Structural Engineering Documents

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# Engineering History and Heritage Structures – Viewpoints and Approaches

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International Association for Bridge and Structural Engineering (IABSE)

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# Preface

## Foreword

The roots of modern construction historiography reach back to the 19th century when for example in France the engineer Auguste Choisy (1841–1909) began to explicitly analyze the construction of historic buildings and to place them in the center of construction history.[1] In the last third of the 20th century, such approaches followed systematically and in an increasingly professional way. A long arch spans from the works like those by Jacques Heyman (1925) who interpreted ancient techniques and theories related to vaults by means of modern structural engineering approaches,[2] to the historic–theoretical research and publications like those by Karl-Eugen Kurrer (1952).[3]

In the meantime, several chairs and professorships in construction history were created and there is an impressive variety of conferences and publications. Every three years since 2003, the scientific community gathers at the International Congress on Construction History (ICCH). There is no doubt that construction history has established and consolidated internationally as an independent discipline.

Actually, what is construction history? Professor Werner Lorenz, member of the IABSE WG9 Construction History, defines construction history as follows:

*Structural engineering is the entity of the practices and products of conceptual design, dimensioning and construction of technical structures and components in the process of the constructional designing of the environment. Construction history describes and interprets these practices and products in their historic sequence. For that purpose, construction history interrogates the products of construction and all associated written and pictorial sources. Both the historic construction research and the methods of static-constructive and scientific engineering analyses belong to the methodical cornerstones.*

Construction history involves architects, monument conservators, historians and engineers in a transdisciplinary approach to fulfill scientific, cultural, didactic and also structural engineering tasks and requirements.[4]

IABSE WG9 Construction History has the general objective to promote this new science and to demonstrate its importance for structural engineers. The three main objectives of the WG on construction history are to:

- increase awareness among structural engineers of historical and cultural aspects of structures and structural engineering;
- illustrate and propagate the social and technical achievements of civil engineering;
- improve methods and practice in structural engineering by showing ways for systematic and targeted integration of historical and cultural aspects in intervention projects to adapt or modify structures of cultural value for future demands.

IABSE WG9 focuses on the role of construction history in the structural engineering practice and is thus intentionally complementary to the classical construction history as understood by the ICCH Community. The main concern of WG9 is thus to implement construction history in the daily work of structural engineers and to demonstrate the importance of cultural values as a basic design parameter when interventions on existing structures are required.

The present *Structural Engineering Document (SED)* is structured accordingly. It shall be understood as an introduction into construction history and how to consider the cultural values of structures in intervention projects. Although this *SED* is addressed primarily to IABSE structural engineers, it may also be useful for nonengineers.

This *SED* begins with the Editorial written by one of the “deans” of construction history: Tom F. Peters. Personal statements by several WG9 members testify a surprising variety of ways how the access to construction history was found and how it influenced professional activities. In the next chapter, Nicolas Janberg provides a worldwide survey on the activities and contacts in the domain of construction history. In the following, the papers by Max Johann Beiersdorf and Josef Steiner are contributions similar to essays on the aspects of construction history.

Twenty-five case studies on rehabilitation and modification of structures form the core material of this *SED*. Every case study outlines on a maximum of four pages the cultural values of the structure and highlights the appropriate measures for its respectful preservation. References and contact data of the author serve the reader to obtain detailed information. The case studies obviously range from ancient to modern structures and from medium to high cultural values, comprising various types of structures. Requirements of cultural heritage shall be taken as inspiration (and no longer as “hindering constraint”) for better intervention projects on existing structures. Construction history and cultural values of structures have yet to be understood as basic structural engineering disciplines.

With the present *SED*, the IABSE WG Construction History intends to make a significant contribution to modern structural engineering and to provide access to construction history for practicing structural engineers.

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**Eberhard Pelke, Chairman of IABSE Working Group 9 Construction History**
**August, 2017**

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# Frost Damage and Restoration of Limestone Domes and Spheres in a Heritage Building

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## Introduction

Domes and spheres have been used extensively in heritage buildings during baroque and rococo periods as well as in 19th-century buildings. Used as ornaments and as coverings and roofs, these curved elements add to the monumental character of imposing buildings, which are presently considered a part of the cultural heritage. The number of historic buildings containing domes and spheres is impressive and includes some of the world's most famous structures. Most of these ornaments and coverings are made of limestone because of its excellent quality and durability. However, because limestone is a sedimentary rock, consisting mainly of calcium carbonate, it may deteriorate due to acid rain and frost. The latter introduces cracking, allowing water ingress and subsequent further cracking. Depending on the crack width, further moisture ingress is fostered, and cracks grow. In the present paper, this progressive effect is being assessed by numerical simulation. Obviously, all types of limestone blocks and ornaments are prone to degradation due to frost. However, a brief survey of various degradations shows that curved shapes are more vulnerable. The reason for this is yet to be found. The ratio of exposed surface to volume of a sphere is not significantly different from the value for an equivalent cube. However, if rainfall is considered from a single direction, for instance, vertical, the relative exposure ratio of spheres is three times larger than that of cubes. This might give some indication of the larger degradation of curved surfaces.

## Southern Pressure House, Antwerp

The Southern Pressure House, in Antwerp, consists mainly of two long buildings, the first of which contains the machine room and the steam hall and parallel storage depots for coal and oil.[1] The boiler room and the warehouses are separated by a corridor that opens to a courtyard. The second building houses offices, homes for personnel, a repair workshop and a forgery house. Of all these, the imposing unit containing the accumulators for water pressure (*Fig. 1*) is the most valuable. This is mainly a brickwork building decorated with limestone façade blocks, which were intended to enhance the view as the city particularly wished to improve the appearance of the neighborhood.

The front view of the building clearly shows the two vertical parts containing the water accumulators. The entrance door and ground level appear rather massive; the twin columns are richly decorated, suggesting the cylindrical accumulators inside, and the narrow openings underline the vertical orientation of the building. Both towers are covered by domes carved from single limestone blocks. An individual dome is shown in *Fig. 2*. The domes are supported by white sandstone cylindrical masonry. The total height of the structure reaches 24.5 m. *Figure 2* also shows some of the heavy cornices, column capitals and decorating spheres. The highly decorated industrial building was highly appreciated in the second half of 19th century and displays the wealth and prosperity of the port of Antwerp in industrial times. The style of this building may appear to be excessively heavy, but the exterior form clearly shows the particular purpose of the building. In addition, the domes entirely correspond to the inside equipment.

*Figure 1 Southern Pressure House: front view*

*Figure 2 Top of the vertical part with the dome*

Although the installation was decommissioned in 1977, the whole complex was listed as protected heritage in 1979. About 20 years back, a complete restoration was undertaken, and the buildings became a center for performing arts. This lasted until five years ago when the theatre company ceased to exist. Since then, events are being organized in the 4000 m$^2$ building with its seven rooms, except for the front unit (*Fig. 1*) which remains unused. The activities include seminars, smaller concerts, receptions, discussions and workshops, as well as art studios. During the inspection of the heritage building in January 2012, several limestone ornaments and blocks were found to be heavily cracked. In addition, during the 1985 restoration, inferior products were used at some locations. After some of the limestone debris fell, a second inspection was organized in December 2012. As both inspections were conducted in winter, it was hoped that frost was at maximum and recent degradation would be detected. Cracks reached a width of 10 mm, and some parts needed immediate removal as there was a threat of debris falling on to the footpath below. The inspections also showed that some parts of the structure were already missing. These findings have urged the owners to apply for necessary funding for a restoration program and to install safety measures in order to avoid endangering passers-by below the building. However, the largest concern applies to the domes as these also suffer from cracking. *Figure 3* shows a detail of the cracked state of the domes. It is clearly seen that the limestone surface is eroded in horizontal layers. This seems to be characteristic of domes and spheres.

*Fig. 3: Degradation of the dome*

# Simulation of Dome Cracking

The domes are relatively small and consist of hemispheres with an inner radius 1.22 m and an outer radius 1.40 m, the thickness being 0.18 m. The base of the dome consists of a flat ring with an outer radius of 1.63 m, thus providing a larger support and stiffening the dome. The idea was to constitute a model of volume elements and to introduce cracking as soon as tensile stresses exceed the tensile strength of the limestone. The tensile strength value of 5.67 MPa is considered rather low, far below the average compression strength of 140 MPa or a characteristic value of 126 MPa. This type of approximation allows reasonable assessment of the influence of cracks on dome resistance. In further steps, nonlinear material characteristics may be considered, although it is believed this will not consistently modify the results. The approach consists of introducing cracks into the model, assuming subsequent water ingress and allowing the effect of frost. The latter will start the progressive effect, the issue being how far this process may continue and eventually lead to the destruction of the dome.

Modeling of the effects of frost proved to be delicate. A first approach considers that an initial crack is completely filled with water. As the water freezes, its volume increases by 9%, thus causing an internal pressure in the crack. This internal pressure needs to be applied to the crack surface. The main issue is to identify the magnitude of the pressure. This, and other approaches based on the Washburn equation,[2] all disregard the actual process of freezing in natural stone. The latter has been researched more extensively in Ref. [3]. Although the research is considered to be idealized, it enumerates the various phenomena involved during freezing. The model is based on the importance of the flow of water toward the solidification front of ice, as well as on the existence of thin films separating the ice and the surrounding stone, as mentioned earlier. The thickness of these films varies from 15 to 30 Å. These films also exert an attractive force on the pore water and a disjoining pressure that pushes the ice and the stone apart, which is the pressure we are seeking. The fastest damage growth rate occurs in the range from –4 to –15°C.

In Ref. [3], the case of a spherical cavity has been studied using the Gibbs–Duhem equation to describe the change from liquid to solid state, the van der Waals interactions and the Clau-

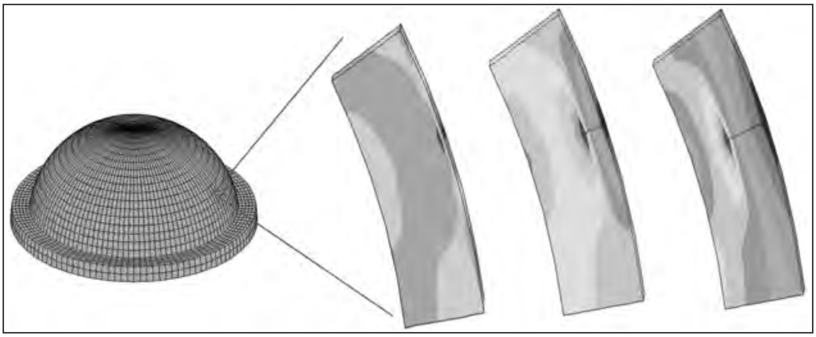

*Fig. 4: Cracking of the dome wall*

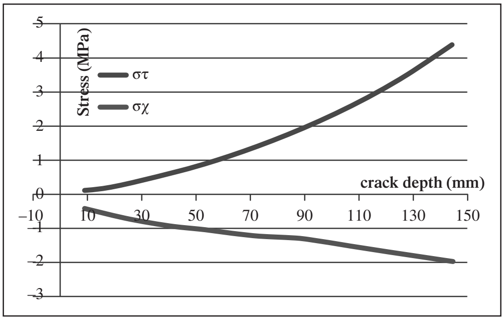

*Fig. 5: Evolution of stresses with crack depth*

sius–Clapeyron equation. The porosity of the stone has been taken into account, and three examples have been worked out. It appears that dense rock-like granite can certainly crack due to freezing water as the pressure rises up to 25 atm or 2.533 MPa. However, in the case of sandstone, in a spherical cavity, pressure would rise to 12 atm or 1.22 MPa, and this value also corresponds to limestone. In porous stone, the main pressure rise is due to the pre-melting stage when the ice is very close to the stone. The flow then reverses, and the water flows toward the solidification front. This explains why the pressure rises sufficiently to cause cracking only in the case of very impermeable rock. Consequently, the research in Ref. [3] has been adopted for the present simulations. The pressure in a spherical cavity is most probably higher than that in a longitudinal crack, which has a larger surface area in contact with air. Consequently, an internal pressure of 1.22 MPa has been applied to a crack on the outer surface of the dome. This crack runs along a quarter of the circumference of the dome, its depth being increased stepwise. Looking at a cross-section of the dome, the local meridian stresses can be found as shown in *Fig. 4* for crack depths of 1/20, ¼ and ½ of the dome thickness.

The former cracks have been assumed to exist before water ingress and freezing. The stresses shown in *Fig. 4* may either cause excessive tensile stress at the crack tip or may crush the crack opening at the surface. In addition, the crack may be widened due to internal pressure. In all of these cases, the crack will increase until these quantities decrease below a critical level. The diagram in *Fig. 5* summarizes the tensile and compression stresses as a function of the crack depth. The upper blue line shows the tensile stresses, which in all cases is below the tensile strength of 5.67 MPa. This simply implies that the cracks will not increase due to frost, and there is no progressive deterioration. This also applies to the compression stress, which is two to three times lower than the tensile stress. According to these results, water ingress and subsequent frost cannot be responsible for damage to the domes. In addition, the evolution of crack width with the depth has been summarized in the graph in *Fig. 6*. This illustration also shows that the crack width is moderate. Hence, the model has indicated that cracking of the limestone

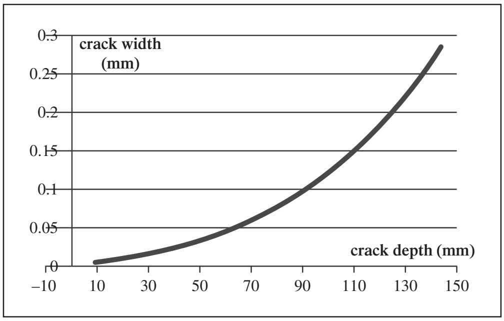

*Fig. 6: Evolution of crack width with depth*

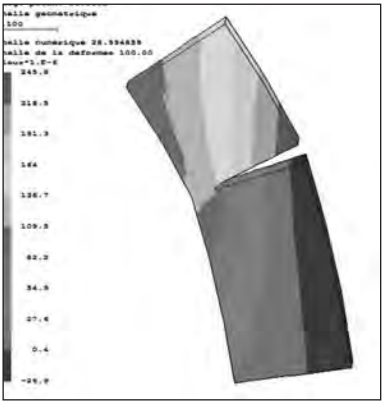

*Fig. 7: Developed crack*

ornaments is probably not due to freezing of water in the cracks. Calculations were continued until 80% of the dome wall thickness was cracked, and yet no progressive effect was seen. At this particular point, the crack width grows to about 0.3 mm. When all loads are considered, the dome still remains stable. The deformations at this stage are shown in *Fig. 7*, the crack opening being clearly visible, including the effect at the tip inside the stone. In view of these results, the crack length has not been varied, nor has the exact location been modified, and further analysis becomes irrelevant.

# Restoration

As the present state of deterioration of the domes and other limestone parts of the Southern Pressure House in Antwerp cannot be due to frost, the cause must reside in chemical attack due to increase of $CO_2$, thus favouring the dissolution of the material. Due to the nature of limestone, the calcium carbonate may dissolve if the pH of rainwater is sufficiently low because of $CO_2$ content. Therefore, refurbishment should preferably make use of soft lime mortar to close the surface cracking. Deeper and larger cracks, endangering further decay and disintegration of the parts, may be treated by injection of epoxy-based products. Former calculations have shown that injection pressure may easily reach 5 bars (0.5 MPa). However, these epoxy-based products are harmful to the limestone as they have little permeability and can become rather rigid in the stone. Hence, they should be used in-depth only and after the surface treatment of cracks with lime cement is complete. After successive inspections and temporary measures to avoid accidents, the restoration of the Pressure House is presently being considered. The project will require more extensive evaluation of the various repair methods. However, it may have become clear that water ingress and frost are not the main reasons for the degradation.

# Conclusions

Recent inspections have revealed that important limestone parts of the Southern Pressure House, a heritage building in Antwerp, show large cracking and may fall from the building. Water ingress and frost are thought to be the cause. The domes show horizontal cracks that might be of particular concern during future restoration. An extensive numerical model has been used to predict cracking due to frost. Various approaches to model the effect of water ingress and frost have been considered. Among these, the approach based on the successive stages during ice growth, the presence of a water film separating ice from the surrounding stone and the internal water flow toward the ice front seems the most successful. Application of this approach clearly shows that the effect of frost is incapable of fostering progressive cracking as both the tensile stress at the crack tip and the compression stress at the surface are sufficiently small. In addition, crack width may increase with depth, and this quantity also remains small.

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