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WINTER SHELTERS FOR MARBLE SCULPTURES OF THE SCHLOSSBRÜCKE BERLIN: CLIMATIC CONSTRAINTS

Siegfried Siegesmund[1], Stephan Pirskawetz[2], Frank Weise[2], Rudolf Plagge[3] and York Rieffel[4]

1 Geoscience Centre of the University Goettingen, Goldschmidtstr. 3, 37077 Goettingen, Germany
2 Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany, e-mail: stephan.pirskawetz@bam.de
3 University of Technology Dresden, Institute of Building Climatology, Zellescher Weg 17, 01069 Dresden, Germany
4 State Office for the Protection of Monuments, Klosterstraße 47, 10179 Berlin, Germany

Abstract

The long-term exposure of marble objects leads to a successive deterioration of the rock fabric and may cause severe damage on cultural heritage objects. The magnitude of disintegration depends on the rock fabric as well as on the climatic conditions. Some types of marble show no considerable damage even if they have been exposed in northern Europe for several decades or centuries. In contrast, other marble varieties are showing severe damage after a few years of weathering. The present study shows that marble decay, along with the initial thermal degradation, is mainly influenced by the hygric and thermo-hygric load, respectively. The influence of the rock fabric on the resistivity against weathering is also documented. The factors causing marble decay were compared to extensive climate data, which were collected during a scientific project that was started with the aim to develop a covering system for marble sculptures in Berlin. Based on the hygrothermal material properties of the marble and on the climatic conditions, the heat and moisture transport inside the material and hence the hygrothermal load changes were calculated with a high spatial resolution. The calculations showed that the temperature and moisture fluctuations inside the material are mainly controlled by the dimensions and orientation of the sculptural elements. The current state of preservation was investigated by two-dimensional ultrasonic tomography. The results show a good correlation to the calculated distribution of the hygrothermal load. Based on this finding, requirements on a protective winter shelter system for the sculptures were defined. The project results show that in addition to protective covers, regular inspection and maintenance combined with regular cleaning ensures an effective and sustainable protection of marble objects in northern Europe.

Keywords: Schlossbrücke, marble decay, weathering processes, ultrasound wave velocities, climate impact, numerical simulation, maintenance

Introduction

The "Schlossbrücke" over the Spree Canal is situated in the centre of Berlin on the edge of the Museum Island, a UNESCO world cultural heritage site. It provides a traffic link between Unter den Linden, the Lustgarten (Pleasure Garden) and Berlin Palace which is under reconstruction. Eight monumental sculptural groups made of Carrara marble border the bridge on high pedestals. The central concern is the in situ preservation of these historical and valuable sculptures. Due to their long exposure to the elements the sculptures now show signs of considerable damage. Empirical findings show that even a traditional wooden cover reduces the damage to the sculptures. No scientific study has been done on the weather-dependent moisture penetration and the climatic conditions in such protective enclosures or on the damages to marbles related to the effect of weathering processes. An inter-disciplinary model project—supported by the Deutsche Bundesstiftung Umwelt (DBU)—was planned with the aim of developing an innovative winter covering system for these marble statuaries (Rieffel et al. 2010). It included a detailed evaluation of the restoration history, the current condition of the sculptures as well as a distinct climate monitoring and a numerical modelling of the effect of different winter shelter systems on the microclimate inside.

Figure 1: Small pictures: Current state of the sculptures. The photos are arranged in the same order as the sculptures in the historical photo. Historical photo of the “Schlossbrücke” before 1857. One sculpture (to the left) has not yet been assembled in this view.

History of the sculptures

In the beginning of the 20th century Berlin was one of the capitals that displayed the most public monuments in Europe. The “Schlossbrücke” with the sculpture ensemble was constructed between 1822 and 1824 in the classical style according to a design by Karl Friedrich Schinkel (Fig. 1). The theme of the eight sculptures is to create larger than life representations of ancient goddesses with young warriors.The Schlossbrücke ensemble of sculptures made from Carrara marble evokes the feeling of the Ponte Sant’Angelo Bridge in Rome. It can be considered an excellent example of the 19th century Berlin School of Sculpture, which attained a European wide reputation. When compared internationally, these figures belong to one of the most elaborate sculptural assemblies created from this period.

The sculptures were constructed during the period from 1842–1857 using the “best second grade Carrara marble (Ravacione)” by sculptors from the Schadow and Rauch School. In the period between 1855 and 1916 a regular maintenance and cleaning of the sculptures is documented. They were treated with a coating of soluble glass, with an emulsion wash and they were cleaned regularly with Venetian soap (saponified olive oil). Up to 1943 no further work on the figures is documented, and a comparison of historical photographs shows that regular cleaning and care of the statues was no longer carried out. The condition of the figures deteriorated progressively, and in places they were distinctly blackened. In 1943, the sculptures were stored at various locations in the western part of the city to protect them from war damage. The transport and the poor storage conditions led to significant damage of the sculptures. At the end of the 1960s, the sculptures were reassembled again, stored under a shelter and missing parts were replaced. From 1978, they were stored in a “lapidarium” to protect them from weathering. After the sculptures were returned from West Berlin to the GDR in 1981, they were cleaned, reinforced with silicone resin and treated hydrophobically. In 1983/84 they had been erected at the original location. During a restoration work in 1992/93, the silicone resin coating was removed abrasively by microblasting. In 2007, a careful restoration program began. It was based on a minimal intervention concept.

Marble weathering

The degradation process of the marble started about 150 years before when the sculptures were assembled on the Schlossbrücke. The initial degradation is caused by thermal dilatation processes. Calcite shows a pronounced anisotropy of the thermal expansion coefficient in different crystallographic directions (Kleber 1959). This leads to stresses inside the material during temperature changes. When these stresses exceed the threshold of cohesion, a non-reversible deterioration is observed which is not limited to the surface. Depending on the rock fabric the formation of microcracks results in non-reversible changes in length (Kessler 1919). Even small temperature changes of 20–50 °C may result in damage (Battagliaet al. 1993), but this process stops after a few heating cycles if moisture is absent (e. g. Sage 1988; Koch and Siegesmund 2004). In the presence of water, a progressive residual strain, indicating an increasing deterioration, is observed on thermally treated marbles (Siegesmund et al. 2007, 2008). Within the project, a Carrara marble was treated thermally at four cycles (20 °C – 60 °C – 20 °C) under dry conditions, followed by five heating cycles at 60 % relative humidity and 90 % relative humidity for the next eight cycles. The measured residual strain (Fig. 2) indicates that a progressive deterioration also occurs at high air humidity without the presence of liquid water.

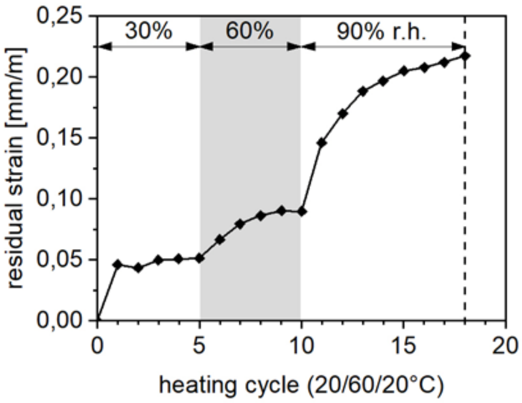

Figure 2: Residual strain of a marble comparable to the marble of the sculptures during thermal treatment under different moisture conditions.

The hygro-thermal deterioration is limited to a zone near the surface where the influence of the environmental conditions on the amplitude of material moisture changes is significant.

For a fresh Carrara marble freeze-thaw action plays a secondary part and chemical solution processes just roughen the surface if the matrix is dense. These processes accelerate the subsurface deterioration process, but not until the cracks are open to a certain extent and the capillary water uptake increases (Ondrasinaet al. 2002; Ruedrich 2003).

Present condition of the sculptures

The macroscopic fabrics of the marbles show a bright white color and irregular dark grey veins which are typical for Carrara material. The veins have no preferred orientation and they range in width from 0.3 to 1.0 cm. Two samples were drilled out from the plinths of two sculptures on the south side of the bridge in order to estimate the microfabric and the petrophysical characteristics. The grain fabric of these samples is nearly equigranular polygonal with a grain size between 20 and 600 µm, but frequently the grain size is around 180 µm. Compared to Carrara marbles, which usually have an effective porosity of around 0.2 Vol.-% (e. g. Weiss et al. 2000), a porosity of 0.5 Vol.-% in both samples is significantly greater.

As a result of their eventful history and their long exposition time the sculptures show considerable signs of damage. Significant mechanical damage was caused by the incorrect transport and storage during World War II. These damages have been repaired and missing parts have been replaced. In general, the back-weathering of the original material is moderate. The surface locally shows a pronounced roughness and in some areas a sugar-like crumbling. In these parts, the marble fabric is strongly deteriorated.

Even if the sculptures were carefully cleaned in 2009, the surfaces have shown apronounced biological colonization. In areas of increased roughness the biofilm penetrates deep into the microcracks and accelerates the deterioration.

The structural integration of the sculptures was

Figure 3: Results of the ultrasonic measurements on the sculpture on the south-west side of the bridge. The ultrasonic velocities are given in km/s. The comparison of the velocities and measurement distances clearly show that the deterioration is more pronounced on filigree parts.

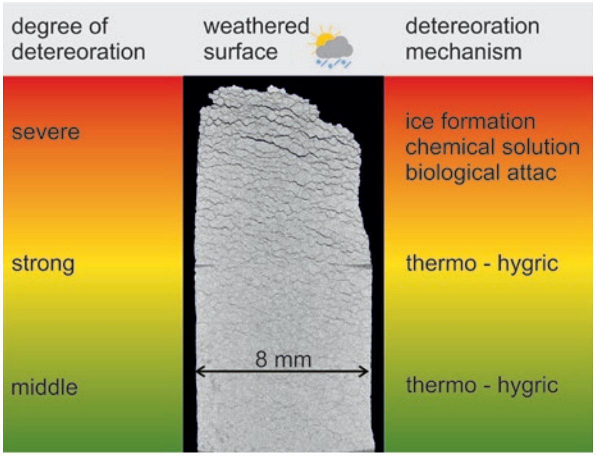

Figure 4: The x-ray ct- image of a drilling core shows a pronounced damage profile with a distinct cracking near the surface. The condition of the material is related to the depth and to the assumed deterioration mechanism.

assessed by measurements of the ultrasonic velocities. Figure 3 shows the results for the sculpture on the south-west side. According to a damage classification for Carrara marble presented by (Köhler 1991, Siegesmund & Snethlage, 2011), the condition of the sculptures can be described in the following way: massive parts with diameters above 15 cm show ultrasonic velocities between 3 and 4 km/s. The condition of these parts can be classified as „increasingly porous“. The ultrasonic velocities of more filigree elements with a thickness below 15 cm such as the wings of Nike or the arms and legs typically range between 2 and 3 km/s. After the classification by Köhler these parts can be designated as “sugar-like disintegrated”. Therefore, the sculpture can be classified as distinctly deteriorated, but the stability is not in acute danger. The distribution of the ultrasonic velocities in general points to the conclusion that the deterioration is more distinctive near the surface (Fig. 3). The results are representative for all sculptures of the Schlossbrücke, except one sculpture, which is in a critical condition.

A drilling core was taken from a vertically oriented surface of the sculpture on the south-east side of the bridge. The x-ray computed tomography (Fig. 4) clearly shows a distinct damage profile. Near the surface strong microcrack deterioration parallel to the surface can be observed.

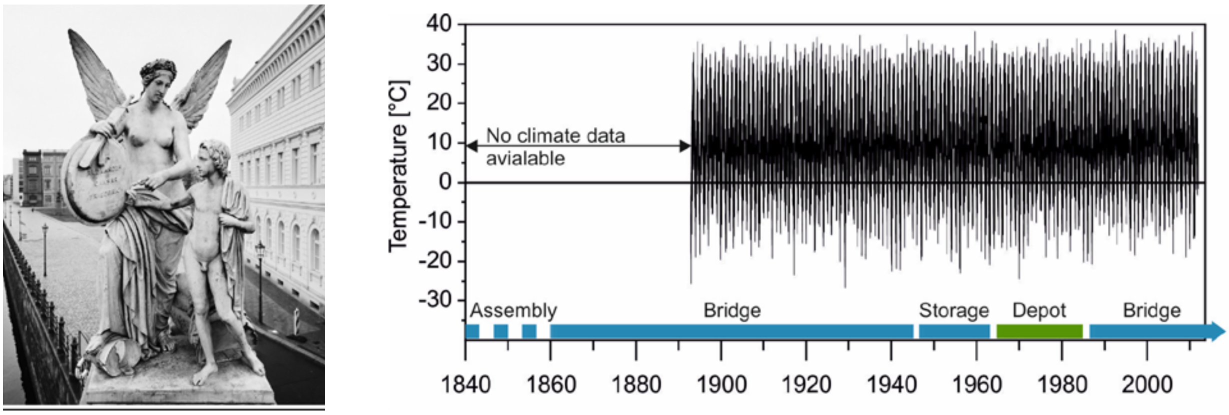

Figure 5: Daily maximum and minimum air temperature in Potsdam (data based on (DWD 2012)) compared to the exposition history of the sculptures at the Schlossbrücke in Berlin.

Climatic conditions

The current state of preservation of the marble sculptures is a result of their long term exposure to the climate. Figure 5 illustrates the weathering history of the Schlossbrücke. The present data originates from a meteorological station in Potsdam, located about 30 km south-west of the Schlossbrücke. Since 1893, air temperatures range from −25 °C in the winter up to 40 °C in the summer. This represents a temperature span of about 65 °C. During their exposure on the bridge, the sculptures may experience about 140 air temperature fluctuations ranging from −15 °C to 30 °C. Even under dry conditions these temperature fluctuations led to a deterioration that also affects voluminous parts of the sculptures. Besides these long term fluctuations, the daily temperature changes also play an important role. Since 1893, on more than 4500 days the difference between the temperature maximum and minimum is greater than 15 K, and on more than 20,000 days it exceeds 10 K. In combination with the air humidity, that typically ranges from 50 % to 95 % in summer and 75 % and 95 % in winter, these high number of temperature fluctuations is responsible for the high degree of deterioration in the near surface zone. Due to the partially increased porosity, the surface is locally sensitive to freeze-thaw action. The climate data from Potsdam show that during the last 120 years on more than 700 days the temperature decreased from +1 °C to −5 °C and on about 1600 days the maximum temperature was below −3 °C. Therefore, the impact of freeze-thaw action is not negligible. In order to acquire more detailed information for the project, an extensive climate monitoring was operated for three years. Generally, local climate data such as air temperature, relative humidity, wind speed and global radiation as well as surface temperatures and surface humidity were measured at three sculptures. The comparison to the climate data from Potsdam in the same period shows a good correlation.

The data show that the surface temperature of the sculptures is determined by the temperature of the surrounding air and by the global radiation. But the influence of the solar radiation is lower than expected. In winter the difference between the surface temperature on the north and south side did not exceed 4 K, and also in the summer the maximum surface temperature difference was below 10 K. However, it also has to be considered that the surface during the measurements was clean and white. In historical periods when the surface was blackened by air pollution, the impact of the solar radiation may be higher.

The combination of thermal and hygric fluctuations is the most important driving force for marble deterioration. The measured climate data shows that during the spring and summer, when the daily temperature rise is the highest, the surface temperature of the sculptures almost every morning falls below the dew point.

Figure 6 illustrates an additional phenomenon that accelerates marble degradation. On the 3rd of July

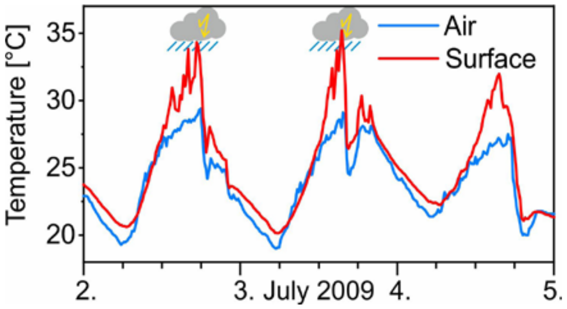

Figure 6: Air and surface temperature measured on the sculpture at the south-west side of the bridge at the beginning of July 2009. Sudden temperature drops are due to driving rain.

2009, the air temperature on this sunny day increased from about 20 °C in the morning to about 30 °C in the afternoon. At the same time, the surface temperature on the west side increased from 20 to 35 °C. In the afternoon, the temperature on the west side suddenly decreased to 27 °C within 1 h. The reason is a sudden rain shower. After the rain, the temperature again reached up to 30 °C and the surfaces dried. Events like this may be relatively rare but they are significant for marble deterioration. On the afternoon of the 4th of July 2009 it started raining again, but due to the temporarily overcast condition, the temperature drop was less abrupt.

Numerical simulation of heat and moisture transport

The basis for the simulation of environmentally dependent heat and moisture transport inside the sculptures are the hygrothermal material properties of the marble (Table 1). Since a complete determination of the material functions requires numerous samples, the valuable original Carrara marble of the sculptures cannot be sampled in the required amount. Therefore, a comparable Carrara marble has been selected for the measurements, representing the inner parts of the sculptures. Due to the increased deterioration and to historical conservation treatment, the marble surface shows different properties. Two small samples of the original marble were used for the estimation of the surface properties.

The complex geometry of the sculptures does not allow the simulation of all the details. Thus, in the numerical model the sculpture is represented by elements like arms and a head with a smaller diameter and a massive torso and strong legs.

In the first step, the temperature and moisture distribution within a freely exposed sculpture were calculated (Fig. 7) based on the climate data from Potsdam. The results of the simulation clearly show that the moisture fluctuation inside massive sculptural parts are relatively low, whereas the moisture within around 5 cm below the surface ranges between 40 and nearly 100 % relative humidity. In regards to the deterioration mechanism mentioned above, this is in a good agreement with the present condition of the sculptures.

In the second step, the microclimate inside of different types of winter shelter systems and their effect on the sculptures were calculated. Different influence factors such as the air ventilation rate inside the shelter, the diffusion coefficient and reflectivity of the walls were varied. The output functions of these models are very complex and they show that the different studied design concepts have individual advantages and disadvantages. In order to find the optimal design for winter

Table 1: Basic hygrothermal material parameters of Carrara marble (total sampling collective n = 125 specimen)

Parameter	Symbol	Unit	Mean	Std Dev	Min	Max
Bulk density	*q*	kg/m^3	2,614	17.5	2,515	2,644
Specific heat capacity	*c*	J/kgK	728	18.8	687.9	766.7
Thermal conductivity	*k*dry	W/mK	2.27	0.103	2.03	2.49
Total porosity	Opor	m^3/m^3	0.0137	0.0066	0.0024	0.0509
Capillary saturation	Ocap	m^3/m^3	0.0101	0.0023	0.0085	0.0117
Water uptake coefficient	Aw	kg/m^2s^{05}	0.0015	0.00028	0.0013	0.0017
Water vapour diffusion	*l*dry	–	353	243	75	737

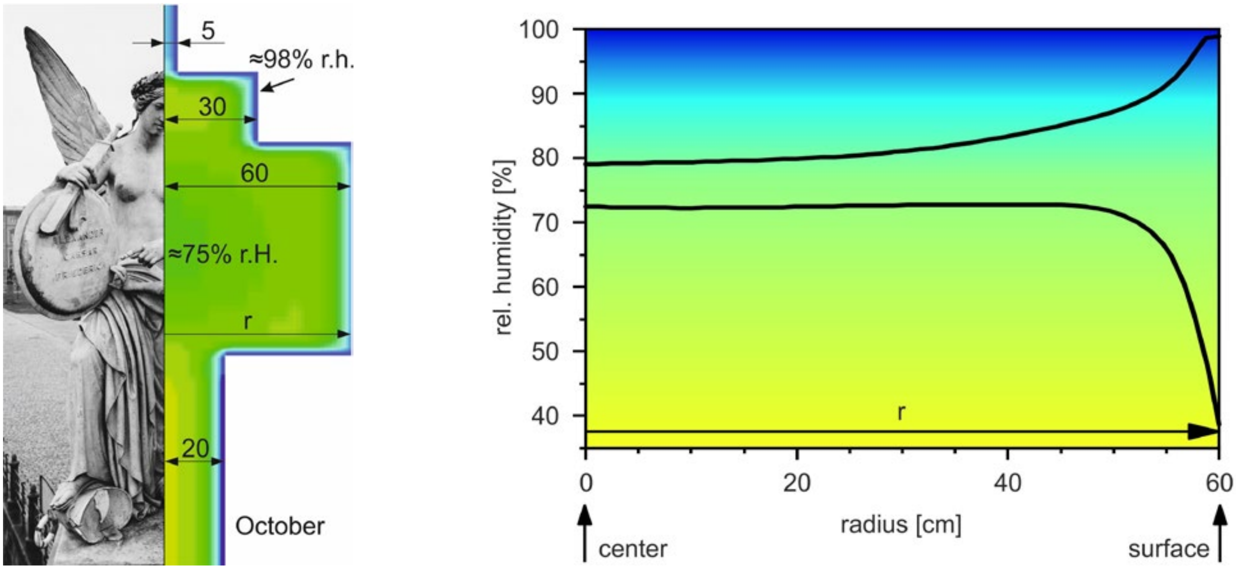

Figure 7: Calculated moisture distribution for October in a numerical model of a sculpture (left) and moisture fluctuation (minimum and maximum) from October to April along the cross section (r) of the torso.

shelters for the sculptures on the Schlossbrücke, a system of five performance indicators have been developed. These indicators, describing the thermal and hygric treatment of the marble, should be minimized by the design concept of the shelter. Regarding the technical limitations, the evaluation of numerous simulation results implies that a shelter with an airtight and opaque membrane skin provides the best protection against weathering.

Care and maintenance

Today public monuments are not maintained on a regular basis. Instead, the already damaged or endangered sculptures and statues are restored at great cost, only to be abandoned after these restoration measures have been completed. In the long term, however, continuous maintenance proves more economical—and more appropriate to the value of the objects—as monuments and as art—than extensive, costly restoration measures, which always go along with a loss of authenticity and originality.

In addition to protective covers, only regular inspection and maintenance ensures an effective and sustainable protection of marble objects in northern Europe. Such a maintenance program is the precondition for preserving the sculptures on the Schlossbrücke as a historical ensemble. Therefore, the Berlin State Office for the Preservation of Historical Monuments decided to initiate long-term maintenance work at regular intervals on the public statues in the centre of the city as a pilot project because of their outstanding artistic, historical and urban value. The maintenance concept developed by the public restoration office comprises a multi-phase, systematic time schedule and was introduced in 2009.

For this purpose, a specific plan was developed for 30 statues. In general, it comprises the documentation of the condition (mapping, photos), a regular inspection once a year (check-list), maintenance according to requirements of the fabric including regular cleaning, anti-graffiti coating, and—last but not least—preventive measures to protect the objects by a fence and winter covers. As a result of the inspection, the necessary measures required can be carried out depending upon what is demanded in the short, medium or long-term situation.

Summary

The Schlossbrücke is one element of the historical sculptural ensemble in the centre of Berlin. The central concern for conservators is the in situ preservation of the culturally and historically significant sculptures of the bridge. The goal of the project presented in this paper was to develop a winter sheltering system, with regards to the complex interaction between the marble, the deterioration mechanisms and the climate.

The study involved a detailed documentation of the conservation history, the ascertainment of historical and current local climate conditions, the assessment of the current condition of the sculptures and investigations on marble deterioration from a geoscientific point of view. Along with these findings, many numerical simulations of the effect of different shelter systems on the microclimate around the sculptures were done. The requirements for an effective shelter system are formulated on the basis of these results. The project shows that winter shelters are a reasonable measure for protecting marble sculptures, but the results also point out that the local climatic loads during spring, summer and autumn are significant for marble disintegration.

Since it is not possible or desirable to cover the sculptures all year around, a regular inspection and maintenance program is essential.

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