Marble facades structural decay due to bowing – A comprehensive review

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Summary: *Natural stones are used in facades for centuries. Initially, stone elements were rather thick when used as load bearing construction elements and the durability was excellent. Scientific research on the properties of marble began in the late 19th century. In the following years, the thickness of stones decreased from over 1000 mm to 20-50 mm to lighten the weight of the slabs (in cladding applications) and because of new cutting technologies and equipment developed by the industry. Even though most marble claddings perform satisfactorily, durability deal appeared at an increasing rate after a few years of using thin cladding. They bow, warp and break. Results of investigations indicate that cyclic temperature variations and moisture are key factors in the reduction of the life of the building envelope. This work describes an updated and comprehensive review of marble facades structural decay due to bowing, consolidating the understanding of marble slabs deformation.*

Key words: *Natural Stone; Building Materials; Cladding; Marble; Bowing*

1. Introduction

Natural stone has been used in facades for centuries. Initially, stone elements were rather thick when used as construction elements, and the durability was appropriate. Scientific research on the properties of marble began in the late 19th century. In the following years, the thickness of natural facade stones decreased from over 1000 mm (as load bearing elements) to 20-50 mm (in cladding applications) to lighten the weight of the slabs and because of new cutting technologies and equipment developed by the industry (Pires, 2013), (Amaral et al., 2015), (Schouenborg, Grelk, Malaga, et al., 2007), (Hoigard & Scheffl, 2007).Even though most marble claddings perform satisfactorily, durability problems have begun to appear at an increasing rate after some 50 years of using thin cladding (Sousa & Sousa, 2019), (Gutiérrez et al., 2012). Well-known buildings such as the Amoco Building in Chicago, SCOR tower in Paris and the Finlandia Hall in Helsinki have had their marble cladding replaced after less than 30 years at the cost of many millions of Euros (Koch & Siegesmund, 2004), (Vázquez et al., 2011).

The deterioration gives a considerable change in the appearance of the stone panels. They bow, warp and break. Most cases of bowing involve Italian marble from the Carrara district, simply because it is the most widespread and used marble type. It is, however, vital to emphasize that most building facades with Carrara marble perform well, and marbles from other areas also exhibit durability problems. The bowing of marble is not only restricted to buildings but also be recognised in ornamental architecture. For example, marble monumental cemeteries gravestones and toponomastic signs are also known to bow. Nowadays, most of the well-known cases are from Europe or North America, most likely because of the much more widespread use of thin marble claddings in these regions. In Europe, there are building facades with bowed marble slabs in both the cooler climates of Finland and Denmark and the warmer climates of Portugal and Spain. Bowed slabs can also be found in Austria, Belgium, France, Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, and the UK (examples in Fig. 1). Numerous works already published are entirely focused on the possible factors responsible for the deterioration of marble, and they clearly show that cyclic temperature variations and moisture are key factors in the decay processes. The interaction of temperature and moisture must be a crucial external factor for the bowing and strength loss of certain marble lithotypes. Still, an updated and comprehensive review of marble facades structural decay due to

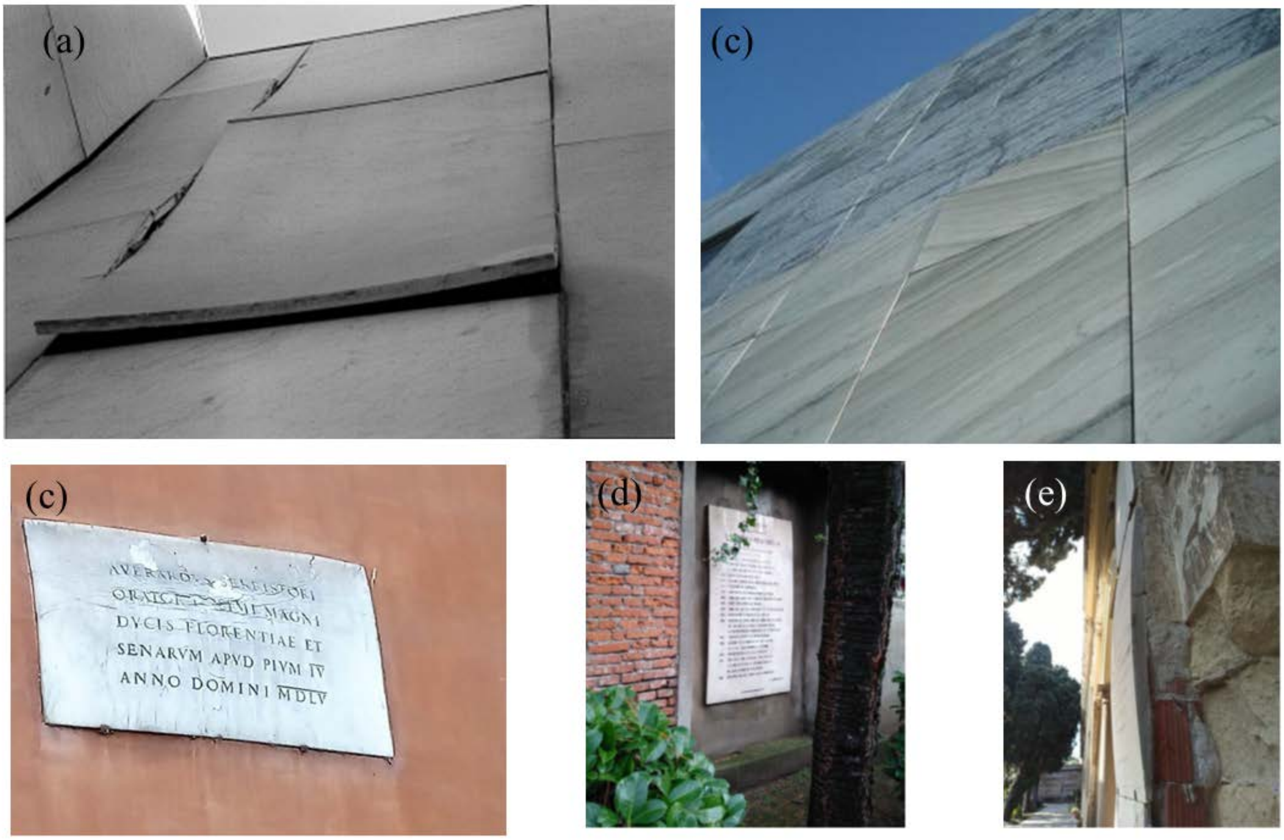

Fig.2 Examples of damaged marble slabs through bowing: (a) Alvar Aalto's Finland Hall cladded with Carrara marble slabs (Helsinki, Finland) (Royer-Carfagni, 1999)*; (b) Vatican City cross road (Vatican State); (c) Marble Façade depicting bowing, (Lisbon, Portugal); (d) Porta Vicentina building (Milan, Italy); (e) Bonaria monumental cemetery (Cagliari, Italy). Photos by authors.*

bowing is not available. In this sense, there is a need to consolidate the understanding of marble bowing.

2. Intrinsic and predisposing cause of bowing

Thermal stresses and moisture subject the thin slab of cladding to the permanent deformation. The main factor responsible for this pathology is to be ascribed to the anisotropic structure of the crystals and their interlocking arrangement. Calcite crystals have different rates of thermal expansion coefficient (α) along the crystallographic directions, and this differs in the way of accommodating the stress induced by heating-cooling cycles (Weiss et al., 1999), (Siegesmund et al., 2008). α of calcite is deeply anisotropic (Kleber, 1958): $\alpha_{11} = 26{\cdot}10^{-6}$ K^{-1} parallel and $\alpha_{22} = -6{\cdot}10^{-6}K^{-1}$ perpendicular to the crystallographic c-axis. This means that calcite contracts normal to the c-axis and expands parallel to the c-axis during heating cycles. Additionally, it has been found (Weiss et al., 1999) (Siegesmund et al., 2008) that dolomite, although having a similar value of around $26{\cdot}10^{-6}$ K^{-1}, exhibits positive coefficient and it is about $6{\cdot}10^{-6}K^{-1}$ parallel. These difference in α triggers, especially in thin slabs, thermal expansion and contraction phenomena, which may also differ between the surface exposed to weathering agents and the more protected reverse surface. All this has severe consequences on the structural integrity of the stone: propagation of microcracking leading the increase of bowing. In more severe cases, the claddings are subjected to failure, posing a significant risk to the stability of the structure.

3. State of the art in marble bowing study

Numerous investigations are entirely focus in the possible factors responsible for the deterioration of marble bowing (Jornet & Rück, 2000), (Stocksiefen, 1996)(Hook, 1994), (Wonneberger, B., 1999), (Bellopede et al., 2016), (Sassoni et al., 2018) (Schouenborg, Grelk, Malaga, et al., 2007)(Grelk et al., 2006).(Grelk et al., 2007)(Sousa & Sousa, 2019)(Vázquez et al., 2011)(Siegesmund et al., 2008)

Although all of them brought relevant knowledge to the topic of marble bowing, a selection was made to understand the steps already taken by several research groups and the most relevant conclusions that should be accounted for future studies.

3.1. TEAM project - Testing and Assessment of marble and limestone

One of the most significant pioneering investigations took place in 2007, based on inspections of more than

200 building facades with marble cladding, was carried out during the European research TEAM project - Testing and Assessment of marble and limestone. Significant efforts were committed to: (1) Understand bowing phenomena mechanisms; (2) Develop the principles for a European test standard; (3) Advance a concept for assessment of facades, including a monitoring system to predict strength development and improve safety and reliability; (4) Analyze if surface coating and impregnation could prevent or diminish the degradation; (5) Address quality control aspects to optimize the production conditions. And improve safety and reliability (Schouenborg, Grelk, & Malaga, 2007).

TEAM project results brought to light several possible causes for marble bowing and the testing data strongly suggested that the variations in temperature and moisture as well as the microstructure were considered as the most important factors. Additionally, the project investigated the field application of an onsite measurement tool - bow-meter, which was a tool to measure the bowing amplitudes with high precision and reproducibility. This tool could be used for onsite façade monitoring to measure the bowing evolution through time. Experimental results showed good correlation with the long-term residual strain but not with the loss of strength. Besides, the TEAM project was involved in the draft of the first and unique bowing test standard (EN 16306) which included the development of an accelerated testing methodology and the adjacent grain analysis (AGA), a combination of grain size and grain shape analysis, which gives a reference about the suitability and bowing propensity of a marble. According to Annex C in EN 16306 standard, values of AGA index from 8 upwards denote marbles with good characteristics, an AGA of 7 is intermediate, and 6 indicates a low-level material, and, according to the standard, this classification is valid only for calcitic marbles.

3.2. On site inspection and measurements combined with laboratory accelerated aging bowing tests

In 2008 a thorough research which included on-site damage analyses combined with laboratory bowing tests brought new results and new topics to the discussion of marble bowing (Siegesmund et al., 2008) This study was dedicated to three marble cladded buildings: i) The Oeconomicum (OEC, Gottingen); ii) The State Theatre of Darmstadt (STD, Darmstadt) and iii) the State and University Library (SUB, Gottingen). All the selected buildings presented pronounced bowing after a short time of exposure. The cladding materials were: Peccia Marble (It), Rosa Estremoz (Pt) and Carrara marble (It).

The experimental bowing data clearly demonstrate that after 40 heating cycles combined with the effect of moisture a certain impact on the decay rate is observed. In the case of demounted panels the bowing tests show that already strongly deformed panels from the building exhibit a lower bowing potential than those with lower amplitudes of bowing.

The on-site measurements with the bow-meter were made to assess the frequency and distribution of bowing in the three buildings. The relation between the bowing level and visible damages (examples: cracks and ruptures) were accounted for. Also, 87 panels from a part of the south façade in the SUB were chosen to evaluate the correlation between expansion and bowing. The effect of the panel's size was correlated to the bowing level and to the façade orientation. The age of the panel was correlated to the annual bowing rate in one of the studied buildings. Bowing impact on the marbles mechanical performance was studied through flexural and anchorage breaking load tests.

Conclusions were thorough and allow important and relevant advances in the marble bowing knowledge and interpretation, a summary is presented as follows: i) The three studied marble were susceptible to bowing in both real and experimental conditions and bowing was not dependent on the buildings solar exposition and orientation; ii) The degree of bowing was intrinsically linked to the degree of damages; iii) The three marbles had different microstructures and smaller as well as the coarse-grained marbles presented bowing also, there was a connection between the fabric of the marbles and the degree of bowing iv)The observations from the SUB building and the laboratory tests depicted that any simple marble type/bowing or bowing rate correlation was missing particularly for the Portuguese marble under study; v) The correlation between in situ and experimental bowing data was more uniform for Carrara marble; vi) the combination of the in situ studies and building maps achieved through the inspections together with the study of the properties of the rock (mineralogy and rock fabrics) as well as the laboratory bowing tests were considered as the most fitted tool for the prediction of service life of marble claddings.

3.3. Laboratory study to understand the importance of complementary test methods to interpret EN 16306 bowing test results

Few years later, another research group performed an extensive study on eleven varieties of marble to investigate the importance of adding complementary testing methods to the accelerated aging bowing test standard method (EN 16306) (Bellopede et al., 2016). Selected marbles from Italy, Portugal and Greece were tested by means of this laboratory ageing test. Non-destructive tests such as the measurements of ultrasonic pulse velocity (UPV), adjacent grains analysis, open porosity and water absorption have been executed together with the conventional flexural strength test.

Results show that 5 distinct marbles in terms of flexural strength and fabric depicted more than the maximum recommended permanent bowing after the accelerated aging bowing test. According to Annex A of EN 16306, limit values should be fulfilled for a marble suitability for outdoor cladding: maximum 0.40 mm/m permanent bowing after 50 cycles and 0.02 mm/m for the rate of increase in bowing in the last two measurements.

Another important remark of this study lies in the fact that the worst marbles in terms of safety (bowing and decreasing in flexural strength), had a maximum grain size of 0.6 mm.

This study concludes with the importance and relevance of performing the laboratorial bowing aging test according to the standard EN 16306 to forecast the long-term performance of marbles. Also, it highlights that both flexural strength and AGA are essential to complete a full analysis. Likewise, it highlights the relevance of a thorough: microstructural and fabric analysis; flexural strength loss examination and ultrasound pulse velocity determinations before and after the aging tests. In these last two methods a loss of 20 – 25% was considered low.

A relevant conclusion also points out that not all the suitable marbles (in terms of bowing rate and flexural strength decay) presented an AGA index of 8 or higher as recommended in the test standard. Moreover, the less suitable marbles showed flexural strength losses higher than 25% after 50 testing cycles: ultrasound pulse velocities variation higher than 25% and an increase in their porosity.

As a suggestion for future work improvement, this research gave important suggestions: i) In a future revision of the EN 16306 test method, it is advisable to build a broader database and understanding by training and intercomparison trials among laboratories trained on the AGA calculation; ii) Explanations about the handling of the test specimens; iii) Flexural strength lower expected value could be used for dimensioning instead of the mean value.

3.4. The application of FEM numerical simulations to help on bowing decay preliminary assessment

A more recent research from 2019 (Sousa & Sousa, 2019) a stability evaluation of a 15-year-old building façade cladded (located near the ocean) with Portuguese marble affected by bowing and subjected to wind pressures was undertaken. This evaluation was focused on the stone slabs and was performed through finite element model (FEM) numerical simulations of slabs submitted to wind pressures and through lab tests using samples of stone slabs removed from the building façade.

The main goal of this work was focused on the validity of computational tools to help on the bowing prediction and preliminary assessment.

As reported by the authors, test results obtained in the selected case study were not entirely conclusive regarding the effect of bowing on the mechanical properties of the marble, since original sound stone slabs (without bowing and aging effects) were not available and the authors could not have access to a large number of test samples.

Yet, achieved results showed a flexural strength loss of 23% and a bowing magnitude measured on site of 5 mm/m. It was highlighted that, besides bowing, other damaging effects might have also contributed to the flexural strength loss suggesting the importance of also assessing other properties when inspecting similar situations subjected to strong wind pressures.

This case study analysis concluded that it is possible to establish a reliable relationship between lab tests on bowed marble specimens and calibrated numerical simulations. This could be an important complementary tool to evaluate the stability/security conditions of marble slabs affected by bowing or/and other degradation agents, either for slabs already in use or to be used in ventilated cladding. Nonetheless, accelerated bowing aging tests should be performed according to EN 16,306] test method to allow a more accurate assessment of the bowing trend and possible magnitude, including strength decay of the marble slabs

4. Bowing accelerated aging test

According to the EN 16306 test method, at least 6 marble specimens with dimensions of 400 x 100 x 30 mm should be exposed to moisture from beneath and heating from above the amount of bowing should be measured every 5 cycles.

Specimens are dried in a ventilated oven at (40 ± 5) °C for one week and then cooled to ambient temperature (20 ± 5) °C before the start of the exposure.

Specimens are partly immersed in demineralized or distilled water for 24 h. Only the lower (5 ± 2) mm of the specimens are to be submerged while the top 25 mm shall remain above water level. The water level shall remain constant during all cycles.

The specimens are placed on the filter cloth in a container, which is filled with demineralized or distilled water so that the specimens are partly immersed in the same way as described above. The specimens are exposed to a temperature cycle, heating the surface of the black reference from 20 °C to 80 °C in 3h-4h. The rate should not exceed 0.35 °C per minute and the maximum temperature is maintained between 1 and 3 h. Thermal cycles should have a temperature curve controlled by the surface temperature of a standardized black reference material (80 °C).

The heater is then turned off and the specimen cool down to ambient temperature (20 ± 5) °C. No control of the cooling phase is necessary, other than making sure that ambient temperature has been reached before measuring the bow of the specimens. (22 ± 2) h after the cycle started (approximately 1h to 2h before starting the next T-cycle) the bow of the specimen is measured.

Every five cycles the exposed specimens should be dried and measured for permanent bowing. This measurement is compared to the one at t_0 in dry conditions. An important difference in the drying procedure compared to most other stone standards is that it is necessary to use 40° C instead of the more commonly used 70° C to avoid influence of a potential temperature-induced strength loss before the test starts and after the temperature cycling has been stopped.

After each bow measurement, the magnitude of the bowing is given by the difference in ''height'' from the first reading. This normalized bow measure is calculated as the height difference in millimeters, for a specimen with a length of 1 m, Flexural strength values of reference specimens and exposed specimens provide useful information about the potential strength loss that may occur.

5. MA_4CLAD Project: comparative multi-analytical study to forecasting marble structural degradation in building facades

The MA_4CLAD project aims to fill the knowledge gap of the causes and quantify the damage caused by the bowing, deepening the methodology described in the normalized conditions, through an analysis of the thermal gradients in real-time and through the bending strength evaluation measured along the cycles of temperature and humidity (not only in the end of the testing cycles). This will explore the analysis of the causes that lead to the loss of mechanical resistance and allow the development of an innovative experimental methodology and a specific manual for marble dimensioning. The decrease in mechanical strength associated with bowing is a problem that has no solution currently and most marbles are not clearly studied in this context. All marbles have a unique degradation curve and therefore any prediction of life expectancy must be developed individually and for the specific type of marble in combination with the microclimate (especially surface temperature variations). The Project team is composed by: Vera Pires, Fabio Sitzia, José Mirao, Luis Dias, Luis Lopes and Samuel Neves.

6. Conclusions

Significant work has been made by several research groups mainly in Europe according to the TEAM test method, also several improvements have been researched and tested after the development of a European test Standard for bowing evaluation.

As it was possible to highlight in this review, several revisions have been suggested and hopefully they might be included in the standard test method soon. All the presented suggestions were based upon struggles on the results interpretation. This is mainly because there is still a lack of a wider database that might bring insight and help on disclosure of less expected performances in certain marbles.

Another important observation of this review was the fact that all previous research considered the accelerated bowing test method as a fundamental tool to aid on the marble performance analysis especially for ventilated facades.

Also, it is very clear that until there are more results available, all marbles should be carefully tested to bowing to assess its full suitability and to prevent premature failure of the façade.

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