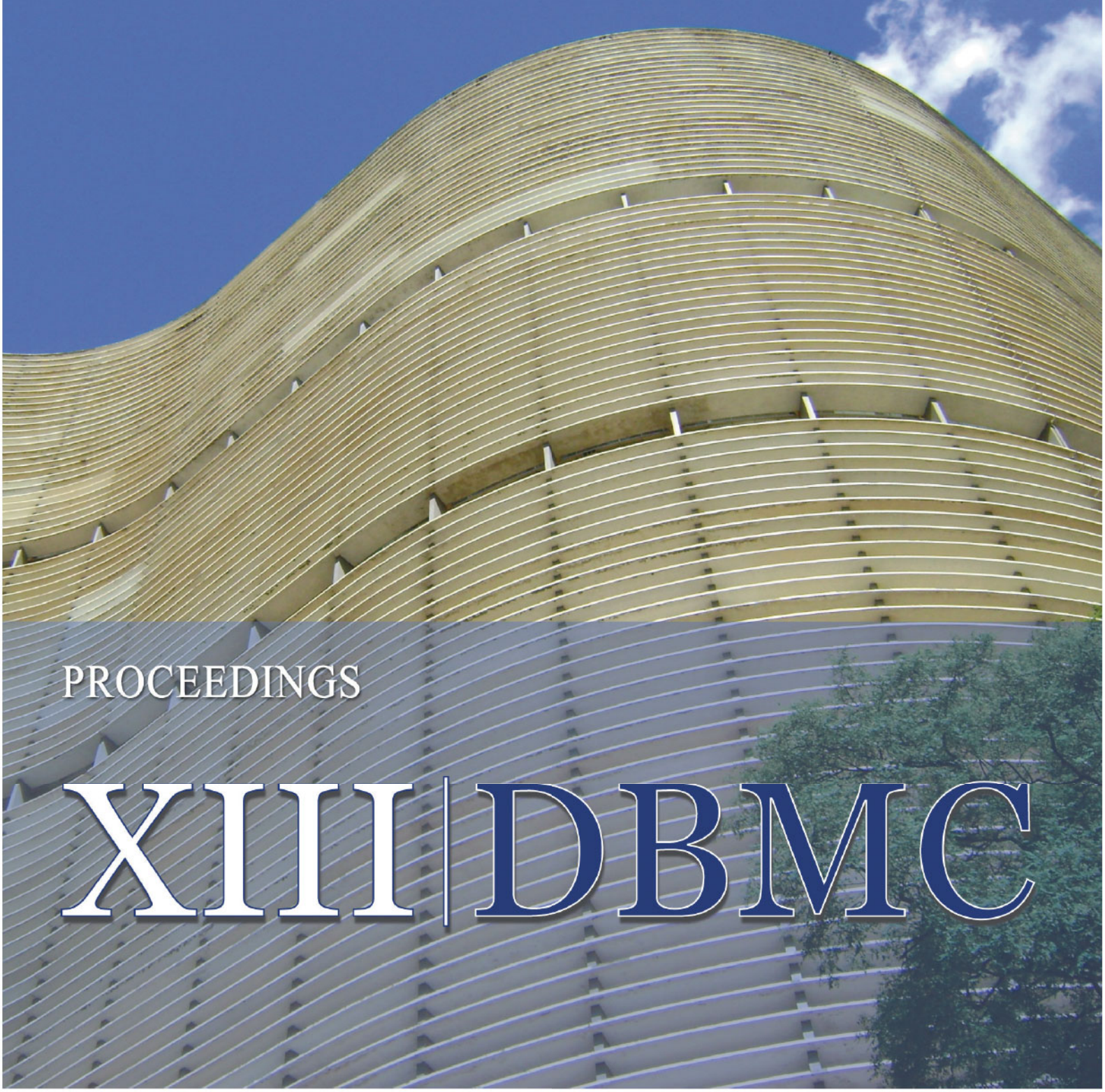

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Edited by M. QUATTRONE and V.M. JOHN

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Proc. of the 1st DBMC
Ottawa, 21-23 Aug. 1978.

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Report 42: 'Acoustic Emission and Related Non-destructive Evaluation Techniques for Crack Detection and Damage Evaluation in Concrete' - Final Report of RILEM Technical Committee 212-ACD (e-ISBN: 978-2-35158-100-1); *Ed. M. Ohtsu*

Preface

The ability to predict the service life—the durability—of a new building material is being ardently sought after in many parts of the world. Widespread efforts are correspondingly being made to increase the durability of materials already in wide use. Any estimate of the economic losses resulting from failures in durability lead inevitably to dollar figures so astronomically large that they are usually regarded with incredulity.

R. F. Legget
Proc. of the 1st DBMC
Ottawa, 21-23 Aug. 1978.

Some 35 years after the 1st DBMC (Ottawa, 1978), sponsored by ASTM, NIST and NRC, durability is an even more important subject. At that time, an accurate service life estimate was considered a condition to life cycle cost (LCC) analysis. Nowadays, service life is also crucial information for the environmental life cycle analysis (LCA). The relevance of durability became widely recognized among scientists: in 1992 the World Business Council for Sustainable Development coined the term "eco-efficiency", referring to a higher production with fewer environmental and economic resources and less environmental impact. The increase of durability (or service life) of products is one of the critical tools to improve eco-efficiency.

In that period the research community, which was organized into CIB and RILEM working groups, developed a methodology to plan and predict the service life of buildings and constructed assets at the design stage, which was consolidated in the ISO 15686-x standards. As a result of these scientific advances, the degradation factors and mechanisms of most materials and their assemblies are now much better comprehended. Information Technology advances facilitate to mapping the relevant environmental variables by using GIS platforms. Dose-response functions are available, making possible the estimation of degradation rates by combining environmental variables with material characteristics. Even effects of climate change on service life have been a matter of discussion. Altogether, it is an impressive achievement, recorded in the previous 12 DBMC conference. However, despite this scientific progress, the use of these tools in day-to-day production processes, including materials and components R&D, architecture and civil engineering design, and environmental and economic life cycle analysis is still very limited in most countries. Today's research challenge is not only to increase the knowledge in the field, but also to make this knowledge readily available to the society, by developing more user friendly tools and better educate engineers and architects on the use of these tools.

The 13th edition of the DBMC conference was sponsored by ASTM, NIST, Rilem, CIB and University of Porto. It was joint organized by Polytechnic School of University of São Paulo and Secovi-SP, the most important Brazilian real estate industry's association, an union that simbolizes our commitment to transfer the knowledge to the society. The support of Saint Gobain Group, Grace Construction Products, Votorantim Cimentos, Gerdau, Fapesp, CNPq and Capes made the conference possible.

We expect that these proceedings will help professionals and academy to incorporate service life planning concepts in their day-to-day decision-making processes.

São Paulo, 25-Aug-2014
Marco Quattrone
Vanderley M. John
Editors

Contents

MULTI-PHYSICS MODELLING FOR DURABILITY EVALUATION OF ETICS

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ABSTRACT

The External Thermal Insulation Composite Systems with rendering (ETICS) are a building envelope technology widely used both in new construction interventions and in energy refurbishments. Installed ETICS display multiple failure modes, which are often the result of the repeated action of multiple agents inducing cyclic stresses and strains, thus fatigue. In this study, to predict the performance decay over time and to assess the durability, we coupled two numerical models: a hygrothermal model, computing the Heat and Moisture Transport (HMT) in porous media, coupled to a Thermo-Mechanical Finite Element Method model (TM-FEM). The transient temperature profile computed with the HMT model was the input for the TM-FEM simulations, with which we assessed the thermal stress over time, and the frequency of the events exceeding the critical stress thresholds, beyond which the base coat is subject to fatigue. As variables, we considered the moisture response of the base coat, and the optical properties of the finishing coat, in a set of Southern European climates. Especially we focused our attention on the frequency of thermal shocks and freezing-thawing cycles in HMT analysis as the main causes of cracks in case of temperature variation in a preliminary 3D TM-FEM model analysis.

1 INTRODUCTION

External Thermal Insulation Composite Systems with rendering (ETICS) are a very popular building envelope technology, which consist of an insulation board bonded onto a new or existing masonry or concrete wall, and mechanically fixed with anchors. The insulation board is then protected by a base coat, usually 3-4 mm thick, made of the cement mortar with resin used as adhesive, but reinforced with a glass fibre mesh. Onto the base coat is applied a 'key coat', or primer, and then the finishing, which is usually a thick (1.5-2 mm) top coat [1]. This technology is very common all over Europe, since its low cost and since it allows to continue to use a building while it is being refurbished. However, failures of ETICS are widely documented [2][3].

After a previous analysis of the mainly failure modes which occur in ETICS (cracking, detachments, bulging, wrinkling, and biological growth) and thanks to a previous survey, we saw that cyclic thermal shocks, water absorption and sometimes freeze-thawing are, in Southern Europe climates, the most relevant mechanisms that cause degradation, loss in performances, and failures of ETICS [6]. Whether the relevance of their effects on ETICS is

known less studied, instead, are both the intensity of the shocks, which shall be reproduced in the laboratory, and their frequency in different climate areas. In fact, intensity and frequency are fundamental knowledge to study the durability of objects exposed to cyclic stress. Moreover, among the different loads that ETICS bear, the stresses due to thermal variation are most of the time much higher than the ones due to gravity. Both night and day temperature changes and seasonal fluctuations cause thermal movements and, as a consequence of different material properties, stresses inside the insulation boards and in base and top coat. Although ETICS have been used for years, there is still a lack of understanding reasons and mechanisms of different failure cases and, even if there have been some attempts to study the failures, mainly by numerical simulation (especially by the Finite Element Method), most of these attempts didn't succeeded because of the low availability of the necessary material properties, and especially of fracture mechanical properties [7].

This work concerns the analysis carried out by means of simultaneous Heat and Moisture Transport (HMT) numerical simulations of ETICS with mineral wool (MW) or expanded polystyrene (EPS), and different base and top coats. The aim is to highlight the different behaviour in terms of frequency and intensity of events that may be critical for durability, in a set of Southern European climates. Thus, the HMT analysis provides the temperature distribution through the layers, which is used as input data for the finite elements thermo-mechanical simulations (TM-FEM) that provide the stress-strain.

2 CALCULATION MODEL AND INPUT DATA FOR HMT

We performed a parametric study to assess the number of events (thermal shocks, water absorption and freeze-thaw) that cyclically repeated could jeopardize the service life of the system (i.e. about 35 years for an ETICS). To assess the intensity and frequency of these critical events, we used the software tool WUFI 5.2 (developed by the Fraunhofer Institute for Building Physics), [8] compliant with EN 15026 [9] benchmark test validation requirements. WUFI uses the finite control volumes method to resolve numerically the transient heat and moisture transport in building materials. Weather data for the selected representative cities for Southern Europe were obtained from the *Meteonorm* database. Solar absorbance (α) was varied between 0.10 and 0.90 (0.01 and 0.99 are used just as ideal lower and upper limits). The ETICS was modelled for two years oriented in the four cardinal directions. Just the data for the second year were analyzed, when the moisture content achieved its long-term trend.

3 HYGROTHERMAL ANALYSIS

3.1 Thermal shocks and moisture content

For the thermal shock analysis we considered the differences in surface temperature between two time steps (i.e. one hour), counting the sudden temperature variations over one year (Figure 1). We computed the thermal shock events combined with the moisture content in terms of liquid water occurrence in the base-coat (more sensible to capillary water absorption) with a value greater than 50% of the free water saturation. This was assumed as the threshold above which there is a reduction of mechanical resistance (compressive and tensile strength), as presented also in [10]. With low water contents in the base coat, these events do not occur frequently in the Southern European climates that we analyzed. In general, the absolute number of thermal shock events per year is higher in Southern European contexts, such as Barcelona, than in Atlantic contexts, such as Nantes. Events comprising a sudden surface temperature variation coupled to a rain event are computed to be twice more frequent in Barcelona than in Nantes.

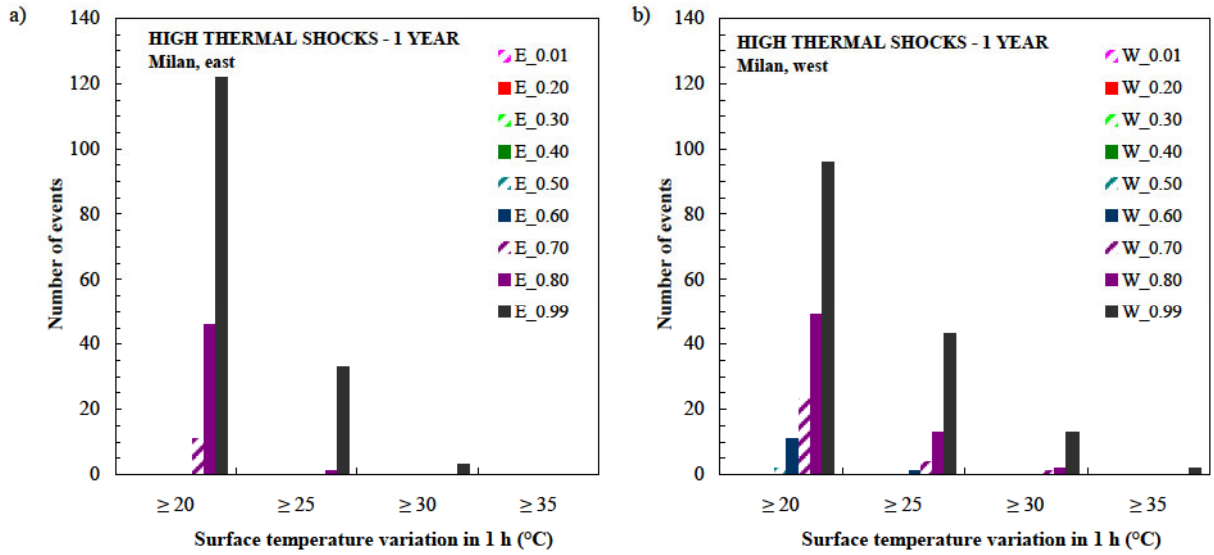

Figure 1: Thermal shocks with temperature variation greater or equal to 20°C, Milan.

3.2 Freeze-thaw

Predicting the damage due to freeze-thaw cycles is a critical point due to two main factors:

- The critical temperature for which freezing occur in the material pore structure, because it is conditional on dissolved salt presence and on the pore dimension;
- The critical moisture content in the material, above which, if it is freezing, it will cause the damage due to the pressure generated by expansion in becoming solid and it depends also on the pore size distribution and interconnection.

We assumed the freezing temperature of water in the pores below -5°C, after the Literature on the freeze-thaw in concrete [11]. We counted the occurrences when the temperature in the base coat – the layer that is more exposed to freeze-thaw – drops below -5 °C, then rises above to 0°C, and the water content is above the critical value (Figure 2), as done also in [12]. In our case the critical moisture thresholds are 70%, the 80% or the 90% of free water saturation. With low moisture contents in the base coat temperature not often lower than -5°C, the freeze- thaw cycles do not occur for the cities of Southern Europe with solar absorbance greater than 0.2, as showed for Milan. In a city further north, such as Zurich, they occur for absorbance up to 0.6.

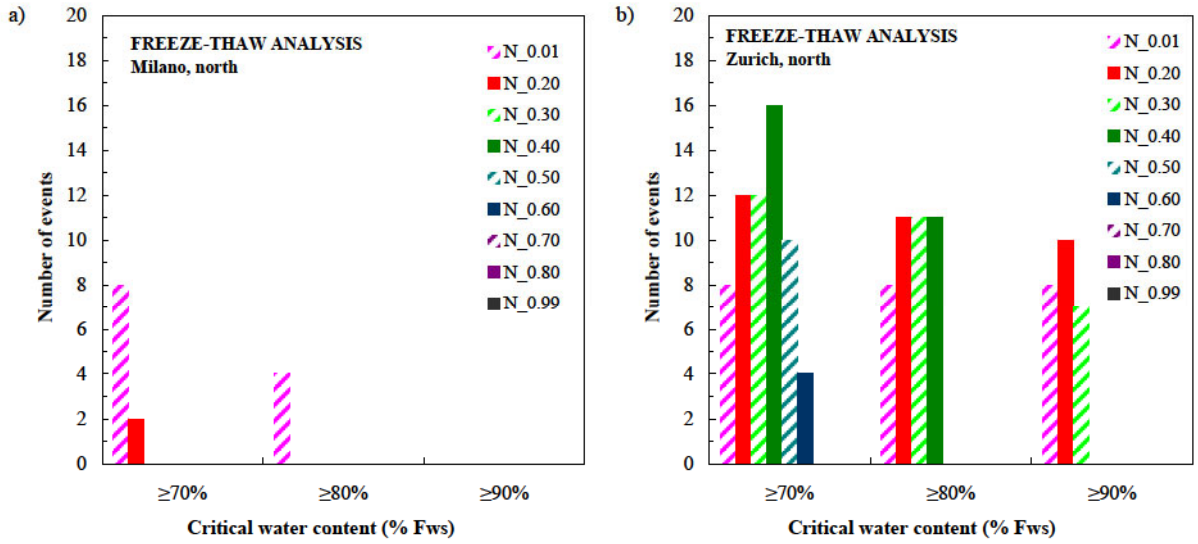

Figure 2: Freeze-thaw analysis for a) Milan and b) Zurich, North direction.

3.3 Comparison between ETICS with EPS and MW

We modelled the hygrothermal response of two identical ETICS assemblies, except for the insulating material. In one case, we included mineral wool (MW), in the other case, we considered an expanded polystyrene (EPS) panel having the same thermal conductivity as the MW, but with all the other properties typical of EPS boards. MW ETICS with solar absorbance higher than 0.5-0.6 have a lower number of thermal shock events than the same ones with EPS (roughly 15% in average). These events occur in winter conditions, right after sunrise of when a façade a few instants before in the shadow is immediately sunlit. Right before the thermal shock, the base coat over a MW panel is actually moister than over EPS, and, thus, to produce a rapid surface temperature variation a phase change of the water in the base coat must occur, and that water has to be dried out by the sunbeams. The differences in the moisture contents in the base coat over EPS and over MW are no more than 10 kg m^{-3}, but this is sufficient to produce a different balance of extreme thermal shock events. This difference seems to be driven by the different water vapour resistance of EPS and MW (that of EPS more than 30-40 times that of MW). For an EPS-ETICS, the water vapour flowing through the wall assembly from the inside, during cold nights, condensates in the most external sections of the insulation panel, and once in liquid phase is stuck there since the closed pores structure of EPS. In case of MW-ETICS, water flows into the base coat, since the water vapour permeability of mineral wool is close to that of the air and itself is capable of hygroscopic moisture sorption getting in equilibrium with environmental conditions.

4 TM-FEM ANALYSIS

Since temperature variations are known to be one of the most common causes of ETICS failure [13] and the consequences of a wrong definition of them in a TM-FEM analysis are often underestimated. Although most of the studies in the Literature couple thermal and mechanical simulation in a single FEM analysis [14], it was chosen not to do so in order to take into account the (important) role of moisture in determining the temperature inside the ETICS. In this study, the temperature distribution obtained from HMT simulations is used as input of the TM-FEM analysis.

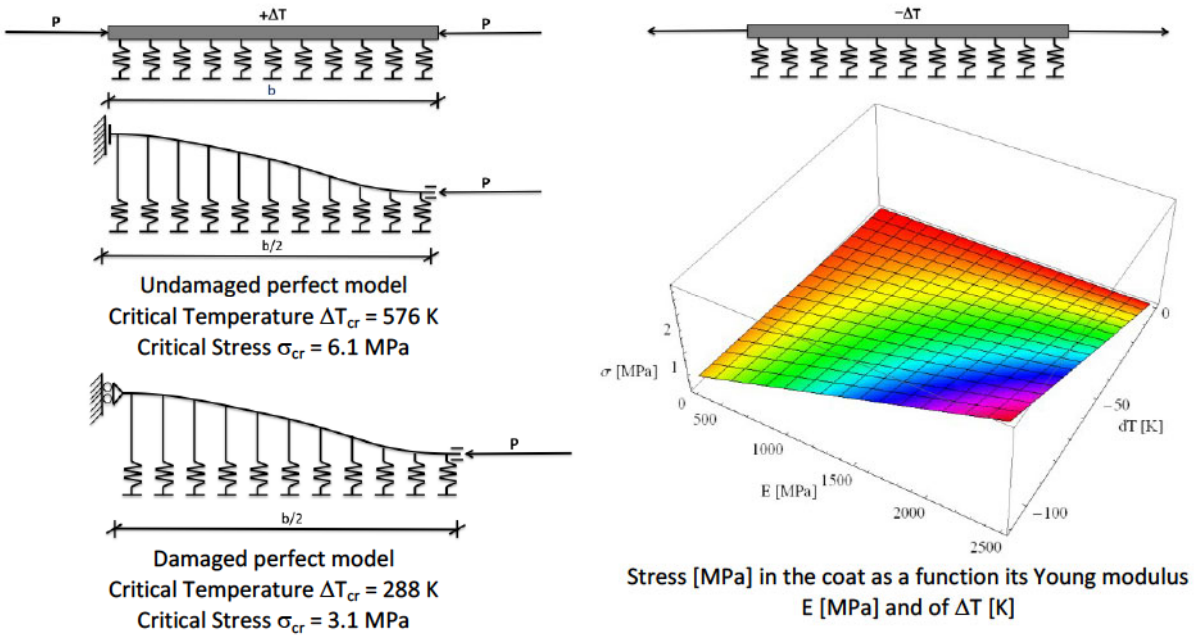

Figure 3: Main results of the mechanical model.

The definition of the geometrical model for the TM-FEM analysis raised some interesting questions. Even if the width and length of the insulation panels and the thickness of the layer are defined by shape and size of commercial products and by code of practice [15], the effects of deviation from the declared value due to (production or construction) tolerances and of different type of constraints have to be taken into account. A simple 1-D analysis has been made to understand the influence of mechanical properties of coat and insulation panel on the development of cracks on base (and top) coat. Figure 3 shows the main results of the analysis: regardless the type of insulation panel (here modelled as a layer of springs) a temperature increase cannot be the only cause of cracks (due to instability) on the base coat (σ_{cr} = 6.1 MPa, ΔT_{cr} = 576 K) even if the base coat is already cracked (damaged perfect model, σ_{cr} = 3.1 MPa, ΔT_{cr} = 288 K); a temperature drop may cause cracks on the base coat but only for a material with a (medium to) high Young modulus (Figure 3, Stress in the coat as a function its Young modulus and of ΔT). These results change if (construction and production) errors and imperfections are taken into account, for example a small difference in the thickness of two insulation panels placed side by side causes a huge decrease of the minimum temperature drop to have cracks (Figure 4). These preliminary results were confirmed by some later 3D FEM analyses where a model made of seven insulation layers (all of MW) with a cement based coat has been investigated using temperature distribution obtained from HMT analysis (in this case study the Milan climate has been used). If the model has no imperfections (due to errors in construction or to tolerances of materials) then there are no signs of possible cracks; if one insulation panel (the central one in this case study) has a different thickness (1 mm thicker in this case study) then displacements (Figure 5) and stresses (Figure 6) in the (base and top) coat show significant stress concentrations at the joints of flanked insulation panels.

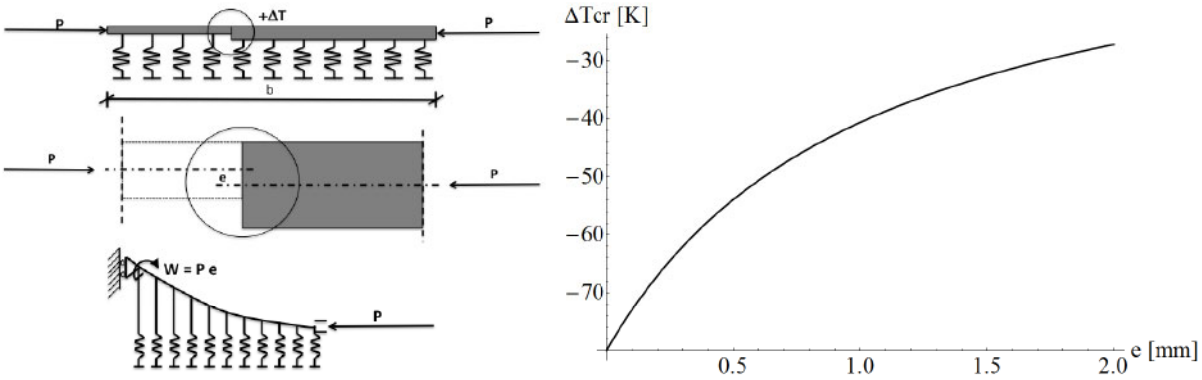

Figure 4: Influence of imperfections on ΔT_{cr}.

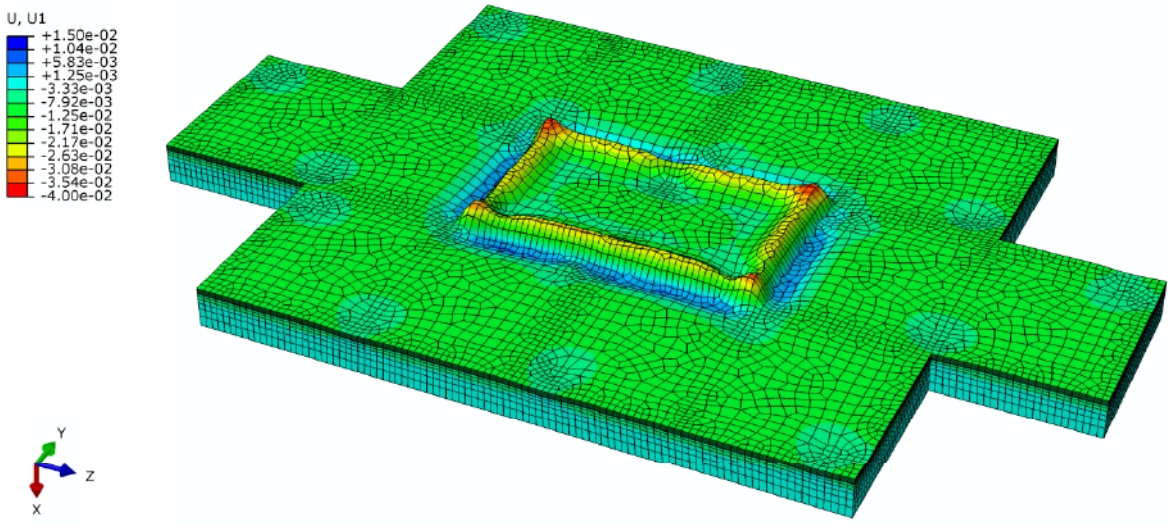

Figure 5: Displacements in x direction (thickness) [mm], for a positive temperature variation.

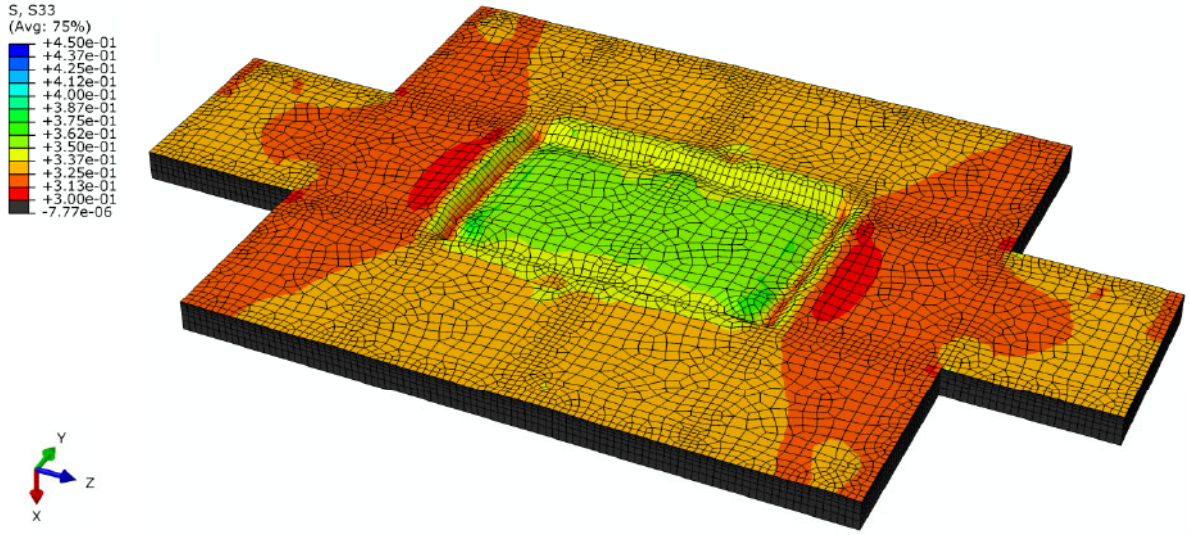

Figure 6: Stresses z direction [MPa], for a negative temperature variation.

In brief, cracks on the coat of ETICS will develop in the following case:

- the external face of the insulation panels does not belong to a perfect plane; a small step from one panel to the near one may be due even to a small tolerance in the

thickness of the panel (manufacturing defects) or to defects in the support layer and it's always present (gluing panels directly on a brick wall may not be a good idea, a plaster as regularization layer may be needed).

- the coat has a high Young (elastic) modulus (most of the coats on the market have a high elastic modulus).
- there are high temperature variations (between day and night and from one season to another); in most of the places where there is a high solar radiation there are likely to be high enough temperature variations, in sunny place beware of dark colours.
-

5 CONCLUSIONS

Considering thermal shock events, we noted a lower number of critical events for MW ETICS than for EPS ETICS, for solar absorbance higher than 50-60%. We impute this difference to the higher vapour permeability of MW compared to that of EPS, which allows for higher – although non-harmful – moisture content within the base coat over MW. After a cold night, a latent transformation occurs when the exterior surface is heated by the sunlight, and MW ETICS reach surface temperatures slightly lower than EPS ETICS. These considerations need to be verified with more extensive studies, and laboratory testing, because the approximations in material properties might have introduced systematic differences.

More interesting is that where thermal shocks are more frequent and potentially harmful, namely in Southern Europe, freeze-thaw does not seem to be an issue. Freeze-thaw cycles occur and eventually produce failures just in some case and for very low absorbances. However, due to soiling (i.e. dirt deposition) of the exterior surfaces, those very low solar absorbances are actually impossible in practice. From the results of the numerical sensitivity analysis we infer that with solar absorbances lower than 0.60 the risk of thermal shocks is remarkably limited, which is a lower limit to solar absorbance than that proposed in the European ETICS Association guideline. On the other hand, with solar absorbance higher than 0.20-0.30 the risk of freeze-thaw is also reduced in Southern European climates.

Considering the frequency of thermal shocks and of freeze-thaw, we conclude that for Southern European a base coat can be developed focusing more on resilience to thermal shocks than on resistance to freeze-thaw cycles, preferring a lower Young modulus, although with low capillary water absorption (which is critical for thermal shocks and freeze-thaw).

With the 3D FEM analysis, using the temperature distribution obtained by HMT simulations, we demonstrated that if the model has no imperfections (due to errors in construction or tolerances of materials) there are no cracks on the coat. The cracks will develop if the external face of the insulation panels is not perfectly plane, and the base coat has a high Young modulus and there are high temperature variations.

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