Balad, the historical district of Jeddah, is on the UNESCO world heritage list since 2014. The hot and humid climate at the east coast of the Red Sea provides temperatures between 26 and 42 °C in July and between 15 and 32 °C in January with a relative humidity of 61 % averaged over one year [1].

Until the invention of electric driven coolers the residential buildings in Al-Balad were not equipped with any active cooling system but wooden shutters in the wind facing facades to control the natural ventilation of the whole building. Only night cooling – when a big amount of cooler and relative dry air streams from outdoors through every room – could achieve a comfortable thermal indoor climate.

The challenge was to keep the inner surface to a temperature and moisture level of the inner room surfaces lower than the fresh but hot and humid outdoor air, which was necessarily streaming through the rooms during daytime. So the building construction can absorb heat and moisture coming from ventilation and infiltration and accomplish a more comfortable indoor climate. But does the building material influence the indoor climate in a significant way?



Figure 1: Al Balad, Jeddah. View from the rooftop of Al Nasif House. Al-Nawar House is located in the far back corner of the block of old buildings.

The up to six story high houses in Al-Balad are built of coral stone from regional quarries. Al-Nawar House represents the classical building construction with mainly coral stone masonry used in large blocks and reinforced by horizontal layers of wooden beams

at a distance between 80 to 120 cm, depending on the specific situation of wall openings (see figure 1) [2].

BUILDING SURVEY OF AL-NAWAR HOUSE

In the year 2011 a group of scientists from Vienna University of Technology and King Abdul Aziz University of Jeddah performed a contour-accurate building survey of Al-Nawar House using a 3D laser scanner on site for plan mapping in scale 1:50 (see figure 2). Also a damage mapping was drawn up by a photographic documentation of all room surfaces [3]. The information about the way of living in such typical, about 300 year old residential building came directly from Sami Nawar, the former inhabitant and actual owner of Al-Nawar House. Literature study provided the background information such as the connection of Al-Nawar House to the history of Jeddah and its people [4, 5].



Figure 2: First floor of Al-Nawar House. The surveyed room 101 is located on the upper right corner in north-western direction. The façade openings are just filled with wooden shutters [3].

But how can we prove the thermally comfortable functionality of a room without any active air conditioning system in such a hot and humid outdoor climate zone? Which data has to be collected in addition to a conventional way of building survey, such as described in the paragraph above?

RECONSTRUCTION OF THE INDOOR CLIMATE

Does the materiality of the components enclosing the room influence the indoor climate? First step to answer this question is to monitor or calculate the indoor climate.

Subject of investigation is room 101 on the first floor of Al-Nawar House (figure 1, 2 and 3). Geometry and construction of the room envelope are known from the building survey on site and from literature study [6]. Usage scenarios were described in interviews with Sami Nawar.



Figure 3: Condition of the Room 101 on the first floor of Al-Nawar House in the year 2011. The openings are facing in western and northern direction. The walls are constructed of load bearing coral stone blocks, covered with whitewashed lime plaster. The openings are filled with wooden shutters, which can regulate the airflow and daylight impact into the room [3].

The physical characteristics of coral stone, lime plaster and wood for the shutters and furniture are based on a material dataset [7] and measurements on a single coral stone block with remains of plaster, which was taken from a recently demolished neighbouring building of the same type and similar construction date like Al-Nawar House (table 1).

			coral block	lime plaster	old wood
bulk density	ρ	kg/m ³	980	1600	740
specific heat capacity	c	J/kgK	840	850	1500
thermal conductivity	λ	W/mK	0,45	0,70	0,18
porosity	Φ	% _{vol}	40	30	-
water vapor permeability	μ	-	7	7	223
sorption at 20% r.h.	w(20)	kg/m ³	8	8	30
sorption at 80% r.h.	w(80)	kg/m ³	30	30	104

Table 1: Material characteristics.

A long-term monitoring of indoor climate for each room of the building was not accessible. A simplified calculation model describes the hourly profile of indoor air temperature and air humidity in room 101.

Equation 1 describes the change of indoor air temperature, equation 2 the change of absolute indoor air humidity within a certain time span.

$$\begin{aligned} & (c_{wall} \cdot A_{wall} + c_{wood} \cdot A_{wood} + c_{air} \cdot V \cdot \rho) \cdot \frac{\Delta T_i}{\delta t} \\ & = (c_{air} \cdot n \cdot V \cdot \rho + U_{win} \cdot A_{win}) \cdot (T_e(t) - T_i(t)) \end{aligned}$$

Equation 1: Change of air temperature in room 101 over the time.

The left side of equation 1 describes the heat flow into and out of the wall, wooden furniture and shutters and room air multiplied by the change of indoor air temperature over the time t . The specific effective heat storage capacity c_{wall} (building components of the room envelope) and c_{wood} (wooden furniture and shutters) were calculated according

the modelling principles described in ECBS Annex 41 [8]. The data source for the necessary parameters, such as specific heat capacity c , bulk density ρ , thermal conductivity λ , water vapour permeability μ and liquid water content at 20 % and 80 % relative humidity $w(20)$ and $w(80)$, is the Fraunhofer material database [7], assumption out of similar materials or direct measurements on the wall stone probe. A_{wall} and A_{wood} are the surface areas of the components.

The right side of equation 1 assumes convective (air stream) and conductive (window shutters) heat transfer depending on the differences between outdoor and indoor temperatures T .

$$C_{\text{hyg}} \cdot \frac{\Delta u_i}{\delta t} = n \cdot V \cdot (u_e(t) - u_i(t))$$

Equation 2: Change of absolute humidity in room 101 over the time.

The left side of equation 2 describes the change of absolute indoor air humidity Δu_i over the time t depending on the effective moisture storage capacity C_{hyg} of the wall and wooden furniture and shutters. The right side characterizes the transport of moisture from outdoors into the room by ventilation.

Jeddah climate data comes from a meteonorm dataset [1].

The air change rate n is basically assumed with 0,1 per hour (infiltration from outside through closed shutters). When the outdoor air temperature is more than one degree Celsius lower than the indoor air temperature, the air change rate n rises to 3,0 per hour (opened shutters). The presence of two persons is assumed from 7 to 12 o'clock; during that time the air change rate n is fixed to 0,3 per hour.

The outer wall consists of a 30 cm thick load bearing coral stone layer, covered on both sides by 3 cm limestone plaster. The shutters are constructed by 2 cm thick wooden elements.

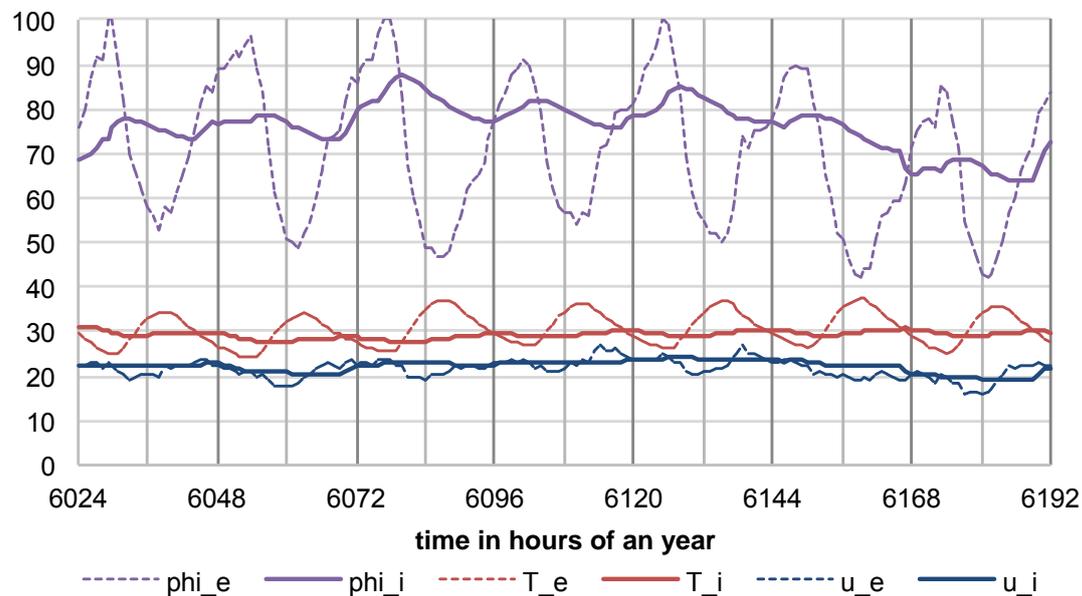


Figure 4: Measured outdoor climate and calculated climate in room 101 from 8th to 15th of September.

Figure 4 depicts the results of the calculations. In comparison to the outdoor climate profiles the fluctuations of temperature, relative and absolute humidity in room 101 are significantly attenuated; the peaks of the amplitudes are shifted for several hours.

HYGROTHERMAL SIMULATION OF OUTER WALL

Is there an interaction between the hygrothermal behaviours of the building component and the indoor climate? After providing the hourly indoor climate (temperature and relative humidity) over one year the one-dimensional simulation of an outer wall can be performed using the simulation software WUFI pro [9]. The availability of parameters such as thickness, bulk density ρ , porosity, heat capacity c , thermal conductivity λ and water vapour permeability μ for each material layer of the building component are prerequisite for the calculations [10, 11]. WUFI depicts the dynamic change of temperature, water content, heat and moisture fluxes within and on the surface of a building component according to the indoor and outdoor climate situation. Figure 5 shows the range of temperature (light red area), relative humidity (light blue area) and water content (blue area) respectively the temperature (red line) and moisture (blue and dark blue line) profile in the outer wall of room 101 (also see table 1).

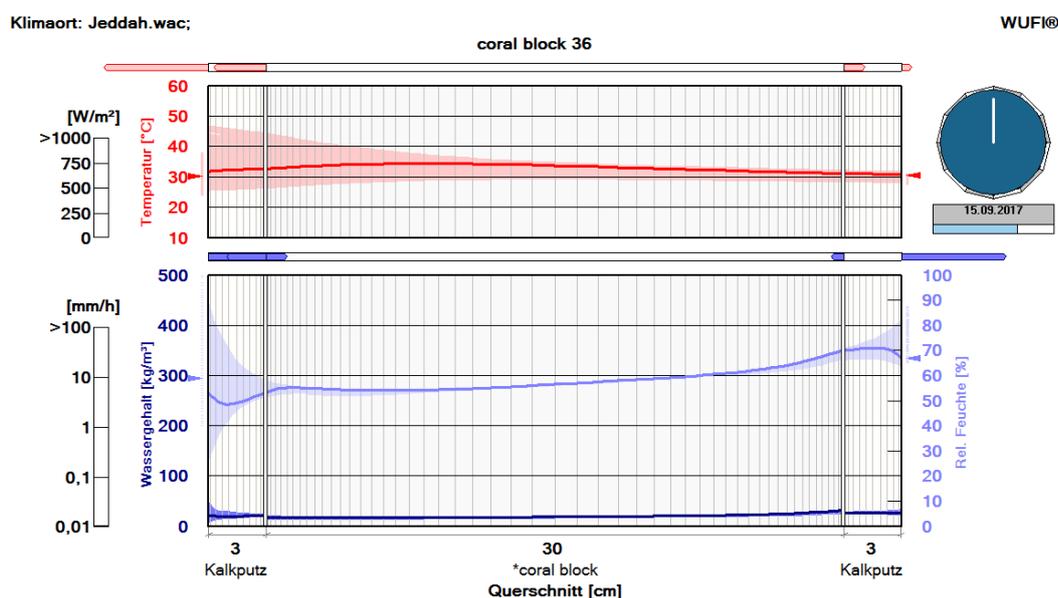


Figure 5: Cross-section of an outer wall built from 30 cm load bearing coral block masonry with 3 cm limestone plaster on both sides with an indication of hygrothermal effects on and within the wall construction between 8th and 15th of September [9].

For example between September 8th and 15th there is no water transport through the outer wall. The highest impact to the change of humidity in the inner area of wall construction takes place in the lime plaster and extends just a few centimetres into the coral block layer. The water content in the lime plaster is looking for compensation with the indoor air humidity, but is always a certain distance behind or in front of the indoor air.

The temperatures in the outer area of the coral stonewall swing closely to the temperature profile of the outer air and the irradiation onto the outer wall surface. In direction to the inner wall surface the amplitude is attenuated according to the indoor air temperature, but reacts with a certain time delay (figure 5).

CONCLUSION AND OUTLOOK

The materiality of a room does influence the indoor air climate, but just within the upper first few centimetres of the building component. In a short time period the air change rate of a room manipulates the indoor air quality in a much more effective way.

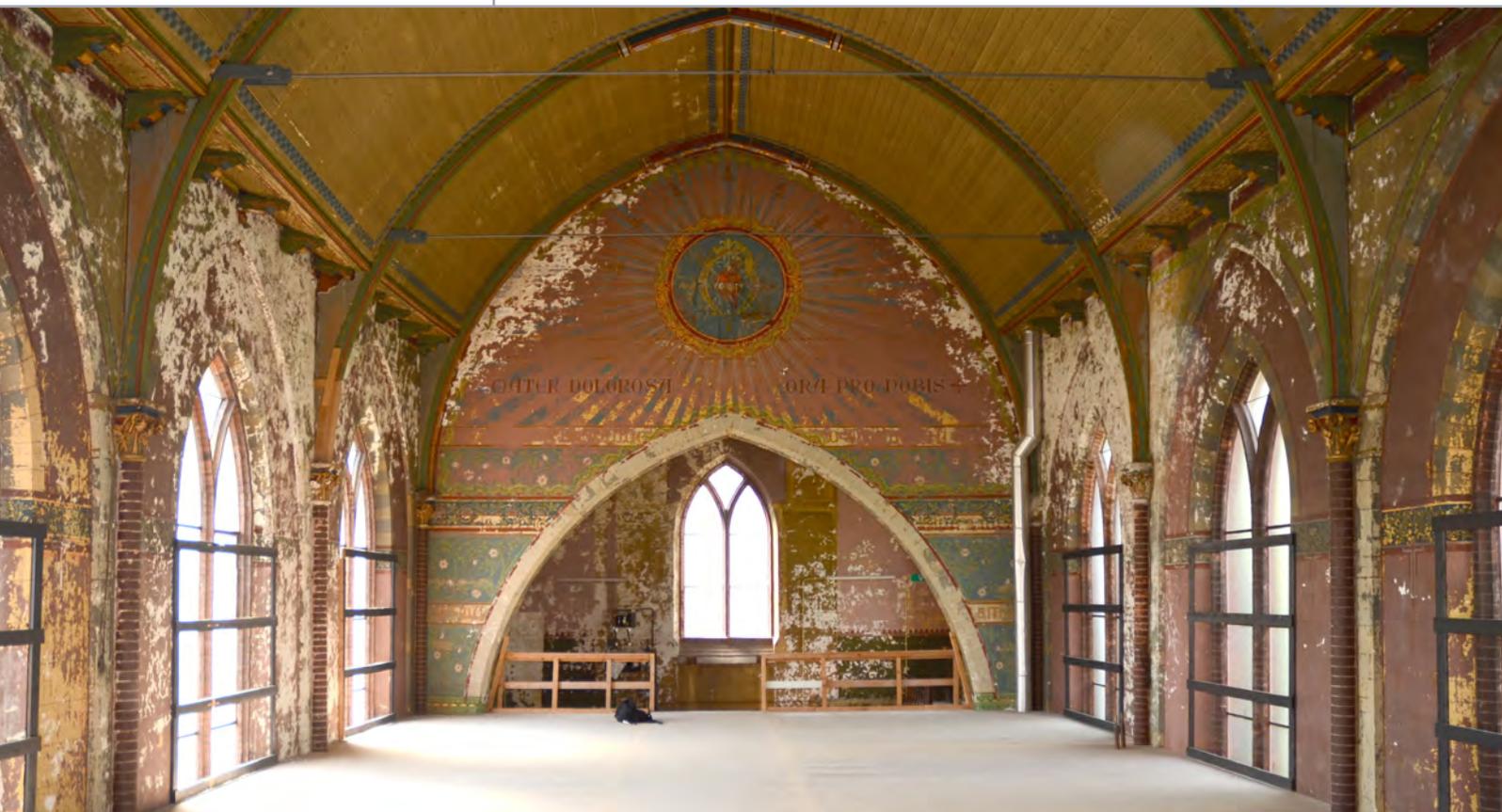
The described method is a first step to reconstruct the hygrothermal behaviour of an abandoned historic room on base of a conventional building survey. Further simulations are necessary for a single room, the whole building and its near surrounding. An easily understandable and comprehensible description of the workflow during the building survey on site to collect matching data for the hygrothermal simulations afterwards are indispensable for an interdisciplinary building research in case of the interaction of climate, building and comfortable living.

Deeper analyses, which are also including the parameters direct irradiation onto the building envelope, interaction with the adjacent rooms and airflow through the building, will be necessary. In a next step a digital twin for a dynamic hygrothermal and airflow simulation will be built.

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PRACTICAL INFORMATION



After successful events in Leuven (2009), Brno (2011) and Stuttgart (2014), WTA Nederland-Vlaanderen and Delft University of Technology, Faculty of Architecture and the Built Environment will organise the 4th WTA International PhD symposium from 13-16 September 2017 in Delft, the Netherlands.

WTA Nederland-Vlaanderen is part of the International WTA Association. The aim of WTA is promoting research and its practical application in the field of building maintenance and preservation of monuments. A primary task here is to transfer the practical experience and to utilize it in order to accelerate the application of new knowledge and advanced technologies.

The aim of the symposium is to unite PhD candidates, post-docs and other junior researchers conducting research in the field of building conservation. It will provide a forum for PhD candidates to present their research, discuss ongoing PhD studies to support future work and give PhD candidates the opportunity to establish contacts within the international scientific community.

Venue

The symposium will take place at the Faculty of Architecture and the Built Environment of Delft University of Technology, The Netherlands.

Program

- Wednesday, 13 September 2017
Welcome reception in the evening
- Thursday, 14 September 2017
Registration | Plenary opening session |
Parallel sessions | Social dinner
- Friday, 15 September 2017
Parallel sessions | Plenary closing session
- Saturday, 16 September 2017
Excursion (on invitation and presenting authors)

Registration

The conference fee is € 250,-, including participation in the symposium, welcome reception, coffee breaks, lunches, social dinner and the proceedings.

Registration via www.wta-symposium.org

WEDNESDAY 13 SEPTEMBER

18.00 WELCOME RECEPTION

BK-City, Bouwpub

THURSDAY 14 SEPTEMBER

09.00 REGISTRATION

TU Delft Faculty of Architecture and the Built Environment - Berlageroom

09.30 SETTING THE SCENE

prof. Rob van Hees, president WTA NL-VL and chairman of the symposium

10.30 COFFEE/TEA BREAK

Session 1: Berlageroom

11.00 DESIGN AND DEVELOPMENT OF SPECIAL CONCRETES - ADAPTION OF MATERIALS FOR SPECIAL REHABILITATION TASKS

Alexander Flohr

11.30 MITIGATING SALT DAMAGE IN LIME-BASED MORTARS WITH MIXED-IN CRYSTALLIZATION MODIFIERS

Sanne Granneman

12.00 LEARNING FROM VERNACULAR BUILDINGS – TRADITIONAL RURAL ARCHITECTURE IN AUSTRIA AND IT'S ADAPTION ON CLIMATIC CONDITIONS

Gregor Radinger

12.30 LUNCH BREAK

Session 2: Berlageroom

Session 3: 01.west.230

13.30 RELIABILITY MONITORING OF THE RAINWATER DISPOSAL SYSTEM FOR HISTORIC BUILDINGS

Nathalie Van Roy

13.30 INFLUENCE OF BIO AND NANO FIBERS IN CLAY MORTARS

Aspasia Karozou

14.00 HISTORIC WOODEN HOUSES OF ISTANBUL WITH THE INFLUENCE OF EUROPEAN STYLES

Saniye Feyza Yagci

14.00 USE OF NANOMATERIALS FOR THE PROTECTION OF HISTORIC STONE ARCHITECTURE: LABORATORY METHODS FOR THE EVALUATION AND INVESTIGATION OF PHOTOCATALYTIC ACTIVITY

Marco Roveri

14.30 PUBLIC PRIVATE PARTNERSHIP IN CONSERVATION AND VALORIZATION PROCESSES: SPONSORSHIP INITIATIVES

Cristina Boniotti

14.30 EXTERNAL STRENGTHENING OF STABILISED EARTH-BLOCKS MASONRY

Kyriaki Papadopoulou

15.00 COFFEE/TEA BREAK

15.30	MATERIALS TESTED BY TIME. QUALITY AND DURABILITY OF THE RESTORATIONS OF THE TEMPLES OF PAESTUM FROM THE NINETEENTH-CENTURY APPROACHES TO THE CONTEMPORARY ISSUES OF CONSERVATION <i>Stefania Pollone</i>	
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16.00 PLENARY CLOSING

19.00 SOCIAL DINNER

Cafe de Sjees, Markt 5 Delft

FRIDAY 15 SEPTEMBER

09.00 PLENARY OPENING

TU Delft Faculty of Architecture and the Built Environment - Berlageroom

Jürgen Frick on behalf of Harald Garrecht - University of Stuttgart

09.30 KEY NOTE

Rob Nijse (TU Delft) - NEW GLASS IN OLD BUILDINGS

10.30 COFFEE/TEA BREAK

Session 4: Berlageroom

11.00 ANALYSIS OF RARE EVENTS AND WEATHER IMITATION FOR THE REALISTIC TESTING OF CONSOLIDATED CLAY-BEARING STONES IN BUILDING FACADES

Ylenia Praticò

11.30 RENOVATING FUSEE CERAMIQUE VAULTS

Wim Kamerling

12.00 DEVELOPMENT OF AMMONIUM OXALATE TREATMENT FOR SITE CONDITIONS - INITIAL RESULTS

Tabitha Dreyfuss

12.30 LUNCH BREAK

Session 5: Berlageroom

Session 6: 01.west.230

13.30 RETROFITTING HISTORICAL BUILDINGS: A PROBABILISTIC ASSESSMENT OF INTERIOR INSULATION MEASURES AND THE HYGROTHERMAL RISKS

Astrid Tijssens

13.30 LIGHTWEIGHT VAULTING SYSTEMS IN THE EARLY 19TH CENTURY, FROM NAPLES TO EUROPE. KNOWLEDGE FOR CONSERVATION OF AN ADAPTIVE BUILT HERITAGE

Lia Romano

14.00 SAFETY ASSESSMENT OF MASONRY STRUCTURES USING ORDINAL OPTIMIZATION

Julián García

14.30 LITERATURE REVIEW ON THE ASSESSMENT OF MASONRY PROPERTIES BY TESTS ON CORE SAMPLES

Samira Jafari

14.30 COMPUTATIONAL MODELING OF THE CYCLIC PUSHOVER TEST ON A CALCIUM SILICATE ELEMENT MASONRY ASSEMBLAGE

Manimaran Pari

15.30 SAFEGUARDING HISTORIC STRUCTURES BY INSTRUMENTED BUILDING MONITORING

Frank Lehmann



Wetenschappelijk-technische groep voor aanbevelingen
inzake bouwrenovatie en monumentenzorg

13-16 September 2017

4th WTA International PhD Symposium

15.00 COFFEE/TEA BREAK

15.30 HYGROTHERMAL BEHAVIOUR OF
BUILDING COMPONENTS IN CON-
TEXT WITH THE ROOM USAGE OF A
HISTORIC RESIDENTIAL BUILDING
IN JEDDAH, KSA
Wolfgang Stumpf

16.00 INTRODUCTION SATURDAY EXCURSION

Wido Quist

16.30 PLENARY CLOSING + DRINKS

Rob van Hees

SATURDAY 16 SEPTEMBER

09.30 - 17.00 BUS EXCURSION TO LEIDEN & ROTTERDAM
Speakers + on invitation only

Organizing Committee

Rob van Hees | Wido Quist | Sanne Granneman

The symposium is co-organised by WTA Nederland-Vlaanderen and the Chair of Heritage & Technology at TU Delft.

Scientific Committee

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Contact

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PROGRAM

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WETENSCHAPPELIJK-TECHNISCHE GROEP VOOR AANBEVELINGEN INZAKE BOUWRENOVATIE EN MONUMENTENZORG

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KvK: 40398619

De WTA stelt zich voor

Er bestaat in binnen - en buitenland, versnipperd over vele bedrijven en instellingen, researchafdelingen en adviesorganen, een uitgebreid aanbod van kennis op het gebied van renovatie en instandhouding van het gebouwenpatrimonium. Van die kennis zou de bouwrenovatiemarkt en daarmee ook de zorg voor de monumenten meer kunnen profiteren dan nu het geval is, en dat eens te meer daar het zwaartepunt van die zorg geleidelijk verschuift van de traditionele restauratie naar renovatie en onderhoud en bovendien de “jonge” monumenten met een geheel eigen conserveringsproblematiek, in de zorg worden betrokken.

Probleem is echter dat dit grote kennisaanbod niet zo gemakkelijk is te overzien en zich bovendien steeds aanpast. Het adagium “bouwen is traditie” gaat steeds minder vaak op, en dat geldt evenzeer voor renovatie - en onderhoudstechnieken.

Kwaliteit, bruikbaarheid en actualiteit van kennis staan daarbij voorop. De Nederlands-Vlaamse afdeling van de WTA kan daarbij een belangrijke rol spelen. De WTA beijvert zich voor onderzoek en de praktische toepassing daarvan op het gebied van onderhoud aan gebouwen en monumentenzorg.

Daartoe worden bijeenkomsten van wetenschappers en praktijkdeskundigen georganiseerd, waar een specifiek probleem inzake onderhoud van gebouwen en duurzaamheid van gebruikte bouwmaterialen en methoden zeer intensief wordt onderzocht. In studiewerkgroepen op onder meer het terrein van **houtbescherming, oppervlaktetechnologie, metselwerk, natuursteen, statische/dynamische belastingen van constructies, versterking en consolidatie, monitoring** worden kennis en ervaringen uitgewisseld.

Resultaten worden vertaald in een richtlijn voor werkwijzen en behandelingsmethoden. Gezien de kwaliteit en de heterogene samenstelling van de werkgroepen, kunnen die richtlijnen, zogenaamde Merkblätters, beschouwd worden als objectief en normstellend. Zij worden in brede kring verspreid door middel van publicaties in de vakpers en in het tijdschrift “Bausubstanz” gepubliceerd dat aan alle leden 4x per jaar wordt toegestuurd.

Leden van de WTA kunnen aldus, door een actieve vertegenwoordiging in werkgroepen bijdragen aan de totstandkoming van dergelijke normstellende advisering.



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In beginsel staat het lidmaatschap open voor allen die vanuit hun functie of belangstelling bij de bouw, restauratie en het onderhoud van gebouwen betrokken zijn. Werkgroepen worden samengesteld op basis van deskundigheid en ervaring van de participanten. Deelname is altijd vakinhoudelijk. Leden hebben het recht voorstellen te doen voor de op- en inrichting van nieuwe werkgroepen en gebruik te maken van door de WTA geleverde faciliteiten zoals een vakbibliotheek en enig administratieve ondersteuning.

Het betreft daarbij niet alleen advisering, maar ook het harmoniseren van de verschillende internationale technische regelgevingen. Hiertoe biedt de Nederlands-Vlaamse tak van WTA een uitstekende mogelijkheid.

Wanneer u belangstelling heeft voor de WTA of één van de hiervoor genoemde vakgebieden of werkgroepen kunt u met de WTA Nederland-Vlaanderen contact opnemen.

Kosten van het lidmaatschap bedragen: € 170,--
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Eenmalig inschrijfgeld van: € 25,--

Een ondersteunend lidmaatschap voor bedrijven en instellingen kost minimaal € 170,-- tot € 610,-- per jaar, al naargelang het aantal werknemers.

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2	Nieuwe ontwikkelingen	1993	
3	Restaureren & Conserveren	1994	
4	Kleur bekennen	1994	
5	Hout	1996	
6	Gevelreinigen	1996	
7	Kalk	1997	90-76132-01-1
8	Metaal	1997	90-76132-02-1
9	Kwaliteit in de restauratie	1998	90-76132-03-8
10	Natuursteen deel 1	1998	90-76132-04-6
11	Natuursteen deel 2	1999	90 76132-05-4
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14	Bereikbaarheid van monumenten	2000	90-76132-08-9
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1-19: niet meer beschikbaar

Vanaf 20: zie website www.wta-nl-vl.org

After successful events in Leuven (2009), Brno (2011) and Stuttgart (2014), WTA Nederland-Vlaanderen and the chair of Heritage & Technology at Delft University of Technology, Faculty of Architecture and the Built Environment host the 4th WTA International PhD Symposium from 13-16 September 2017 in Delft, the Netherlands.

WTA Nederland-Vlaanderen is one of the regional groups within the WTA International Association. The aim of WTA is fostering of building preservation, building repair and monument maintenance related research, as well as the practical application and proliferation of such research. An important task here is to transfer the scientific achievements towards practice and to utilize and apply new knowledge and advanced technologies. The co-organising chair of Heritage & Technology at TU Delft is active in research and education on the technical and construction-historical aspects of Architectural Heritage.

The aim of the WTA International PhD symposiums is to unite PhD candidates, post-docs and other junior researchers conducting research in the field of building conservation. It provides a forum for PhD candidates to present their research, discuss ongoing PhD studies to support future work and gives PhD candidates the opportunity to establish contacts within the international scientific community. From the approximately 40 abstracts, 24 papers have been positively reviewed by members of the scientific committee and have been selected for presentation during the symposium and publication in these proceedings. The papers have been arranged in these proceedings according to the presentation schedule.

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