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SPECIAL ISSUE

Development and assessment of protective winter covers for marble statuaries of the Schlossbrücke, Berlin (Germany)

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Abstract The present study documents the results of an inter-disciplinary model project that was planned with the aim of developing an innovative winter covering system for marble statuaries located on the Schlossbrücke (Berlin). Such a system would need to fulfil the various requirements for structural stability, aesthetics, climate and practical use. This applied research represents the first complex scientific study of the sustainability of a winter covering system. The study is characterised by the use of complex scientific instruments such as special laboratory analysis and numerical simulation tools. The interaction between the environment and the artefacts in connection with the innovative winter covering structures were studied by extensive climatic monitoring.

Keywords Marble sculptures · Marble weathering · Winter cover · Climate data · Numerical simulations

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Introduction

The "Schlossbrücke", with its monumental sculptural groups made of Carrara marble, is situated in the centre of Berlin on the edge of the Museum Island, a UNESCO world cultural heritage site (Fig. 1a). As a result of their eventful history and exposure to the elements, these sculptures now show considerable signs of damage. The most significant deterioration is caused by thermally induced microcrack formation, which is characteristic of many marble types. For Carrara marbles this decay is expressed as a penetrative granular disintegration. Progressive fabric decohesion leads to a sugar-like crumbling of isolated calcite crystals on the sculpture surfaces. A subordinate relief structure can be observed, which is caused by chemical solution processes close to the surface. In spite of numerous restoration attempts, significant dirt is still observable on the figures. This probably results from the high traffic volume (32,000 vehicles per day) along the boulevard Unter den Linden. Gaseous compounds, solid dirt particles such as soot, fine particles, rubber particles and microbiological colonisation are the main causes of the soiling and the pollution on the surfaces of the statues. Remedial action is essential and necessary for preserving these high quality sculptures as a historical ensemble.

On the Schlossbrücke the Carrara marble is a particularly vulnerable material, which needs constant maintenance and care to ensure its long-term preservation in an outdoor setting. Because of their outstanding artistic, historical and urban design value, the continuous care of the sculptures on "Unter den Linden" is a central concern for conservators. Therefore, the Berlin Federal State Monument Conservation Authority has developed an inspection and maintenance concept, which has been implemented since 2009 and is the only such programme of its size in Germany.

Fig. 1 Schlossbrücke, Unter den Linden/Berlin: **a** Marble statuary ensemble on the southern side; **b** Sculpture group 1 "Nike educates the boy in history" by Emil Wolff, 1847; **c** Sculpture group 2 "Athena teaches the young man how to use a weapon" by Hermann Schievelbein, 1853; **d** Sculpture group 3 "Athena arms the warrior" by Karl Heinrich Möller, 1851 and **e** Sculpture group 4 "Nike crowns the hero" by Friedrich Drake, 1853

The conservation programme involves covering the Schlossbrücke sculptures during the winter months. 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. The bridge sculptures represent a special situation, since they are positioned on the bridge edges with exposure to the flowing water below. Presently no research has taken such a situation into account.

This is compounded by the additional goal of making the marble sculptures on the Schlossbrücke visible to pedestrians even during the winter. Scientific studies are non-existent in regards to the protective effect of known enclosure systems covering such sculptures. Furthermore, the complicated structural requirement for covers situated on a bridge necessitates new design concepts.

The inter-disciplinary model project focuses on the following main steps:

- Determining the "state of the art" for winter covers in a national and international context
- Defining the requirement profile for an innovative temporary winter cover
- Analysing the present condition and the material characteristics of the bridge sculptures
- Measuring the climatic conditions
- Determining the hygrothermal material properties of natural stone and membranes
- Comparative monitoring of the microclimate for the sculptures when exposed to the elements and when protected by temporary wooden covers and the newly designed winter covers
- Development of an innovative winter cover, which is suitable for monument conservation
- Weathering simulation to test the effectiveness of winter covers
- Development of a prototype

History of the structure and phases of restoration

The Schlossbrücke was constructed between 1822 and 1824 in the classical style according to a design by Karl Friedrich Schinkel. Artistically, this is the most beautiful bridge in the city of Berlin (Fig. 1a). The sculpture assemblage was built from 1842 to 1857 and consists of eight groups of figures constructed of Carrara marble by sculptors from the Schadow and Rauch School (Fig. 1b–e). These sculptures, such as the goddesses of antiquity (Nike and Athena) with young heroes were also a part of the design plans of Schinkel. High pedestals of red granite were constructed on the stone pillars of the bridge and serve as the base for the larger-than-life sculptures. Between the pedestals there are wrought iron railings decorated with sea horses, tritons and dolphins. The bridge figures made of Carrara marble is reminiscent of the Angels Bridge in Rome, and represents an outstanding example of the world famous 19th century Berlin sculptural school. At that time, sculptures were seen as an important "official" art form, which fulfilled a purpose that was in the public interest. The designers wanted to provide an everlasting monument to what was noteworthy and noble (Bloch and Grzimek 1978). The figures on the Schlossbrücke, with their noble-mindedness and their striving for mythological ideals, were among the most sophisticated sculptural ensembles created in the 19th century. Schinkel wrote about his concept: “The subject requires much time to implement and a great deal of thought, because the aesthetic quality is the main purpose here” (Rave 1948).

The Schlossbrücke over the Spree Canal provides a traffic link between Unter den Linden—the most important east–west artery in the city centre—and the Lustgarten (Pleasure Garden) and the former Berlin Palace. The Schlossbrücke was a counterpart to the Brandenburg Gate in the west and formed the eastern end of the boulevard Unter den Linden, as well as a point of transition to the most important square in the city, the Schlossplatz in front of the former palace. The bridge, with its monumental groups of figures, is a major element of the sculptural programme designed by Schinkel and Rauch. Together with the statues of General Scharnhorst and General Bülow in front of and opposite the Neue Wache memorial, they formed part of the city’s main street, which was designed as a victory road or “Via Triumphalis” in a decade long concept, which was unrivalled in Europe. Today, they line a busy inner city street which attracts many tourists, and is a major traffic artery and forms part of the buffer zone around the Museum Island. This circumstance, i.e. the location of the bridge in the city centre and the fact that it has been in the public focus since it was built, is the main reason why the sculpted figures have experienced such a turbulent history and a variety of restoration phases.

Directly after the sculptures were assembled in 1855 and 1860, they were treated with a coating of soluble glass as a preventive measure against air pollution. For the same reason, the figures were treated with an emulsion wash roughly every 3 years until 1916. From 1881 to 1891 they were cleaned regularly with Venetian soap (saponified olive oil). As early as 1868, critical remarks were made about the soluble glass coating in correspondences between official bodies, noting that “in the denser marble statues such as the statues on the Schlossbrücke soluble glass cannot penetrate the surface, so it cannot have any effect”. The sculptures were made of the “best second grade Carrara marble (Ravacione)”. Already in 1877, the marbles showed “the unfavourable effects of the climate” due to the air pollution in the city centre (Goralczyk et al. 1988). Therefore, in 1892 it was recommended that the sculptures be replaced by bronze figures (Springer 1981). 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 disassembled to protect them from war damage, and they were stored in wooden coverings at various locations in the western part of the city. The poor storage conditions up to 1969 led to a drastic deterioration in the condition of the sculptures, with parts broken off. At the end of the 1960s, the sculptures were reassembled again and the missing parts were replaced. From 1978, they were stored in a “lapidarium”. After the sculptures were returned from West Berlin to the GDR in 1981, comprehensive scientific studies were carried out on the figures for the first time (Goralczyk 1984). In the subsequent restoration, the sculptures were cleaned, small missing parts were replaced with a polyester resin, and then reinforced with silicone resin and treated hydrophobically (Goralczyk et al. 1988). A year after they had been erected at the original location in 1983/84, they were again subjected to partial hydrophobic treatment (Goralczyk et al. 1988). In the course of the planned restoration work in 1992/93, the polyester resin was found to be brittle, and in places there was a distinct lattice of cracks in the marble surface. The silicone resin coating was removed abrasively by micro-blasting, and the cracks were partly sealed with epoxy resin. According to the restoration report, the sculptures were also coated with a solution of Paraloid B72, and several coats were applied in the most porous places.

The restoration that began in 2007 was based on a minimal intervention concept. Previous measures were taken into account as far as possible and focused on the compatibility of the processes and the choice of conserving agents.

A review of the history of the Schlossbrücke figures shows that in the 19th century, the normal practice was already in use for preventing the deterioration of the sculptures by regular cleaning and care, not only with chemical substances. However, this preventive work to preserve the substance of the sculptures was carried out less and less in the 20th century. In view of the many problems associated with the use of chemical conservation agents, especially in the preservation of natural stone, preventive conservation is becoming increasingly important today. This is especially true when significant cost-savings are taken into consideration. Trend-setting examples can be found throughout Europe (Castelli 1997; Accardo et al. 2003), which would be worth copying for the many historically valuable statuaries in Germany.

State of the art winter covers for monuments

Protective structures for works of art or antique artefacts have a long architectural tradition and have been known in Germany since the 19th century. The archives in the

Clemenswerth Hunting Palace (Lower Saxony) show that the stone sculptures, which form part of the structure of the central building were protected by canvas strips as early as 1832. Moreover, winter covers are also documented during the 19th century for the sculptures in the Tiergarten in Berlin and at the Prussian Cultural Trust. The initial motivation for temporary winter covers was primarily to protect cultural works against weathering processes and air pollutants. Very few meaningful microclimate measurements are available that relate mainly to sculptural works, which are firmly attached to the building. However, they do show that winter protection covers delay temperature equalisation, and thus reduce the critical peak values for temperature and condensation (Berry 2005; Blum 2002; Egloffstein and Franz 2005; Wölbert 2005).

The known winter cover systems can be classified as follows: (i) wooden structures, (ii) frame and membrane (textile/plastic sheeting), (iii) wrapping without a frame, with or without spacers, (iv) acrylic glass or polycarbonate glass and (v) individual structures made of different materials (Fig. 2). Traditional wooden winter covers are known to be one of the oldest methods of winter protection. The technical solutions range from primitive casings without any defined ventilation or a ground anchoring mechanism to technically sophisticated and proven models. More recently, frames made of standard framework modules have also been used and covered with membranes, usually PVC-coated polyester fabric; these coverings are mainly experimental in character (Blum 2002).

Directly covering the monuments with an (un)coated fabric, membranes or textiles is a development of the last 13 years. In 1999, at the Institute of Textile and Clothing Technology of the Technical University of Dresden, a winter cover of polyester fabric combined with Teflon was developed (Roedel 2005). Foam spacer elements are attached, which are directly mounted on the artefact and fixed to the building by Velcro fasteners. This system is now used in Saxony and Austria (e.g. Moritzburg Palace, Schönbrunn Palace, Vienna).

A covering known as Tyvek® is used in the Versailles Palace gardens, Hampton Court Palace in England, the Indianapolis Museum of Art and other places. The material is a paper fleece fibre textile made of thermally-bonded fibres of high-density polyethylene (HDPE). Mechanically, the covering has paper-like characteristics and is not suitable for use as a load-bearing membrane. However, according to the manufacturer (DuPont), the permeability is good in regards to water vapour.

Between 1997 and 2003, a research project (Blum 2002) dealt with winter coverings for monuments of natural stone. The aim of the project was to develop a light-weight cover, which would be easy to assemble and visually attractive. The study focused on the palaces of Clemenswerth (Lower Saxony) and Weikersheim (Baden-Würtemberg). During the research programme "Assessing the performance of protective winter covers for outdoor marble statuary—pilot investigation" (Berry 2005), various membranes were tested, such as Tyvek®, polyurethane-coated nylon and polyester fabric with and without polyester insulation as well as a proprietary development consisting of three layers with insulation (Cliveden Winter Cover).

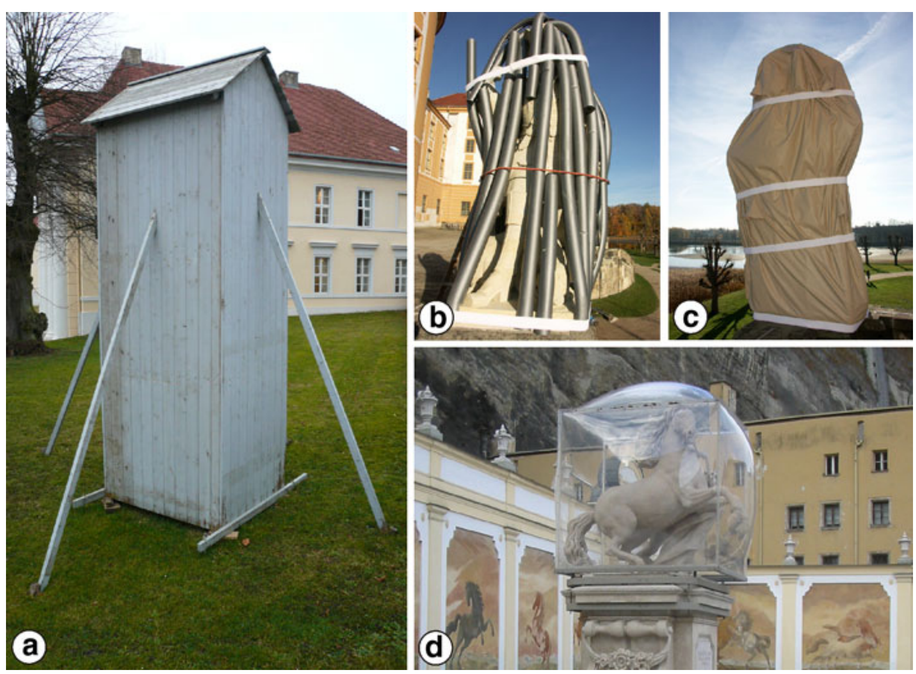

Fig. 2 Different covering systems: **a** Rheinsberg Castle, typical wood board covering, which has been used in this form since 1930 by the Prussian Palaces and Gardens Foundation; **b**, **c** Moritzburg Palace, winter protection with a textile covering of polyester fabric and Teflon; **d** Salzburg, horse trough with polycarbonate winter cover

Structures made of acrylic glass or polycarbonate glass are mainly used for prominent objects to ensure that they remain visible during the winter months. Sunlight enters the structures almost unhindered. This means that the light not only shines on one side of the object, but also that a greenhouse effect is created, which leads to increased condensation and a lack of ventilation. Therefore, these covers are detrimental to the natural stone.

In 2009, a patented multi-layer light-weight housing was developed with walls manufactured as a sandwich structure (Schmidt 2009, 2010). The inner layer consists of foam; the outer layer is made of fabric-reinforced plastic with a UV protective coating (http://www.ciccum.de/ciccum1.htm). At present, no systematic scientific study has been undertaken on the effects of the different covering systems and the associated effects on the weathering processes for marble.

Marble and its state of preservation

Macroscopic damage phenomenon

Due to their long exposition time and diverse history, the marble sculptures show various types of decay phenomenon (Fig. 3). The macroscopic damages are characterised by a few replacements of filigree body parts, e.g. substitutions for fingers, hands, wing parts, etc. Moreover, the original marble locally shows a pronounced surface roughness, which can be traced back to chemical solution processes. Sporadically, a sugar-like crumbling can be observed. In these parts, the marble fabric is strongly deteriorated (Fig. 4a). However, in most cases the back-weathering is moderate. Only one sculpture group represents an exception. For this marble sculpture group, networking cracks like a craquelling can be observed. In areas of strong fabric decay, macrocracks and material break-outs are also common. Most of the damages can be traced back to marble weathering. Mechanical damages are also common, which can be traced to the incorrect transport and storage during and after the confusion generated by World War II.

Marble weathering

Thermal dilatation processes are responsible for the initial degradation of marbles. Kessler (1919) found that repeated heating of marbles may lead to permanent dilatations due to microfracturing (Fig. 4b, c) and that thermally treated marbles show a remarkable non-reversible change in length especially during the first heating cycle (Zezza et al. 1985; Sage 1988; Siegesmund et al. 2000). Even small temperature changes of 20–50°C may result in damage (Battaglia et al. 1993). Marble has a very simple mineralogical composition. It consists of calcite and/or dolomite with other accessory phases (e.g. quartz, mica, etc.). Calcite and dolomite exhibit a pronounced anisotropy of the thermal expansion coefficient at different crystallographic

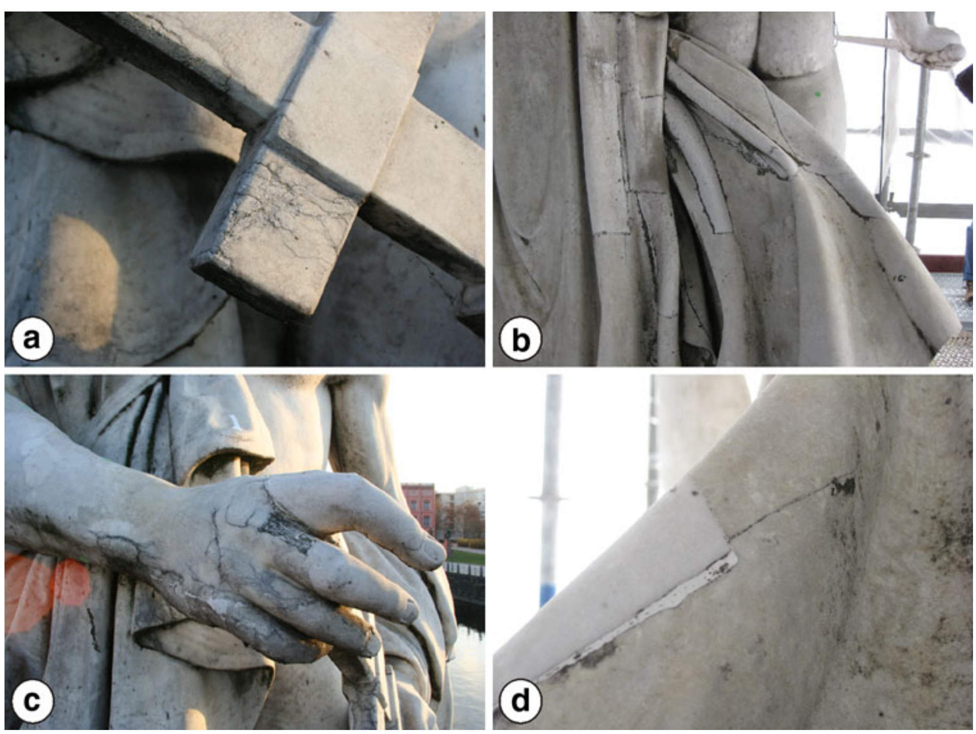

Fig. 3 Main macroscopic damage phenomenon: **a** intensive cracking, **b** replacements, **c** complex cracking with break-outs and **d** new distinct crack growth starting from an older replacement

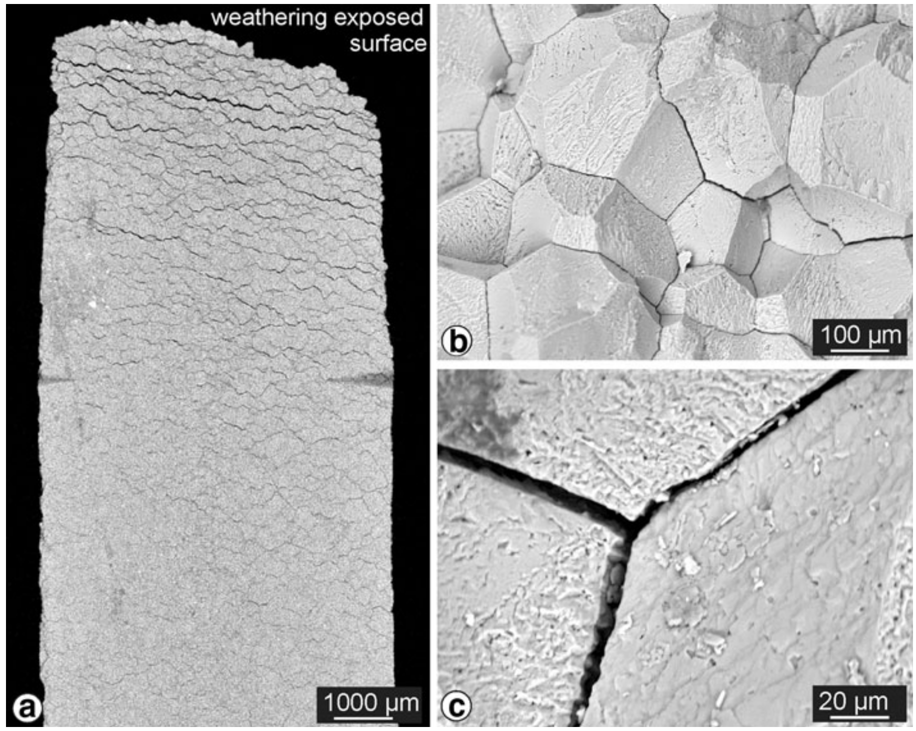

Fig. 4 Microphotographs of deteriorated Carrara marble: **a** CT-image of a drill core shows the strong microcrack deterioration parallel to the surface (sample from figure group 4); **b**, **c** SEM-images (fractography) shows the penetrative granular disintegration along grain boundaries of the calcite single crystals (reference sample)

directions (Kleber 1959) leading to stresses within the sample during heating (Fig. 5a–d). When these stresses exceed the threshold of cohesion, a thermally induced deterioration is observed (cf. Sage 1988; Weiss et al. 2002, 2004). The rock fabric, which includes grain size, grain aspect ratios, grain shape preferred orientation, lattice preferred orientation (texture) and the microcrack populations, significantly controls the material's behaviour during thermal stress (e.g. Siegesmund et al. 2008; Shushakova et al. 2010).

The increase of residual strain and thus the progressive deterioration of marbles stops after a few heating cycles if moisture is absent (e.g. Sage 1988 or Koch and Siegesmund 2004). Therefore, Winkler (1996) pointed out the importance of moisture in the weathering process of marbles. Detailed measurements of progressive residual strain on Carrara marbles were performed by Koch and Siegesmund (2004). Five dry cycles up to 90°C were followed by additional wet cycles on drilling cores with a sample size of ∅15 mm × 50 mm. The wet cycles were carried out in such a way that at the end of the heating stage, the samples in the climate chamber were run until totally dry. The result was an increasing residual strain, which did not stop during the experiments (Fig. 5e). This thermo-hygric process results in progressive crack opening (Siegesmund et al. 2007, 2008).

To acquire more information about the deterioration by cooling, comparable Carrara samples were treated in the following way. Four dry cooling cycles up to −14°C were followed by 10 additional wet cycles in drilling cores with

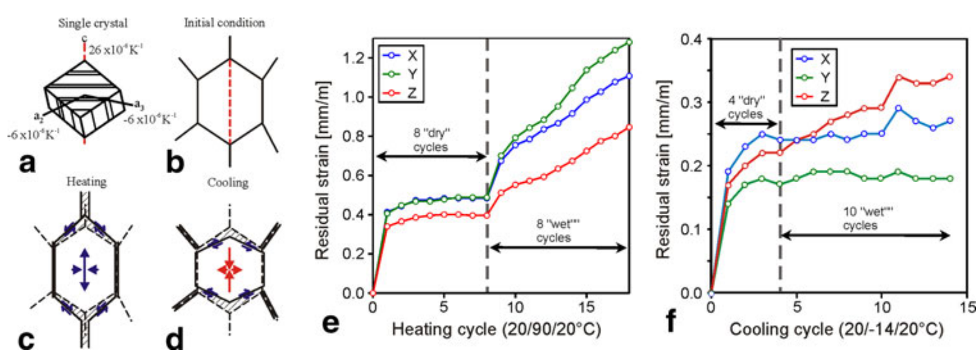

Fig. 5 Marble deterioration: **a** Thermal dilatation coefficients of the calcite single crystal with respect to the crystallographic orientations, **b** schematic illustration of a calcite crystal at initial conditions, **c** volume change by heating and **d** by cooling, **e** progressive residual strain under dry and following wet conditions induced by heating and **f** by cooling measurements

the same sample size. For the first dry cooling cycle a strong residual strain also occurs (Fig. 5f). In the experiment the residual strength is the half compared to heating. But also the absolute temperature difference was the half. Thus, in the initial dry thermal deterioration the residual strain is a function of the absolute temperature difference. For the further dry loading cycles a slight increase of residual strain is detectable, which is also comparable to the heating situation. In contrast to the dry behaviour, the cooling of wet samples only shows a slight increase of residual strain. This implies that for the investigated samples freeze–thaw action only plays a secondary part. Other experiments have shown that if cracks are open to a certain extent, the capillary water uptake increases and weathering processes like chemical solution or freeze–thaw action plays a more important role for marble decay (Ondrasina et al. 2002; Ruedrich 2003).

Rock fabrics

The samples for fabric and petrophysical investigations were drilled from sculpture 2 and 3 on the south side of the bridge. Drill cores from both sculptures with a diameter of 40 mm were obtained from the plinth.

The macroscopic fabrics of the marbles are more or less characteristic for Carrara material. They are bright white in colour and contain irregular dark grey veins. The veins are folded and show a streak-like distortion. They usually range in width from 0.3 to 1.0 cm. A preferred orientation of the veins is not clearly detectable. The samples show a medium decay in the form of granular disintegration.

The investigated Carrara marbles show a nearly equigranular polygonal grain fabric (Fig. 6a, d) with straight grain boundaries and frequently 120° triple-point junctions. The grain size in the white areas is between 20 and 600 µm, whereas the maximum is about 180 µm (Fig. 6b, e). In the *XY*- and the *XZ*-plane of the samples, a preferred grain boundary orientation (subparallel *Y*-direction) can be observed (Fig. 6c, f).

The grey veins are fine grained (average grain size = 50 µm) and the grains have a very strong undulose extinction. Grain boundaries are interlobated and a high amount of fluid inclusions or graphite occurs, which probably causes the grey colour of the veins.

Pore space properties

The porosity and pore radii distributions were analysed in order to obtain more information about the preservation state of the marbles. Hydrostatic weighing was used to measure the porosity. Both samples show an effective porosity of about 0.5 vol% (Fig. 7). In comparison with fresh marbles which show porosities around 0.2 vol% (e.g. Weiss et al. 2000), the pore space volume is significantly enlarged.

The pore size distribution of the samples was determined by using mercury porosimetry (cf. van Brakel et al. 1981). The pattern of the pore radii spectrum exhibit for both investigated marbles an unequal porous bimodal distribution of pore sizes (Fig. 7). The main maximum is marginally below 0.01 µm, and thus in the domain of micropores where no capillary activity is present. In contrast,

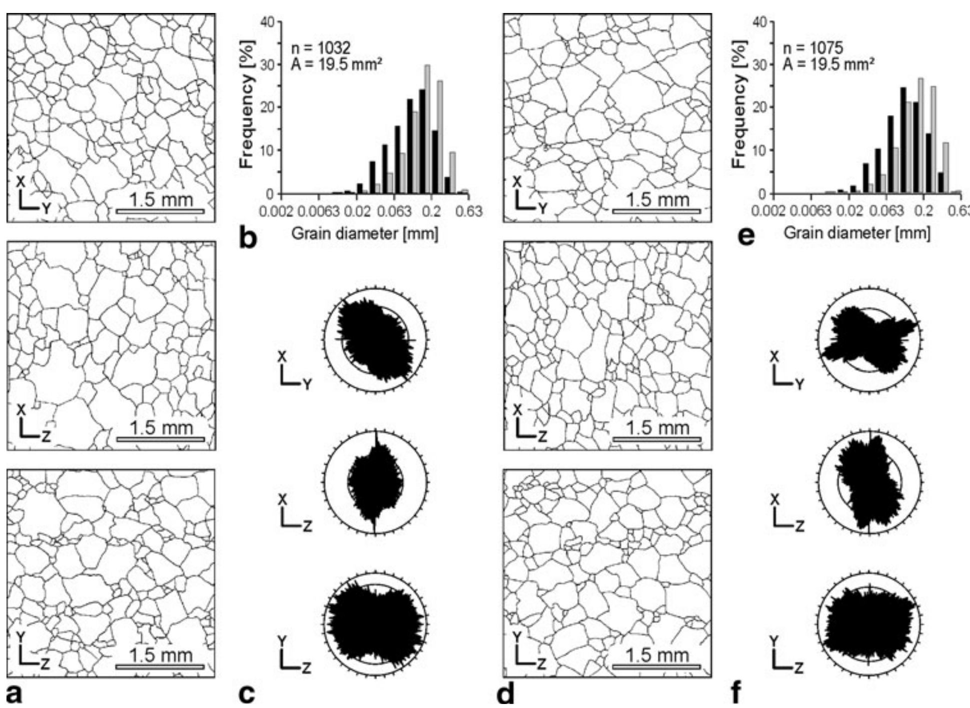

Fig. 6 Fabric properties of the investigated marbles: **a**, **d** grain fabric; **b**, **e** grain size and **c**, **f** preferred orientation of grain boundaries, **a**–**c** drilling core 1 (sculpture 2) and **d**–**f** drilling core 4 (sculpture 3)

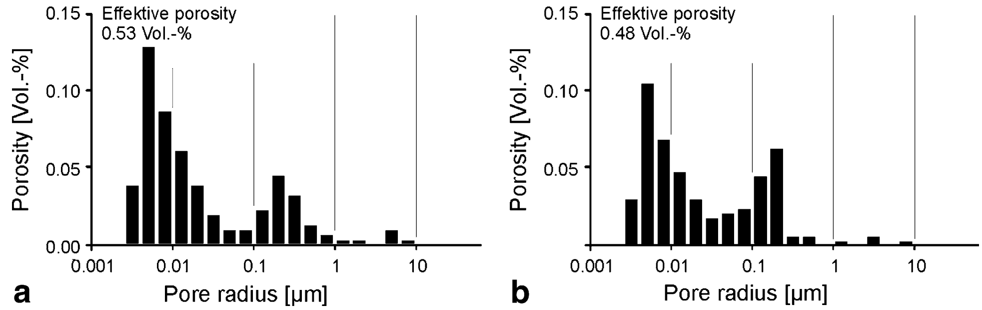

Fig. 7 Pore radii distribution of **a** sample from sculpture 2 and **b** sculpture 3

the second sub-maximum is about 0.1 µm, and therefore in the pore space range of capillary soaking. In the present state of preservation, the capillary water uptake is assumed to be relatively low (cf. Ruedrich 2003). With progressive crack opening caused by further weathering, the water uptake should also increase, and thus the chemical solution at the internal surfaces of the marbles will increase.

Magnitude of fabric disintegration

Ultrasonic velocities were increasingly used as a non-destructive tool for assessing the structural disintegration of the marbles. The basic principle is that the decrease of compressional waves (V_p) is correlated with progressive crack growth during weathering. Köhler (1991) presented a V_p damage classification (Table 1) based on numerous measurements at sculptures made of Carrara marble. In order to analyse the fabric cohesion, the V_p was measured in the drill cores. The transient times of ultrasonic pulses (piezoceramic transducers, resonant frequency of 350 kHz, point coupling) were measured using the transmission technique (Birch 1960, 1961). The measurements were carried out in two directions (X,Y) perpendicular to the length axis of the drill core. To simulate the field condition the analysis was performed under dry and completely water-saturated sample conditions. The measuring points were defined for different distances along a depth profile (Fig. 8) in order to obtain information about the preservation state from the surface to the rocks interior.

The measured ultrasonic velocities at dry sample conditions are between 3.25 and 4.50 km/s (Fig. 8a, b). The mean value is around 3.90 km/s, which can be designated as increasingly porous after the classification by Köhler (1991). At water-saturated conditions, V_p varies between 5.80 and 6.60 km/s and are characteristic for Carrara marbles (Fig. 8a, b). Water-saturated weathered marbles are known to show nearly the same V_p properties as the original values with fresh conditions (e.g. Weiss et al. 2000; Siegesmund et al. 2009).

The V_p distribution along the depth profile at dry sample conditions for drill core 2 exhibits conspicuous changes. Near the surface, a relatively high V_p of 4.75 km/s is detectable. At about 17 mm, depth V_p is strongly reduced to 3.60 km/s and increases with depth up to 4.00 km/s. The same pattern can be determined for the second drill core but the V_p changes are less pronounced. Commonly V_p should be the lowest near the surface because weathering intensity is highest at the surface. This indicates a secondary fabric stabilisation of areas close to the surface. The cause could be chemical solution/precipitation reactions or former consolidation works.

Compressional wave velocities during the drying experiments are given in Fig. 8c, d. The results show a strong correlation between water saturation degree of the marble pore space and the compressional wave velocities. Beneath a saturation degree of about 40%, the influence of water on V_p is strongly reduced.

Table 1 Structural damage classification on the basis of V_p for marble from Köhler (1991)

Damage class	V_p (km/s)	Condition	Porosity (vol%)
Class 0	>5.0	Fresh	<0.5
Class I	3.0–5.0	Increasingly porous	1.3–0.5
Class II	2.0–3.0	Sugar-like disintegration	3.0–1.3
Class III	1.5–2.0	Fragile	5.3–3.0
Class IV	<1.5	Crumbling rock	>5

Ultrasonic tomography (on-site analysis)

To detect the damage of the rocks interior, detailed two-dimensional tomographic investigations with ultrasound (250 kHz) were carried out on-site. The results of sculpture group 3 are given in Fig. 9. Measuring points are defined in order to achieve a tight grid of measuring tracks for each profile (Fig. 9a–c). The analyses were carried out at three different horizontal slices at the shoulder (profile I), the thigh (profile II) and the shackle (profile III) of the warrior. For better signal transmission, a special clay was used between the transmitter and the marble. The calculations of the tomographic inversions were compiled with the programme Migratom (cf. Jackson and Tweeton 1994; Ruedrich et al. 2001; Siegesmund et al. 2009).

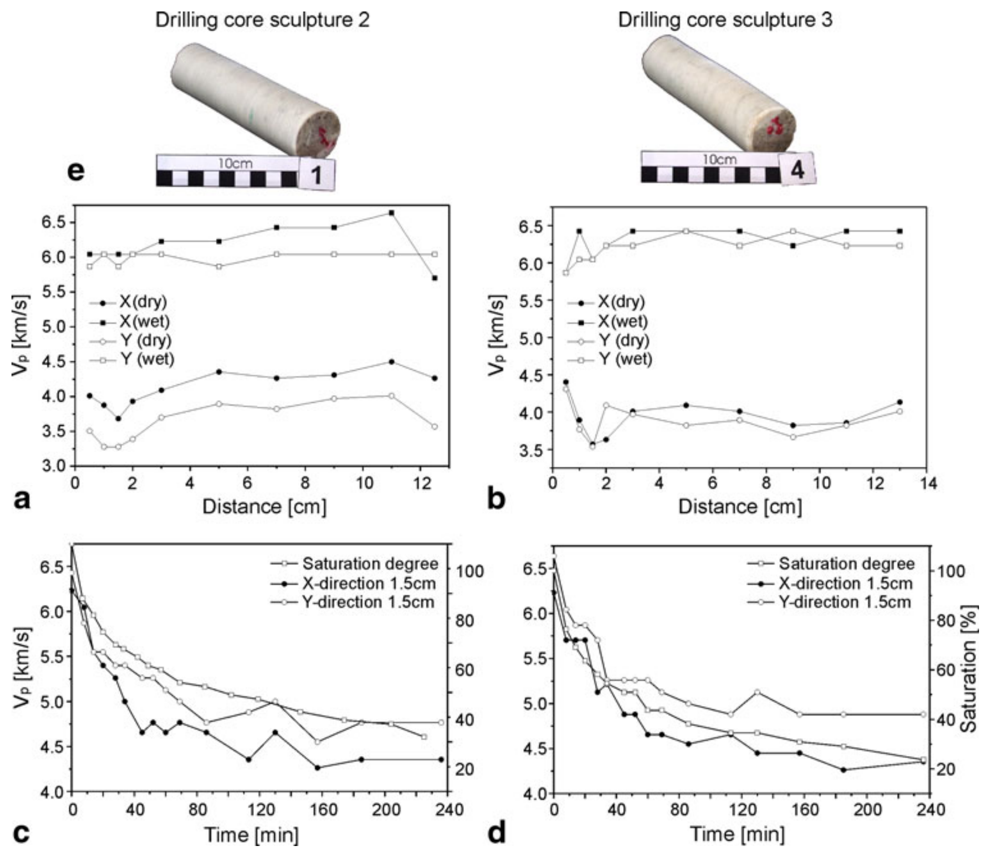

Fig. 8 **a**, **b** Ultrasonic wave velocities (V_p) of drilling core 1 (sculpture group 2) and 4 (sculpture group 3) in a depth profile at dry and water-saturated conditions. **c**, **d** Correlation between V_p and water saturation, **e** drill cores

For the chosen example the ultrasonic velocities in the tomographic profiles vary between 2.0 and 4.1 km/s. The lowest velocities are observable for profile III between 2.0 and 2.8 km/s. This indicates that the smaller sculpture parts are strongly deteriorated than the voluminous parts, and is in agreement with the macroscopic damage observations.

The velocity distribution patterns are different for all profiles (Fig. 9d–f). For profile I and III, the areas of lower velocity are exposition-controlled. More deteriorated parts are non-protected by other sculpture parts, and thus subjected to stronger weathering. Profile III shows a low velocity channel from southeast to northwest. Since the V_p differences are low, this velocity pattern may only be affected by the marble anisotropy. Ruedrich (2003) found an increasing V_p anisotropy up to 30% for Carrara marbles with progressive fabric decay. Comparable ultrasonic velocities in intensity as well as in its distribution pattern are observable for all sculpture groups of the Schlossbrücke.

Acquisition of the climatic conditions with or without a covering

Although the protection of art works by winter covers has a long tradition, there are only a few studies documenting the effect of such covers (Berry 2005; Blum 2002; Egloffstein and Franz 2005; Wölbert 2005). Therefore, the climate monitoring system was designed to create a dense database for the numerical prediction of the effect of protective systems, and to compare the given climate conditions to the known factors influencing the marble deterioration.

In December 2007, the climate monitoring system started operation in order to study the influence of the microclimate on marble sculptures on the Schlossbrücke in Berlin. The first system was installed at sculpture 2 (Fig. 1), followed in 2008 by two systems each at sculptures 1 and 3. General local climate data like air temperature, relative humidity, wind speed and global radiation as well as surface temperatures and surface humidity at the sculptures are measured and stored every 15 min. In December 2008, additional marble reference samples with integrated temperature sensors were attached directly to the sculptures. Temperature distributions can thus be collected inside a marble without damaging the sculptures.

The monitoring system has been designed for long-term operation and is still being maintained. Combined with the hygric and thermal characteristics of the marble, the measured data are a valuable foundation for simulating the effectiveness of different protection systems.

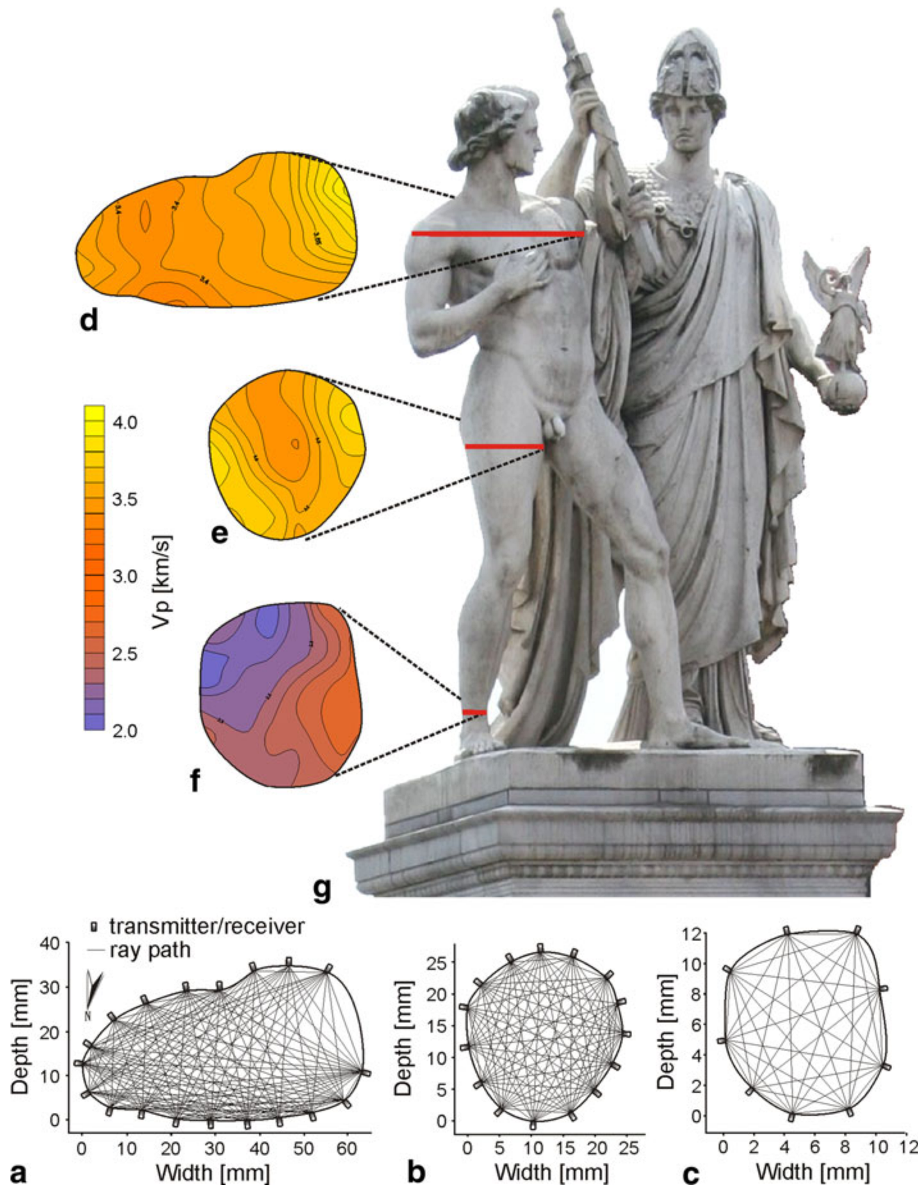

Fig. 9 Tomographic reconstruction of three profiles for sculpture group 3: **a**–**c** transmitter/receiver positions and associated ray paths, **d**–**f** tomographic inversions

Effect of the local climate on weathered sculptures

The recording of the local climatic conditions on the Schlossbrücke comprise more than 2 years of data. Figure 10 shows the air temperatures measured during this time span. To verify the reliability of the data, they have been compared to data from the weather station Berlin–Tempelhof, which is operated by the German Meteorological Service (2010). This comparison shows a good correlation but the temperatures measured on the Schlossbrücke tend to be little higher than the temperatures at Tempelhof. Especially the lowest temperatures at Tempelhof are lower than the lowest temperatures on the Schlossbrücke. The reason is a distinctive microclimate in the high-density area of the city centre and the special location over the river Spree. This is confirmed by long-term averages of the temperatures in the period from 1961 to 1990 at both locations. In Tempelhof, the average temperature ranges from 9 to 9.5°C, whereas the average temperature at the Schlossbrücke ranges from 10 to 10.5°C. The main wind direction is southwest.

The climate data recorded until now show that the temperatures of the sculptures range from −20°C in winter up to 40°C in summer. This represents a temperature span of about 60°C. In combination with wet and dry cycles, this may cause marble deterioration. The temperature of the sculptures is determined by the temperature of the surrounding air and by the global radiation. The humidity of the material depends on the relative humidity of the air. In addition, the infiltration of liquid water from rain or dew increases the humidity of the materials.

The influence of direct sunlight on the surface temperature of the marble can be verified by comparing the

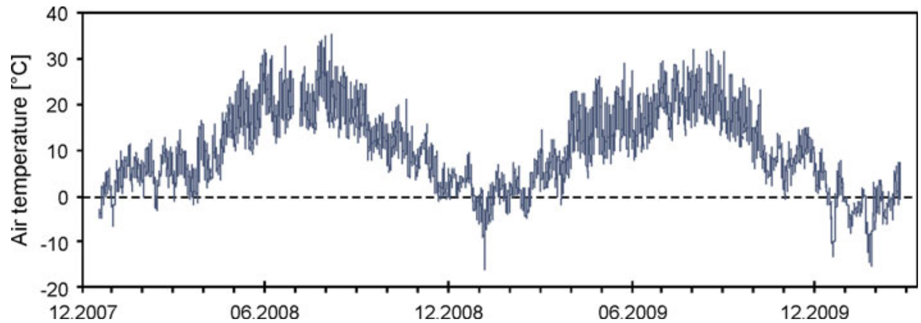

Fig. 10 Air temperature at the Schlossbrücke Berlin during the period of the project

temperatures of the massive parts of the sculptures on the south and north side. Figures 11a and 12a show examples for measured surface temperatures on sculpture 2 in comparison to the air temperature. In winter, the highest temperatures were measured on the south side of the sculptures, where the influence of direct solar radiation is the highest. In the period shown in Fig. 12a, the differences of the surface temperatures on the north and on the south side of the unprotected sculpture are lower than 4°C. Without direct solar radiation, no temperature difference can be seen. Moreover, the increase of the surface temperature by solar radiation in the summer is not very high. In the period investigated, the highest temperatures were measured on the west side. The maximum temperature difference between the north and the south side is below 6°C. The maximum surface temperature difference since the beginning of the measurements is below 10°C.

The main reason for the low influence of direct solar radiation on surface temperature is the high reflectivity of the bright marble. A further reason could be a relatively high thermal conductivity and the high density of the material. The heat which develops on the surface is transferred and spread inside the material.

The most interesting observation of solar radiation and temperature occurred on the 3rd of July 2008. The air temperature on this sunny day as well as the surface temperature 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. Around 12:30 pm, overcast conditions occur for 1 h, and therefore the surface temperature on the west side temporarily decreased to 30°C. Beginning at 3:30 pm, the temperature on the west side suddenly decreased to 27°C within 1 h. At the same time, the temperature on the north side fell to 20°C. 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 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 is less abrupt.

Figure 11a shows the temperature profile measured on a reference sample with one exposed surface oriented to the

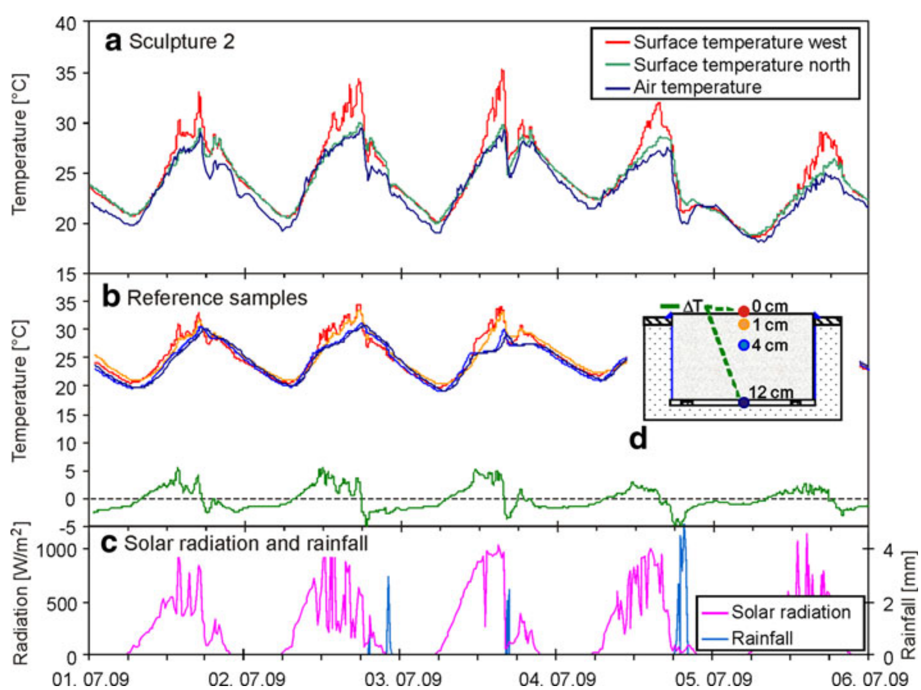

Fig. 11 Influence of the microclimate on the marble temperatures in summer: **a** temperatures measured at sculpture group 2, **b** temperatures in a depth profile from a reference sample with one exposed surface, **c** solar radiation and rainfall and **d** exposed reference sample with temperature sensors at different depths

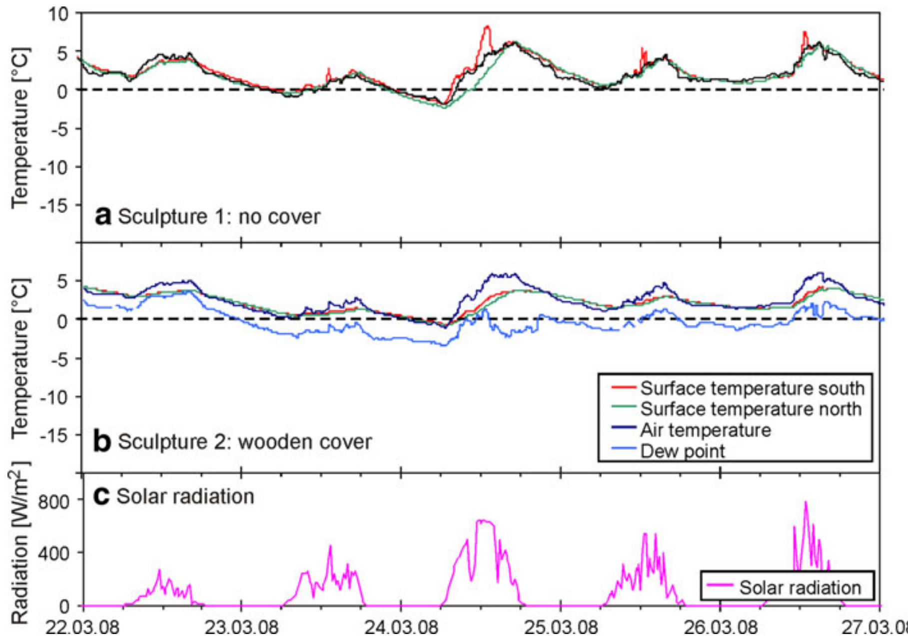

Fig. 12 Influence of climate and the wooden cover on the marble temperatures in winter

southwest (Fig. 11d). The other surfaces of the reference sample exhibit a heat insulation in order to evaluate the thermal behaviour of massive sculpture parts. As expected, the development of the surface temperature in general equates to the temperature profile measured on the west side of sculpture 2. Due to the high thermal conductivity of the marble, the temperature at a depth of 1 cm follows the surface temperature fast. Higher surface temperatures only occur in times of direct solar radiation. In the period from the 1st to 6th July 2009, the highest temperature difference between the surface and the backside of the sample is about 5°C (Fig. 11b). If the environmental temperatures rise, the surface temperature is always the highest. The temperature profile is inverted, if the ambient temperature drops.

Effect of the conventional wooden cover during the winter

A wooden cover was erected in January 2008 around sculpture 2 and it was removed in May 2008. The cover was open below and it had wide vents under the roof. Sculpture 1 wasn't covered in this period. Figure 12 shows a comparison of the microclimate on sculptures 1 and 2 during 5 days in March 2008. Due to the wide vents in the wooden cover, the air temperature effect around the sculpture is insignificant. However, the amplitudes of the surface temperature are slightly lowered compared to the temperatures on sculpture 1. Inside the cover, there is no difference between the surface temperatures on the south side and the west side of the sculpture. Furthermore, inside the cover the surface temperatures follow the ambient air temperature more slowly, and therefore a temperature difference of up to 3°C occurs. The reason might be the reduced heat transfer due to the lower wind speed. The dew point inside the cover during the period shown in Fig. 12 is just a little lower than the surface temperature. During the entire time when the sculpture was protected, the surface temperatures fell below the dew point for a period of 430 h. This equates to about 13% of the 133 days when the sculpture was covered. At the same time, precipitation occurred on 51 days. Unfortunately during this time period, the dew point temperature outside the cover was not being measured. It is probable, however, that the effect of the wooden cover is limited as a protection against rainfall.

Effect of the modern cover with a PVC membrane during the winter

Since February 2009, a steel framework with a white PVC membrane has been erected around sculpture 1 and is still being used on this figure. The area below the cover is open and has no additional vents.

This protective cover shows a similar climatic effect in the interior as the wooden cover. Surface temperatures on the north and on the south sides show no difference, which is similar to the interior climate of the wooden cover. This is caused by the shadowing effect of the cover. During a sunlit day, the air temperature inside the cover increases slightly. In the winter, the weather station is in the shade cast by the modern cover, and thus the solar radiation shown in Fig. 13c does not represent the direct solar radiation. However, the data from the DWD show that the 19th and 20th of December 2009 were both the days in which the sun shone in Berlin.

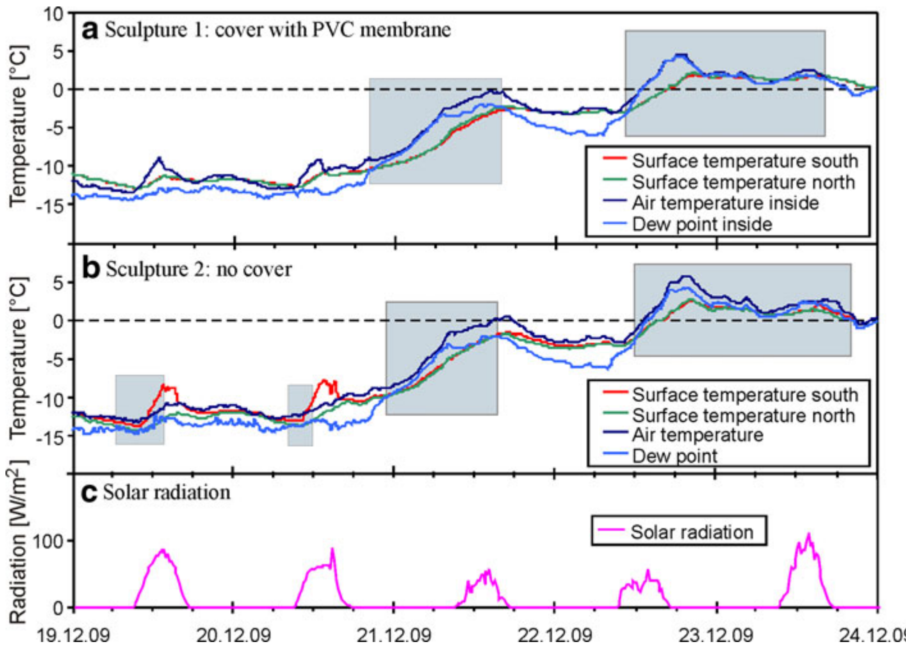

Fig. 13 Influence of climate and the cover with PCV membrane on the marble temperatures in winter. The *pale blue boxes* represent periods where the surface temperature falls below the dew point

Inside the membrane cover, the surface temperatures can also fall below the dew point. In Fig. 13, these periods are represented by the pale blue boxes. If the temperatures are below the freezing point, this leads to hoarfrost on the sculptures. Not until the temperatures rise above the freezing point does the surface of the marble get wet. This occurred on the morning of the 22nd of December 2009 as shown in Fig. 13. The surface temperature is still below the dew point.

During the period from October 2009 to February 2010, the surface temperature of the unprotected sculpture 2 is below the dew point of the ambient air in an overall time period of 960 h. This equates to about 27% of the entire period of 147 days. Inside the modern cover, the surface temperature of sculpture 1 is just 694 h below the dew point. This equates to about 20% of the considered time. Precipitation occurred on 63 days in this period.

The time of direct infiltration of water to the sculpture is shortened by the modern cover, although an intensive air exchange is possible through the opening below. In addition, moisture infiltration can be reduced by closing the opening below the cover. Moreover, more dust accumulates on the sculptures inside the cover than when the sculptures are freely exposed. This is another important reason for closing and sealing the cover completely.

Numerical simulation of microclimate with or without a covering

Numerical simulation of heat and moisture transport phenomena has become a widely accepted and commonly applied investigation method (Galbraith 1992; Grunewald 1997; Kuenzel 1994). The application allows the evaluation of possible environmental effects on resultant damage processes to the marble sculptures. The analysis of the climate inside the cover that affects the marble sculpture requires the implementation of air transport induced by air pressure differences. Bear and Bachmat (1991) give a general physical and theoretical description of the thermodynamic principle. Grunewald (1997) introduced a physical model of couplet Heat Air and Moisture transport (HAM), which fulfils the simulation requirement and is used in the present paper. The transport processes and transmission between solid, liquid and gaseous phases are given for a multiphase system in porous materials. The actual code used for the simulations is called DELPHIN 5.6, as described in Nicolai et al. (2008a, b).

The accuracy and reliability of the numerical results highly depends on the quality of the input data, and thus it requires the setting of highly defined boundary conditions (Hagentoft et al. 2004). Since the microclimate situation at the marble sculptures with or without a covering has been measured, the boundary conditions are also well known for specific positions at the different sculptures.

Hygrothermal material properties of the investigated Carrara marbles

The required hygrothermal material properties have been analysed by laboratory techniques and are supported by a few in situ measurements. The hygrothermal characterisation of the marble is a difficult task. Having a very low porosity, moisture transport and moisture storage, the determination of characteristic material parameters becomes highly time consuming and requires high precision techniques and methods. A general description of the experimental methods used is given by Plagge (2005, 2007). A selection of the basic hygrothermal material properties, including the variation of a Carrara marble is listed in Table 2.

The application of numerical simulation software requires complete material functions, able to describe vapour permeability, the liquid conductivity, both functions of moisture content, and the moisture storage function, specifying the relationship between moisture content and moisture potential. This leads to the task of material modelling, which provides a set of material functions with experimentally determined coefficients. The procedure used is described by Scheffler and Plagge (2009).

Since a complete characterisation requires numerous samples of different size, the valuable original Carrara marble of the sculptures cannot be sampled in the required amount. Based on mineralogical examinations, suitable Carrara marble from the original quarry deposit in Italy has been selected for measurement, representing the inner parts of the sculptures. Only two specimens from a previous sampling (see Fig. 8) could be used for experimental analysis, representing the marble surface of the sculptures. Due to climate induced deterioration, followed by some previous conservation treatments, the marble surface shows different physical properties. The hygrothermal material properties of both marble types are shown in Fig. 14.

The results show remarkable differences between the deteriorated parts of the marble sculpture and the fresh marble sample. The comparison of sorption isotherm and moisture retention indicates an increase of large pores for the weathered marble, whereas the quantity of small pores decreases from 0.0075 to 0.0020 m^3/m^3 by 75%. The increase of moisture transport of around 80% relative humidity can be explained by perfect penetrative granular disintegration along the grain boundaries of planar pores in the calcite crystals. The improvement shows a $\sim$50 times greater transport rate. The increase of large pores from 0.004 to 0.008 m^3/m^3 leads to a higher moisture transport rate, which is $\sim 10^3$–10^4 times greater at a higher degree of saturation. Water vapour permeability increases by 15%.

Simulation of free exposed sculptures

Due to the complex geometry of an original sculpture, it is not possible to simulate all the details. The calculation effort would be too large. Thus, the sculpture is represented by the massive torso and the strong legs. The arms and head show smaller diameters and have a more complex geometry. The idealised shape of a sculpture is depicted in Fig. 15.

Figure 16 shows the results for an exposed marble sculpture, where the yearly fluctuation of climatic conditions influences the hygric status of the marble. The data are given for the 15th of each respective month. During the spring and summer seasons, dry conditions dominate. After the duration of a long drying period (see May), the surface layer has dried. Occasional precipitation leads to periodic wetting of the surface regions, but moisture can continuously evaporate. The intensity of the rainfall and humidity causes the moisture to penetrate into the marble at a certain depth, which fluctuates between a few mm up to 35 mm. During the colder seasons in autumn and winter, the sculpture is dominantly wetted, leading to higher moisture contents and an increasing penetration depth.

Large differences also exist between different marble thicknesses. Thinner parts of the sculpture, like the extremities, show regular water saturation, whereas the massive body never gets fully moistened. During colder periods, drying conditions are poor whereby moisture can penetrate the marble sculpture up to a depth of 200 mm.

Since marble has a large thermal conductivity, the transmission of temperature is quite fast. The simulation results indicate that the outer temperature conditions can easily penetrate the marble. Thus, nearly all marble surfaces show the same temperature behaviour. The surface temperature is independent from the diameter of the sculpture geometry. Only at greater depths within the sculpture, daily or weekly changes of temperature are observable. The temperature difference between the outer layer and the core marble never exceeds a maximum of 8°C. For the actual cases, the temperature differs between 2 and 4°C.

Table 2 Basic hygrothermal material parameters of Carrara marble (total sampling collective $n = 125$ specimen)

Parameter	Symbol	Unit	Mean	Std Dev	Min	Max
Bulk density	ρ	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	λdry	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	μdry	–	353	243	75	737

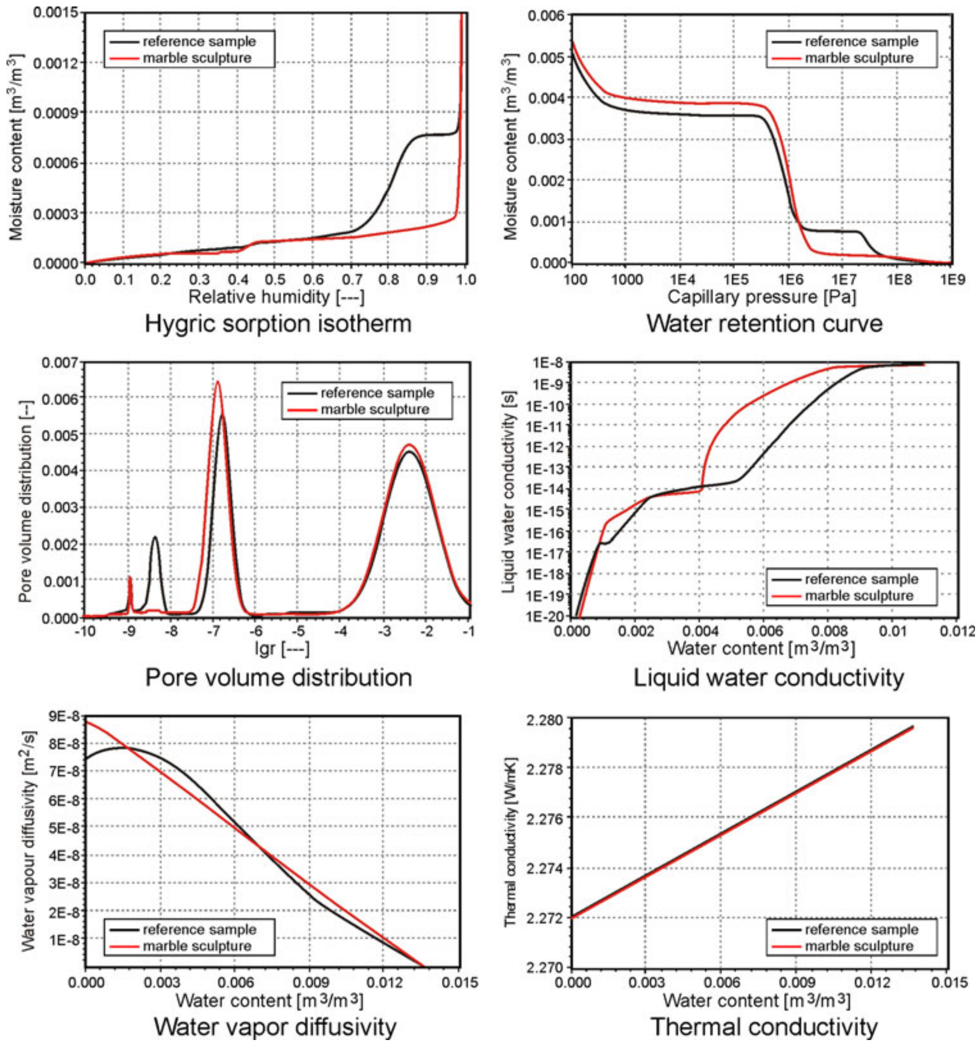

Fig. 14 Hygrothermal material property function on samples of Carrara marble and the sculpture

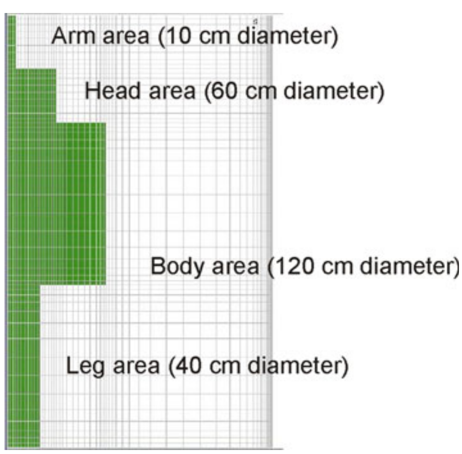

Fig. 15 Idealised simulation scheme of a marble sculpture

Simulation of wooden shelter as a protective winter cover

When developing a new and innovative covering system, it is important to evaluate conventional and multiple used systems. In this respect, two wooden winter covers were compared:

1. an airtight design with reduced air circulation and
2. an air-ventilated design with defined openings at the bottom and top of the housing.

To simulate air circulation within the housing around the marble sculpture, different air exchange rates are used. The velocity of air movement is defined by the pressure difference between upper und lower openings. In the present paper, the differences in pressure used to lie between 0.5 and 5.0 Pa. When wind blows around the protective shelter chimney effects are created, where air passing the upper opening generates air suction through the lower opening. In this manner, air is continuously flowing along the marble sculpture (see Fig. 17). The pressure between the upper and lower entry varies between 0.5 and 5.0 Pa.

In Figs. 18 and 19, different wooden winter covers are compared. To understand the operation of the wooden shelter on the marble sculpture, the mean moisture content of the statue is shown. Relatively airtight constructions lead

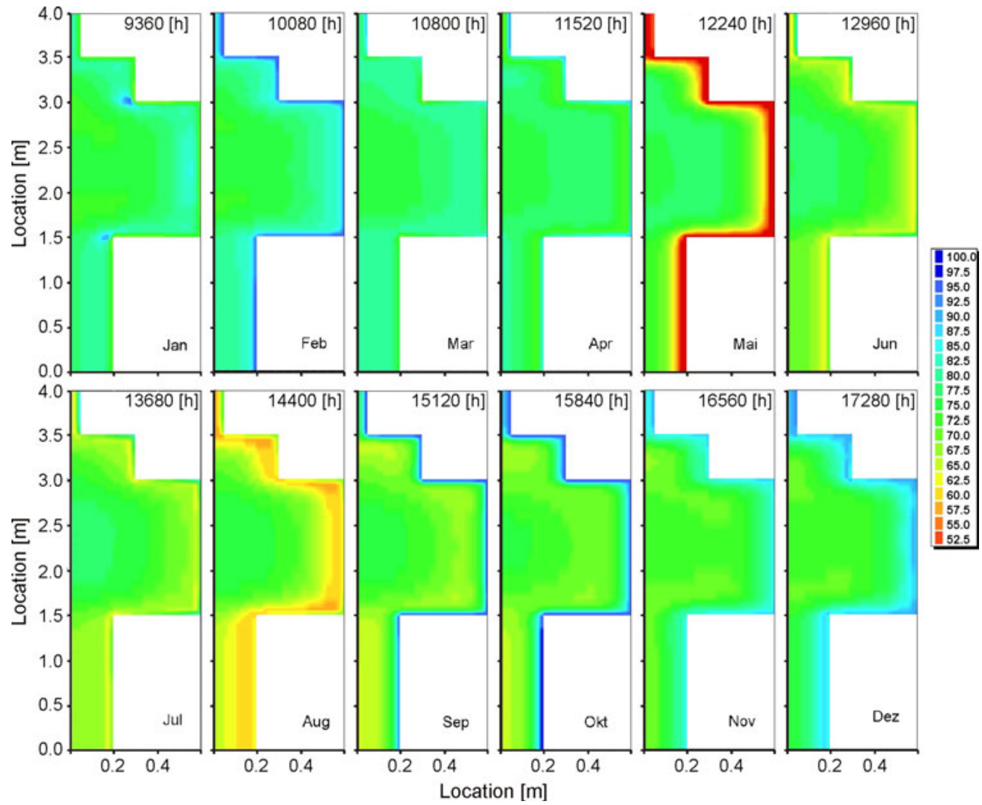

Fig. 16 Moisture distribution within the idealised sculpture influenced by climatic conditions during the year

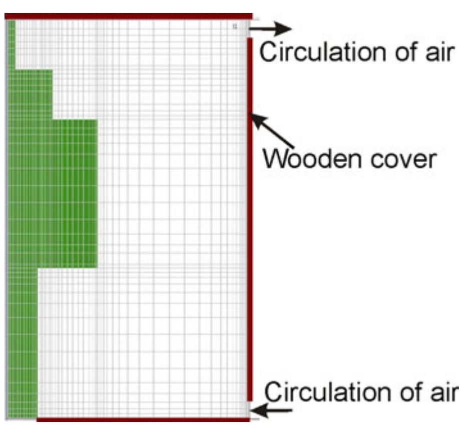

Fig. 17 Simulation scheme of the idealised sculpture having a wooden shelter as a protective winter cover. The air ventilation openings can be opened and closed

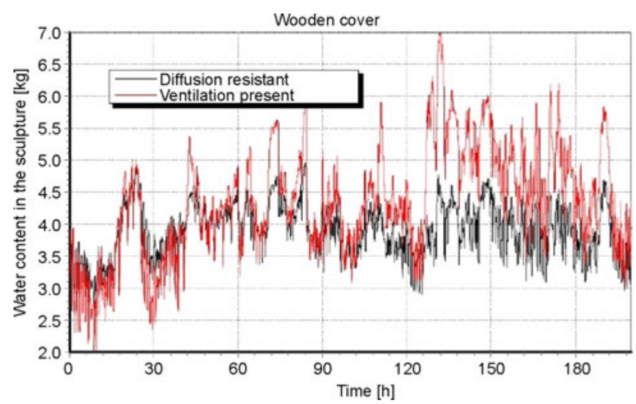

Fig. 18 Total moisture content of the idealised marble sculpture having wooden protective winter covers. Comparison of an airtight and an open winter cover system with ventilation

to smaller moisture contents in the marble. Assuming hygric and thermal dilatation is proportional to the amplitude of moisture and temperature, the relatively airtight wooden shelter is preferred. The variation of moisture for non- and low-circulating systems is 3–5 kg moisture, whereas air-ventilated systems deliver a variation of 2–7 kg. The daily amplitudes are much larger, leading to substantial dilatation in the marble. In spring time, the daily fluctuations are extreme. During sunny days, warm outside air is laden with moisture and passes over the cold sculpture. This results in surface condensation and a moistening of the marble. Since the conditions for condensation have a long duration, the moistening is a dominant process in February and March.

In the case of an airtight and non-ventilated shelter, only little moisture enters the protective winter cover. Increasing temperature within the shelter leads to a decrease of relative humidity in the air allowing the marble to dry. Not every wooden shelter is beneficial, as this investigation has shown.

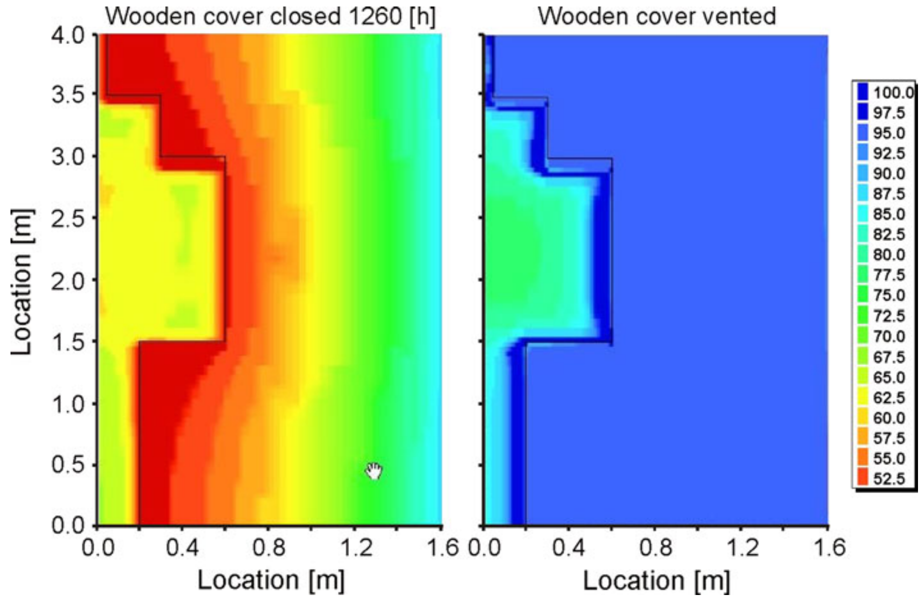

Fig. 19 Comparison of relative humidity calculated for two wooden protective winter covers in the early spring: relatively tight (*left*) and having air ventilation openings (*right*)

Simulation of membrane winter covers

The requirement profile for a sculpture adapted cover has been defined in the project. The central aspects are light-weight, durability, easy construction, simple transport and storage (cf. Will 2009). In view of all the requirements, different cover materials, e.g. glass, acryl, plastics and membranes have been analysed. Based on these investigations, membrane systems were selected because they fulfil most requirements. From various possible membrane systems, a moisture adaptive system has been chosen. All simulation results have been carried out using this membrane type.

Three simulations for different winter covers utilising a membrane system are given below. The different systems compared are:

1. an airtight membrane design
2. a diffusion open membrane design, allowing air ventilation only from a basal opening
3. a diffusion open membrane design, with defined openings at the bottom and top of the shelter allowing air ventilation of 1 and 5 Pa circulation rates

Figure 20 presents the relative humidity of the airtight membrane design and a diffusion open design with a ventilation rate of 5 Pa. The results are shown for 3 days, December 15th, February 1st and March 15th. The comparison shows that the airtight solution has the lowest moisture content than the ventilated case. Analogous to the wooden shelter, surface condensation leads to higher moisture levels in the marble. An increasing ventilation rate results in a higher moisture content, as presented in Fig. 21. At the end of March both systems show comparable results, since enough drying potential exists, but the system stays sensitive. As far as surface condensation is concerned, moisture content in the marble will increase.

Figure 21a compares the membrane shelters using the mean moisture content in the marble sculpture. The distribution of moisture within the sculpture is very relevant, since the dynamic course influences the damage processes and the intensity of damage depends on the amplitude of state variables. A comparison of the relative humidity on the sculpture torso surface at different ventilation rates is shown in Fig. 21b. The ventilation rate leads to a different behaviour, since it is dependent on the outer climatic conditions. Drying conditions are present, if the cold and dry outside air is combined with the warm marble. Wetting conditions are present, if warmer and moist outside air circulate around a cold marble. If a continuous large circulation rate exists, the marble sculpture will cool down during long freeze periods and increase the risk of deterioration.

Because of the large mass of the marble body, the temperature behaviour is more inert than in a small arm, the head or a wing. In that case, the marble can cool down very quickly, reducing condensation events.

Design and development of an object-related shelter system

Cover requirements

The design of statue covers must satisfy an extensive set of criteria including aesthetic, structural and physical performance (cf. Gengnagel 2005). From an aesthetic point of view, there are two fundamentally different approaches: first, the covering serves as an intentional act of disguise

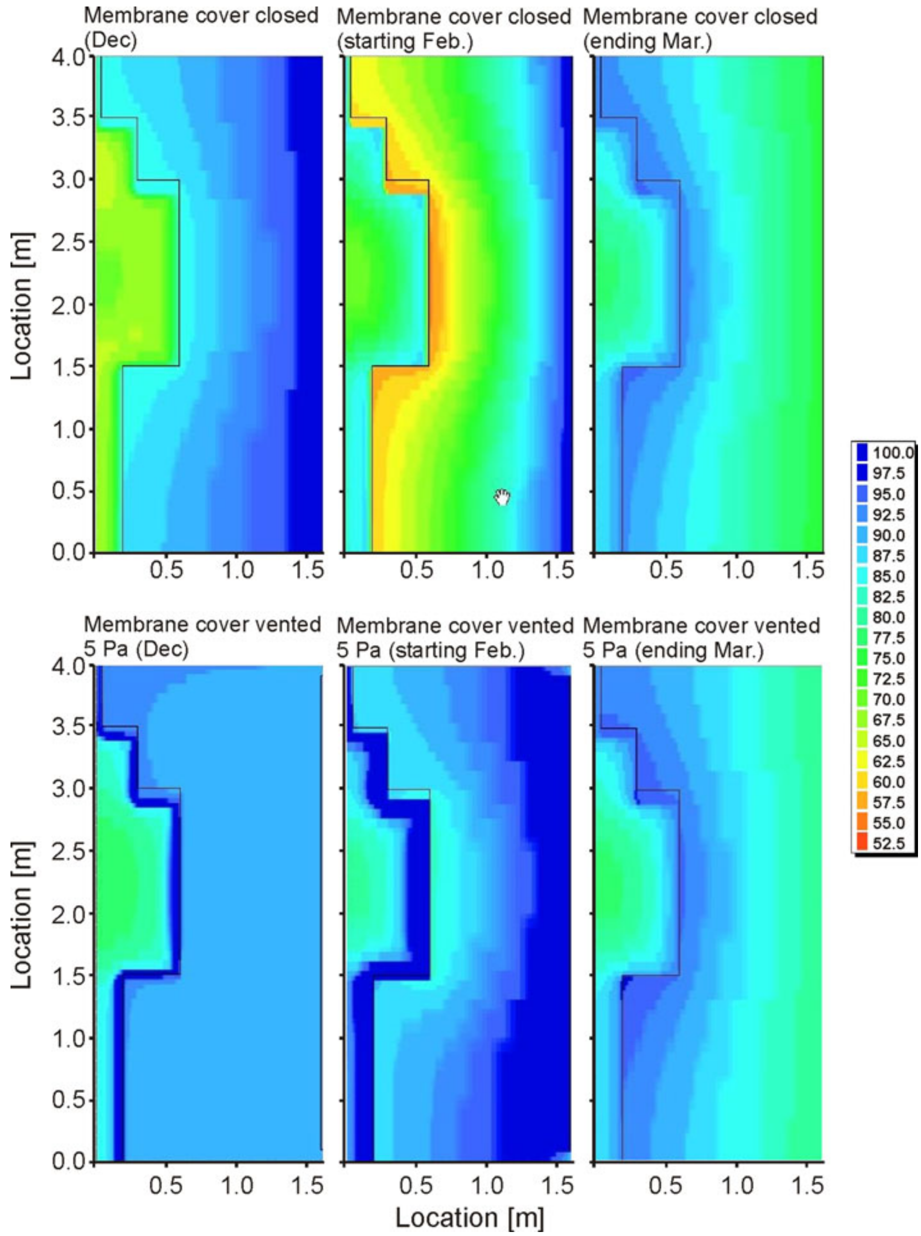

Fig. 20 Distribution of relative humidity within the protective winter covers using a membrane shelter. The results are for December 15th, February 1st and March 30th, membrane cover relatively tight (*diagrams at the top*) and open air ventilation (*diagrams at the bottom*)

and second, the covering serves as an "invisible" protection (where the degree of invisibility depends heavily on design and materials). The disguise approach can act as a cover for the statue while providing a clear reference to its original form and cultural significance. The cover can also be a totally new and neutral entity, a box for example. In both cases, the covering will result in a new object with its own aesthetic identity. The intended effect of transparent coverings is to preserve the viewer's impression of the original statue as far as possible. However, the impact of the still necessary structure can lead to a different end result. Finally, both types of coverings should not only serve as an extension of the existing statue but also as a design object itself.

The covering provides an environmental barrier for the statue. Specific requirements for covering vary with different applications. Each solution provides varying degrees of structural stability, load distribution, water resistance, insulation, vapour and solar irradiation control. All coverings need to sustain applied loads from wind and snow and distribute these to the primary structure and supports. Structurally there are two basic systems: skin or shelter. While the skin system transfers external loads directly to the statue, a shelter protects the statue from exposure to external loads.

The skin system does not improve the overall stability of the statue, but in fact increases the area exposed to wind loads, which can lead to serious stability problems of the

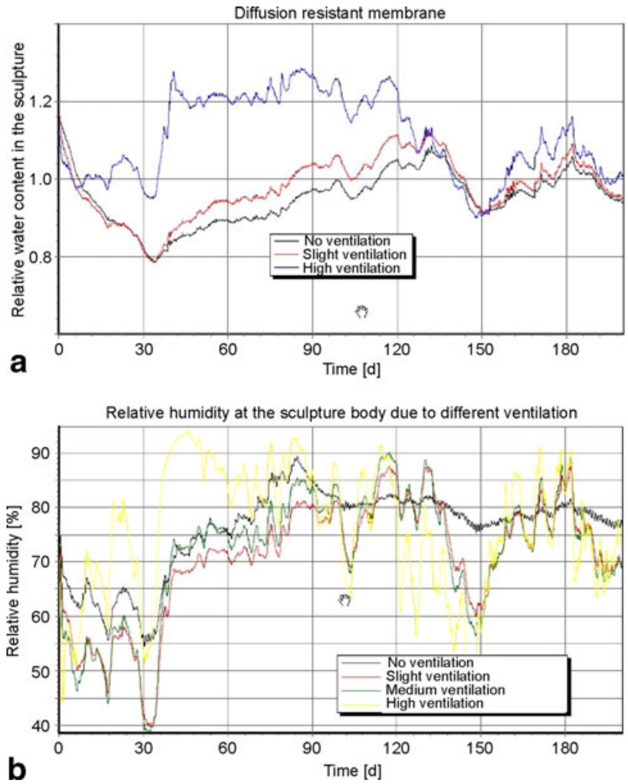

Fig. 21 Comparison of different membrane protective winter cover systems: **a** no ventilation, small ventilation (base open) and high ventilation (5 Pa pressure difference). **b** Relative humidity at the torso of the sculpture: no ventilation, small (0.5 Pa pressure difference and base open), medium (1.5 Pa pressure difference) and large ventilation (5 Pa pressure difference)

statue or parts of it. Another critical issue with skin systems is the risk of damage to the statue caused by concentrated loading during the skin assembly. The performance of skins with respect to complex environmental control is limited. The main advantages being that these membrane skins are light, comparatively inexpensive and can be folded into small volumes allowing the membrane to be transported and erected easily and quickly.

Shelter systems can be differentiated into two types. Type 1 uses a skeleton as the primary structural system and a mostly soft surface as a secondary structural system. Type 2 uses units or hard shells, where the stiff surface is an integral part of the structure. Both types protect the statue from external loads and climatic influences. In general, shelters are exposed to higher wind loads due to the larger surface compared to a skin. The shelter can be supported on the base of the statue or the ground. As shelters often have only few supports, the support forces are high. This affects the preservation of the historical monument as a whole, which demands the design of reversible fixing solutions or the reduction of permanent fixing points to a minimum.

Until recently and for most applications, the protective climatic requirements for shelter systems were of lesser importance. Often, shelters fulfilled only the requirement of water tightness. Generally, shelter systems provide more freedom in optimising the internal environment of an enclosure by using insulated materials or multifunctional elements like sandwich constructions.

Sculpture adapted system

The covering of the marble statues on the Schlossbrücke presents a complex and unique challenge due to their exposition, their dimensions and cultural significance in an urban context. The statues are placed on a base 4.00 m above street level and about 8.00 m above the river Spree. Since their reconstruction in the 1880s, the plinths are no longer monolithic blocks. The plinths now consist of a core made of pre-fabricated concrete elements encased in a curtain wall of marble. The statues themselves are around 4.50 m tall and some suffer from serious stability problems. Most of the statues have very delicate and exposed extremities.

Initial design concepts (Fig. 22) struggled to satisfy all the design constraints. The use of a skin would enlarge the area of the statue exposed to wind loads resulting in magnified stability problems. Shelter-based design concepts proved unfeasible as the shelters may not be fixed to the plinth.

Stable and usable support surfaces for the shelter exist only below the plinth and subsequently below street level. On the water side of the statues, sandstone blocks extend underneath the marble plinths, which can be used for anchoring structural supports. A further anchor point is available on the street side at the pedestrian level; however, an expansion of the covering system into this strongly frequented public area leads to functional and also aesthetic deficits. A support on the pavement was therefore eliminated.

The constraints described above result in a 9 m high structure, which must be installed below street level and from the water side. The use of technical aids (such as a crane) is therefore indispensable.

Concept of the covering system

The shelters can be developed for individual geometric requirements of each statue or as an overall solution for all statues. Individualised solutions would facilitate the minimisation of exterior surfaces and resulting wind loads. A single shelter solution for all statues would result in a larger design but batch production will incur lower costs.

Choosing between an individual and overall solution depends on the geometry of the statues. A study of the statue geometry shows that despite the different motives, the dimensions and proportions of all figures are very

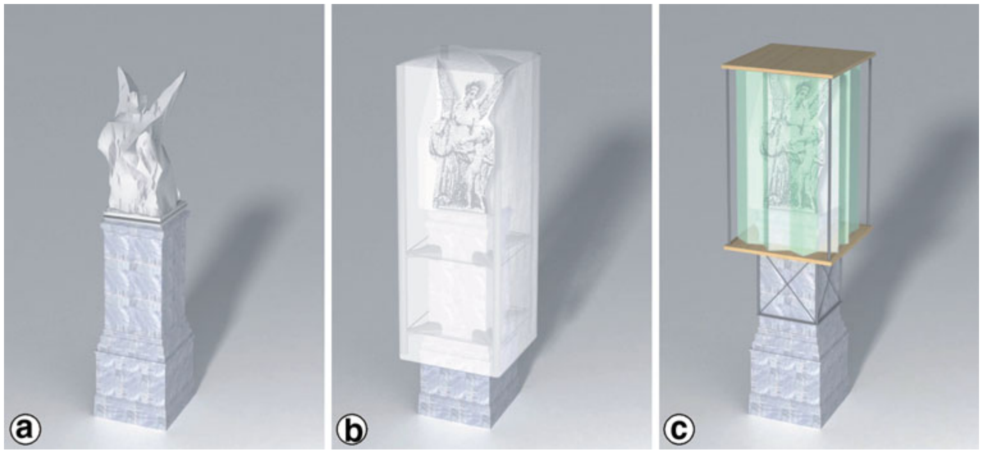

Fig. 22 Different design concepts: **a** soft skin stabilised by underpressure, **b** stiff framework with soft surface and **c** stiff modular surface

similar. Individual solutions for all figures would therefore result in only small deviations and would not reduce the wind loads significantly. On account of this, an overall solution was developed for the statues on the "Schlossbrücke" bridge.

In order to facilitate the development of a generalised covering system, basic 3D geometric profiles of the statues were compiled and superimposed with one another to serve as reference geometry data. The generated superposition does not identify any primary orientation. The cross section of the figures in plan is slightly larger than the upper surface of the plinth.

The geometric constraints, used in developing the covers, were defined by adding a buffer offset to the superimposed 3D profiles. In order to evaluate what impact the cover's cross sectional profile (in plan) has on design and wind resistance, a variety of sections were examined (namely square, polygonal and circular).

On the grounds of aesthetic and climatic design, an early decision saw the extension of the cover to a height below that of the foot of the statue. Another major design decision was the selection of a conical form as a preferred shape for the cover system. The selection is justified by three structural advantages: primarily, the conical form facilitates a constant geometrical transition from the larger figure to the smaller base. Subsequently and secondly, the dead weight and the wind forces are minimised where possible. Third, the buffer offset between the cover and statue is suitably largest at the top of the cone where deflections are also the biggest.

Analysing wind forces to different section profiles shows that a circular section results in the smallest wind resistance and only a very small stress factor (Fig. 23). A further advantage of the circular section is the continuous curvature for the use of a mechanically pre-stressed membrane.

Method of assembly

The method of assembly and disassembly of the statue covers is governed by the following conditions: (i) the assembly and disassembly takes place ever year, (ii) the assembly and disassembly must be achieved simply and quickly with minimal technical aids (i.e. machinery) and (iii) while the statues' plinths are reasonably resistant to light bumps and scrapes during the erection process, the statues themselves are fragile and can be damaged easily. The last constraint is particularly important for the assembly and disassembly of the statue covers. Gaining precise control over the movement of all components of a 9 m high structure during its erection is extremely demanding, all the more so, because of restricted accessibility to the statues on the bridge.

In order to guard against the risks of potential movement of the structure or parts of it during assembly, there are two basic solutions: (i) to select a large structural footprint with sufficient tolerances for movements and deformations and (ii) to remotely control the assembly of the structure and thereby gaining precise control of the kinematic system. The first solution leads to large dimensions and subsequently heavy parts, which makes assembly and disassembly unfeasible. For this reason, a remotely controlled system was investigated and developed as a solution to the assembly and disassembly problem. The proposed solution is a two-step process. The first step involves mounting and assembling all the components and component groups onto the anchor points and to each other, during which large movements can be expected. The second step involves erecting the kinematic system to its final position through application of external loads. As such, any movements are a direct result of the (controllable) kinematic system.

The basic concept of the remotely controlled solution is to isolate all manual assembly processes within the lower

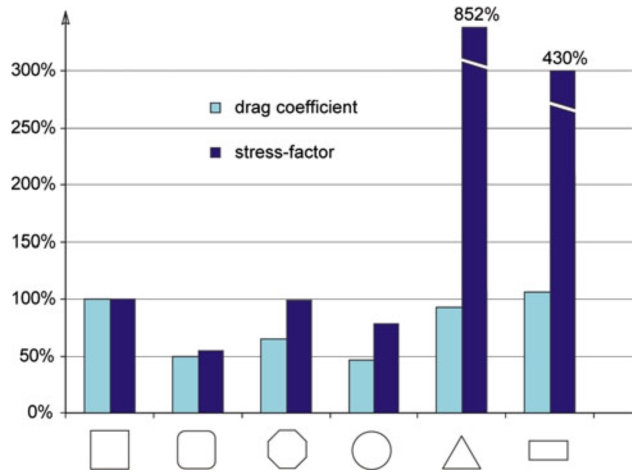

Fig. 23 Drag coefficient and stress factor (drag coefficient/section modulus) of different geometries

and more robust plinth base, where damage cannot be so easily incurred. Then the structure can be assembled upwards encasing the statue from below. Finally a lid is craned into position to close the system from above. Mounting the lid from above poses a low risk since the fragile statue is already encased and protected at this point.

Kinematic system

The proposed kinematic system can be basically represented by two pin-jointed members that connect upper and lower ring beams. An applied force is required in order to induce movement in the system. This force should be applied vertically and directly between the ring bars. Such a force can be achieved using hydraulic pistons or a rack and pinion system. In order to prevent an uneven erection, the force application must be controlled by an electronic or visual feedback system.

Only vertical members, and not diagonal members, can be used for the kinematic system. If the diagonal members are used in the erection process, they would induce horizontal reaction loads resulting in tangential rotation of the upper ring. Therefore, only vertical members are to be used to stabilise the kinematic system, whereas tensile diagonal members (cables) will be used to stiffen the static system. Pre-stressing the cables and membrane can be carried out by the erection. In order to complete the transformation from a kinematic system to a static one, the articulated joints in the middle of the vertical members must be made rigid.

Assembly steps

The final housing system is comprised of aluminium truss members, which will be pre-fabricated into a set of units for assembly (each of which weighs no more than 80 kg, Table 3). The structure would double in weight if it were made out of steel. Therefore, a crane would be required for the assembly of a steel version.

The complete assembling process consists of four main steps (Fig. 24).

Step 1 All three pre-fabricated V-columns are to be mounted onto the anchor points and bolted to one another. The first V-column requires a temporary support during construction. The second and third V-columns will be stabilised by the first and second columns, respectively. When all three V-columns have been mounted, the system will be statically determinate and the temporary support can be removed.

Step 2 The three ring elements (each split into two halves) are to be mounted on top of the existing structure. The membranes will be secured to one half of the ring and when the rings are fixed, the membrane can be pulled through into the other half of the ring.

Step 3 The rings are to be erected vertically starting with the bottom ring and ending with the top ring.

Step 4 The fully pre-fabricated lid (with pre-stressed membrane) is to be mounted on top of the existing structure and secured with bolts. The disassembly of the structure is a repeat of the above steps in reverse.

Structure and covering

The shelter can be divided into two structural subsystems. The first subsystem consists of three ring elements and a roof (Fig. 24a). This subsystem is axisymmetric and equal for all statues, and its structural behaviour equates to a shell. The second subsystem consists of V-columns, which statically behave as a framework. The V-columns start at the rectangular plinth and end at the circular ring elements. Due to the irregular balustrade geometry, the V-columns and support points are non-symmetrical and differ for all corner statues and the group of centre statues.

The V-columns are sufficiently adaptable to fulfil the different geometric constraints at every statue. The four

Table 3 Weights of the different covering elements

V-columns	3 elements	176 kg
Weight ring 2	2 elements	111 kg
Weight ring 3	2 elements	108 kg
Weight ring 4	2 elements	105 kg
Weight roof	1 element	79 kg
Total weight		579 kg

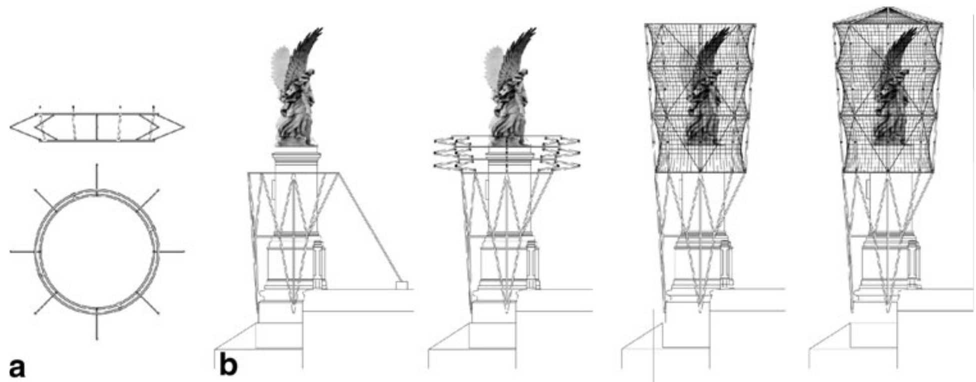

Fig. 24 **a** Kinematic system and **b** concept of erection process of the covering shelter (step 1–4 from *left* to *right*)

shelters in the middle of the bridge have only anchor points on the water side, whereas the corner shelters have anchor points on the water side and on the pedestrian walkway. The difference in height between these points is about 50 cm and leads to additional changes in the geometry of the V-columns. The V-columns are pinned to threaded steel bars, which are cemented into the plinth base. These pins remain permanently.

The structure consists of aluminium hollow sections. The V-columns are intended as round pipes with a diameter of 6 cm, and the ring beams as rectangular cross sections 6 cm × 4 cm.

The covering of the structure consists of a mechanically pre-stressed membrane. The membrane is stabilised by its two-way curvature to avoid noise by beating and flapping. The geometric design puts the membrane inside of the skeleton structure.

The decisive load case combines dead weight, wind loads and snow loads. This load combination produces a substantial horizontal deformation of up to 12 cm. Due to the asymmetry of the V-columns, the deformations vary around a factor of two depending on the wind direction (Fig. 25).

The influence of geometrical imperfections at the support points was also examined. Differences between the intended and the actual structure geometry can result from inaccuracies during fabrication, deformations caused due to inappropriate storage, transport and assembly and deviations in plinth geometry. The imperfections can be minimised but not avoided completely. A deviation of 2.5 cm at one support point leads to additional stresses of 10%, and a deviation of 5 cm to additional stresses of 25%. These distances are small in relation to the total height of 9 m, and therefore the geometrical imperfections must be considered.

Proper handling, transportation and assembly of the components must be carried out in order to avoid causing further imperfections as much as possible. An examination of accuracy to size at regular time intervals can offer sufficient security. Since imperfections in mobile structures cannot be avoided completely, the dimensions of the structure have been calculated with appropriate reserves.

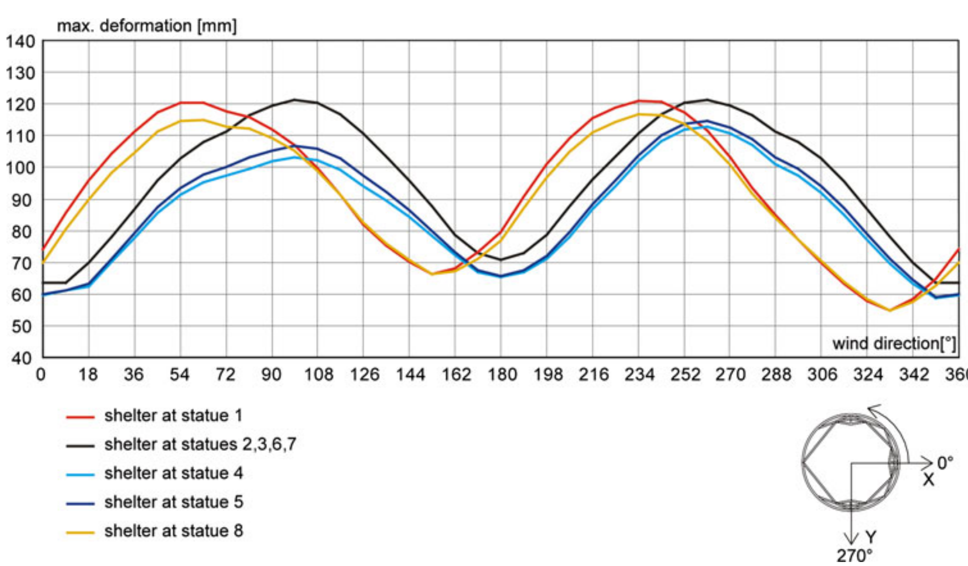

Fig. 25 Deformation of the different shelters depending on the wind direction

Discussion and summary

The investigation presented in this paper deals with a culturally and historically significant group of valuable sculptures made from Carrara marble and displayed in an urban environment. Conservation of cultural assets constructed from natural stones requires regular inspection and maintenance as an effective instrument in preventive monument preservation. Winter coverings are part of the conservation procedures for exposed monuments and consist of highly complex systems. These systems have to be adapted to the climatic conditions, the structural and technical circumstances and the material properties of the statues as well as being applied in a practical way. Moreover, the inventory and restoration history needs to be taken into consideration in regards to the decade's long use of preserving agents, because these can change the nature of the original material as well as the technical/physical properties. The importance and central location of the Schlossbrücke in the periphery of the world heritage site known as the Museum Island, requires a constructive as well as aesthetic and sophisticated assembly for covering these valuable bridge sculptures.

The design demands for the Schlossbrücke winter covers were particularly challenging. The geometry of the sculptures, the balustrades and the side walls differs from figure to figure, requiring each winter cover to be customised, respectively. Structural elements of a shelter system may not be fixed to the marble plinth directly below the figures, but instead must extend 4 m further down to the sandstone base. The structure is subsequently 9 m high and so the assembly, which must be carried out above water, presents a significant challenge. Furthermore, the statues are particularly delicate and could therefore be easily damaged with incautious assembly.

The proposed shelter system has been developed to satisfy requirements for aesthetic design, structural stability and protection of the sculptures (Fig. 26). The structure is sufficiently adaptable to meet the varying geometric constraints at each figure, while maximising component standardisation. Assembly of the aluminium framework and pre-stressed membrane has low-tech demands. The use of a remotely controlled system will facilitate precise erection with high geometric tolerances.

The general requirements for winter covers of outdoor stone statuary are to provide protection against external environmental factors (liquid water, humidity, solar irradiation, frost, strong variations in surface temperatures), chemical factors (acid pollutants, salt damage) and biological factors (invasive flora and fauna). As well as providing sufficient environmental protection, the winter covers must also satisfy further demands on aesthetic performance, structural stability and for transportation, safe assembly and storage. Since some of these constraints conflict with one another, the winter cover cannot satisfy all the demands simultaneously. Instead, a balanced solution must be found by prioritising the criteria.

The climate data presented on some examples are a valuable basis for numerical simulations, for the assessment of protective winter covers and their effect on the microclimate at the sculptures. The data have been collected on sculptures exposed to the weather and on

Fig. 26 View of the shelter systems from the street and river

sculptures inside two different protective covers. By means of these measurements, the influence of the covers on the microclimate near the sculptures can be shown.

The collected data show that the temperature of the sculptures is determined mainly by the temperature of the ambient air. The influence of direct sunlight on the surface temperature is relatively low. Due to the high thermal conductivity, the temperature gradient inside the material is small. A fast drop of the surface temperature can be caused by sudden rain in summer.

Due to the wide openings of the studied covers, no significant difference between the inside and the outside air temperature has been measured. However, the effect of shading and the lower wind speed causes the surface temperature of the massive parts of the sculpture within the cover to show smaller temperature peaks than the surface temperature of weathered sculptures. Besides the protection against the rain, the membrane cover reduces the infiltration of water by dew. This effect might be increased by closing and sealing the cover completely. Furthermore, to avoid the accumulation of dust deposits the cover should remain closed.

The measurements will be continued even when the project is finished in October 2010. An additional measurement system will be installed at a sculpture that will be covered by a new protective system in October 2010. Meanwhile, numerous simulations of the marble and the protective systems have been carried out.

Induced by the climatic conditions at the "Schlossbrücke - Unter der Linden" the exposed marble sculptures become moistened to a penetration depth of 200 mm. Thus, the smaller parts, e.g. legs, arms, head and wing, can become completely moistened. During the spring and summer, the marble can dry completely. Thin and filigree parts of the sculpture have large surface areas, e.g. the feathers of wings will completely dry out and then become completely wet again. Therefore, these sculpture parts are subjected to extreme climatic loads.

Wooden winter housing always brings protection from rainstorms, but there are some other aspects to pay attention too. While airtight wooden protective systems and small air exchanges keeps the marble dry, a large air exchange leads to a wetting caused by condensation. The load by condensation can be very similar in magnitude as from a heavy rain. Membrane winter covers can be an efficient means for protection against downpours, but analogous to wooden housing the ventilation rate can moisten the marble. The moisture balance of the sculpture is a complex relationship between temperature, relative humidity and acting climatic conditions as well. The exchange of air can lead to both a drying potential as well as to a dampening of the marble.

Moisture distribution in different parts of the sculpture, e.g. body, leg, arm, head, wing, is very complex. A climatic change can produce a slight load in the torso part but results in a strong load in the filigree sculpture parts. Thus, one has to define priorities of the sculpture and to optimise them.

The investigations on membrane materials for winter covers have shown positive effects when they are used as a type of insulating membrane. The usage of a double layered membrane, e.g. bubble membrane, could further support the insulation effect.

The numerical results also make clear that the air exchange should be reduced. During the cold months, air circulation leads to moistening. On the other hand, a controlled air exchange can support the drying of the sculpture. This leads to an improvement of a protective winter housing and creates a climate-controlled air circulation.

From a geoscientific point of view, marbles represent a very special building stone, because they show positive and negative properties (e.g. translucent appearance, workability, weathering behaviour, etc.). The extreme anisotropic dilatation behaviour of calcite and dolomite single crystals especially leads to stresses in the rock fabric during changes in temperature, which results in an initial microcracking. Moisture is considered to be a key parameter concerning the marble decay process (Schouenborg et al. 2000, 2003) and can lead to unlimited residual expansion of certain marble types. Many authors (e.g. Sage 1988; Siegesmund et al. 2000; Ruedrich 2003) have demonstrated that the increase of residual strain stops after a few heating cycles if moisture is absent. To discuss these effects in more detail, Koch and Siegesmund (2004) performed measurements of progressive residual strain of different marbles under slightly different conditions (Fig. 27). Eight dry cycles up to 90°C were followed by 25 additional wet cycles altogether, whereby the first six wet cycles were carried out in a way that at the end of a heating cycle the

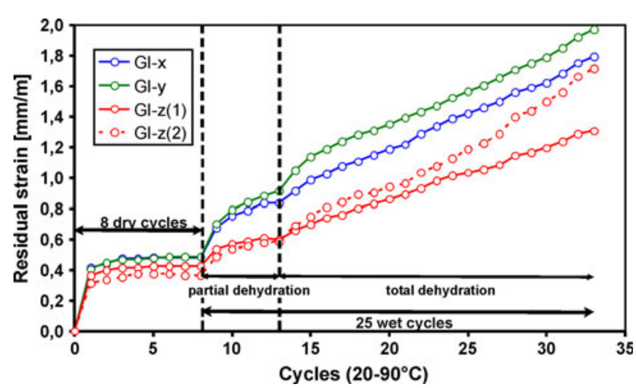

Fig. 27 Progressive increase of residual strain of a Carrara marble as a function of the number of heating cycles under dry (cycles 1–8) and wet (cycles 8–33) conditions. From cycles 8–14, the samples remain humid; from cycle 14 samples run dry after each cycle. The colours of the *curves* indicate different directions of the sample reference system

samples in the climate chamber remained slightly humid but still in contact with water. In the following 19 cycles, the samples were run until totally dry. The findings from this approach are: (i) the progressive residual strain indeed proceeds continuously; the increase is constant even after 25 cycles under wet conditions and (ii) the moisture content after a heating cycle apparently influences the intensity of marble degradation. The strain versus cycles curve (Fig. 27) tends to get flat as long as water is still available during the test cycles. As soon as samples totally dry up after each heating cycle, the durable marble expansion accelerates again.

The thermal expansion behaviour in Fig. 5f also shows a progressive increase of residual strain by freezing marble samples under wet conditions. For freezing under dry sample conditions, no further residual strain occurs. Thus, the decay behaviour for heating as well as for cooling is more or less the same. Accordingly, the worst scenario will be drying during temperature changes. Although the decay magnitude induced by the heating process seems to be more important, the winter period should also cause progressive fabric decay. Consequently, for a winter cover the moisture content should only show a slight variation in range. Situations of drying/wetting induced by ventilation and condensation processes should be avoided from a material point of view.

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