Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Tests on Gothic Sandstone Pinnacles Subjected to a Combined Climatic Load

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ABSTRACT: This paper presents a study of combined climatic effects on sandstone by modeling the action of wind driving rain on aged stone statues. The exposure of two samples (a bare sandstone statue and a statue protected by a chemical treatment) to the combined effect of rain, wind and low temperature cycles in a climatic wind tunnel aimed to model accelerated exposure to natural climatic actions and carry out pilot investigations into experimental techniques applicable for similar studies, Drdácký et al. (2005).

1 INTRODUCTION

An experimental investigation of real Gothic sandstone pinnacles was carried out in the Jules Verne climatic wind tunnel in Nantes (France)* from June 22nd till June 25th 2004. This experimental facility is unique in Europe, and is used for studies of the influence of combined climatic factors that are typical of real situations. Most of the work at the facility focuses on testing building structures, structural elements and means of transport.

Whereas the isolated action of individual climatic factors, e.g. temperature, solar radiation, precipitation, humidity, snow, mist, etc., on a range of materials has been quite well described and is well known, the effects of combining them with wind has not been sufficiently investigated. Moreover, much earlier work has been done on modern technical materials rather than on authentic historic materials. Therefore, a unique opportunity to research the behaviour of historic materials subjected to combined climatic loads was exploited within the ARI (Access to Research Infrastructure) international programme.

Gothic pinnacles from one of the most important late medieval Gothic churches, St. Barbara's in Kutná Hora (Bohemia), were exposed in the wind tunnel for a period of four days in order to test the efficiency of a water repellent (hydrophobic) surface coating. A study was made of the influence of wind on the penetration of rainwater into the stone elements. Temperature and humidity changes on the surface and inside the stone elements were also measured in various climatic situations modelled in the wind tunnel.

Two authentic pinnacles made from typical local Kutná Hora calcareous sandstone were tested. Due to their advanced deterioration, they were dismantled in the course of restoration of the church, and were replaced by replicas cut from new stone. The two elements originally stood on the southern façade of the church, on the first and second buttresses. Their deterioration had been caused by both physical and chemical corrosion processes. Because of the position of the two elements on the southern side of the church, it is likely that their severe deterioration was due to a combination of weathering effects and, above all, temperature fluctuations and cyclically changing gradients inside the volume of the elements under study. Moreover, the stone is very sensitive to sulphur oxides and carbon dioxide, and both of these gases contributed

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substantially to the degradation of the material, above all the loss and transformation of the carbonate components of the rock as a result of the chemical material changes in the surface layers, and changes in the physical characteristics of the rock. The chemical corrosion of stone is further affected by water acting both as a reaction medium and as a transport medium. The penetration of water into the material, drying out, mechanical damage due to frost, crystallization of new minerals or severe temperature and moisture changes pose crucial problems from the degradation point of view, and are considered to be worth studying under real or simulated conditions. The climatic wind tunnel provided an opportunity to acquire new data for use in practical applications in the conservation and protection of historically or artistically valuable artifacts.

2 EXPERIMENTAL SET-UP AND METHODOLOGY

2.1 Test specimens

Two geometrically different sets of samples made from different materials were tested. Comparative tests were carried out on small cubes of dimensions 50 × 50 × 50 mm made of burnt clay bricks, quartzose sandstone, opuka and travertine, which are materials frequently used in historic structures and sculptures, and also on prismatic samples of various types of lime and pozzolanic mortars. Opuka is a Czech name for a rock of marlite or argillite type, with very variable composition and characteristics, which makes it difficult to translate into other languages. The following are considered to be correct English terms: cretaceous marly limestone, arenaceous marl, cretaceous spongillite, calcitic spongilite, argillite, while some authors use the terms marlstone or clay marl, which others do not consider correct. Therefore we prefer the Czech term “opuka” which is a typical name for Central Europe (opóka in Polish). The German equivalents are Flammenmergel, Schwammflistein, Ambergere Tripple, and the French terms are spongolit or gaize. One series of cubes was protected by a paint made of water repellent material (hydrophobic organo-siliceous paint), while the second group of cubes was left unprotected. All were fresh materials.

For the study of a historic material, we used the pinnacles mentioned above. Their shape is shown in Fig. 2, and the characteristic dimensions of the all-stone pinnacle and the second pinnacle with an iron rod on the top were, respectively: height – 1290 mm and 870 mm, base - 300 × 300 mm (cornice 450 × 450 mm) for both pinnacles, top – 70 × 70 mm and 130 × 130 mm, respectively. The cross flower had had a base of about 560 × 560 mm before damage and was about 170 mm in thickness. The all-stone pinnacle (F1) was restored before the tests in the way that had been used for the restoration of St. Barbara’s Church. After careful cleaning, the stone was locally solidified by means of an organo-siliceous injection (IFEST OH), the damaged parts and cracks were filled either with white cement based mortar or with mastic bound by a silicic (acid) ester agent, and finally the whole surface was covered with the hydrophobic organo-siliceous agent (IMESTA IW 290). The second pinnacle (F2) was left in its original state without any conservation intervention.

2.2 Experimental facility, loading conditions and measurements

The tests were carried out in the Jules Verne Climatic Wind Tunnel, run by the Aérodynamique et Environnement Climatique (AEC) Department of the Centre Scientifique et Technique du Batiment (CSTB), which aims to develop the physical knowledge and understanding of the influence of wind and other climatic parameters on buildings, structure elements, industrial equipment and vehicles.

One of the strengths of the facility is the opportunity to simulate and fully control the combinations of climatic parameters to perform tests on a full scale basis, which is often the only relevant experimental scale. In order to offer the widest range of simulation possibilities, two different circuits were built, Fig. 1: The external ring, called the dynamic circuit (or unit), enables the user to reproduce the spatial and temporal evolution of natural wind up to an average of 100 km/h in the environmental test section (5). The modelled air flow can be associated with rain (up to 250 mm/h) or sand storms (the sand concentration can reach 10 g/m^3 in a 10 m^2 section). The highest air flow speed of 280 km/h is reached in the cyclonic test section (1) when the section is reduced to 26 m^2. The equipment in this test section includes a six component balance associated to a turntable and a boundary layer trap. The total power of the adjustable pitch fan is 3200 kW. The internal ring, called the thermal circuit (or unit), can reproduce thermal ambiances from -25 °C to +50 °C and relative humidity from 30% to 100% in the test chamber, the cross section of which is 70 m^2. According to the section of the adjustable nozzle (13), the maximum air flow speed can be set from 90 km/h to 140 km/h. Snow guns are used to produce a thick snow mantle (15 cm/h) on the 200 m^2 floor of the test chamber. The snow quality related to the snow water content is adjustable. Other climatic parameters, e.g., frost, fog, hail and solar radiation can be reproduced. A roller bench (250 kW) with its rotating speed linked to the wind speed, and a burnt gas extractor, are used for automotive testing. The total electrical power necessary to run the thermal unit is 3000 kW, of which 1000 kW is for the fan and 2000 kW for the cooling system.

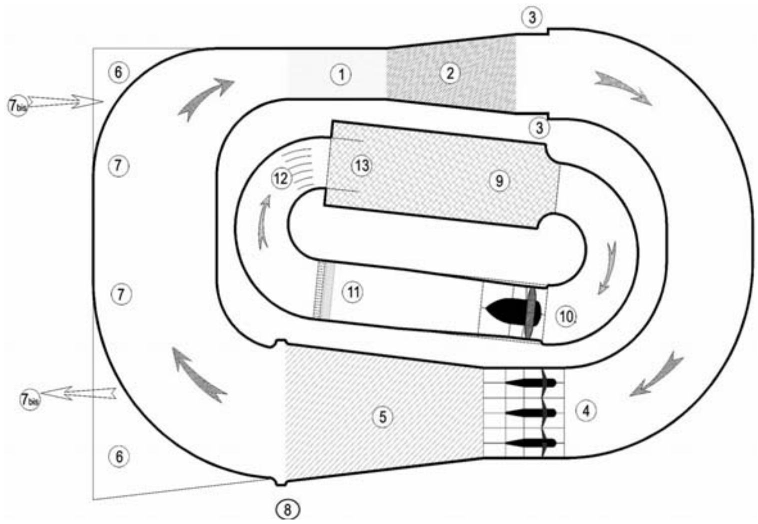

Figure 1 : Layout of the Jules Verne climatic wind tunnel at CSTB Nantes.

The internal ring was used for the investigations described above. During the tests, several combinations of climatic loading factors were applied. These combinations included temperature, rain and wind speed. The temperature was either kept constant at 5 °C or it cycled between +5 °C and -5 °C. The rain was introduced into the airflow up-stream in the test section by a rain system consisting of five pipes. Seventeen calibrated rain nozzles were fitted on the pipes. According to the wind speed settings, the water pressure was set to a defined value in order to produce visually uniform water spreading in the test section. When the test conditions were stabilised, the total water flow was measured. Only two wind velocities were utilized: 5 ms^{-1} and 10 ms^{-1}.

The pinnacles under test were placed in the middle of the test section. The pinnacle being weighed was fitted on the stand designed by CSTB, while the other was placed beside it, as were the small samples of various materials, Fig. 2. During the climatic exposure of the specimens, the temperature and humidity inside the stone were continuously measured by means of one NiCr thermocouple and two Ahlborn FHA 6461 combined temperature/relative humidity sensors. These contain a capacity RH sensor with a span of 0-100 % of RH and accuracy 2 % RH and an N-type Ntc temperature sensor with accuracy of 0.1 °C in the range from -20 °C to +80 °C. Sensor 1 was immersed into the cross flower approximately 30 mm below the surface, and its role was to measure the temperature/humidity changes in a subtle part of the stone pinnacle, Fig. 3. Sensors 2 and 3 were embedded into the central truncated pyramid of the pinnacle towards the wind flow, and measured changes in depth of 50 mm and 100 mm, respectively. The holes which accommodated the sensors were on the pyramid drilled horizontally from the surface protected against wind and wind driven rain (sensors 2 and 3), on the flower vertically from the bottom up, which again protected the sensor from direct rain impact. The data was read and recorded by means of an ALMEMO 2290-8 data logger.

Figure 2 : Specimens prepared for tests in the wind tunnel.

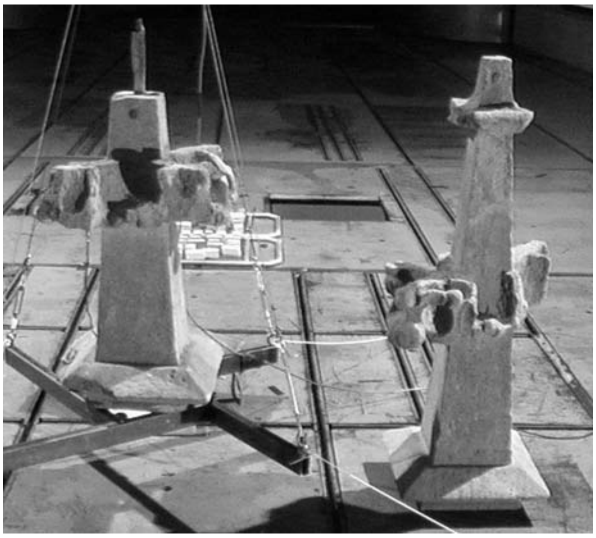

Figure 3 : Positions of sensors.

The temperature on the surface of the stone during the „accelerated life cycles“ was measured by IR thermovision with very high sensitivity, which helped in understanding the dynamics of the thermal changes on the surface.

The weight of the pinnacles was measured during weathering cycles by means of a special hanging balance designed and prepared for the purpose of the tests. The water sorption on the small samples (cubes) was also checked by weighing. For easy orientation, the windward side was marked with a red spot.

3 EXPERIMENTAL RESULTS

3.1 Water sorption of small samples cut from fresh stone

The results of the tests on small samples are summarized in Fig. 4. Stone, brick and mortar samples – protected by water repellent and unprotected – were exposed to repeated wind driven rain (intensity of the rain: 55 mmh^{-1}, wind: 10 ms^{-1}, duration of the first period: 60 minutes, duration of the second period: 135 min. For comparison, we include the absorptiveness of the individual specimens measured by immersion in water before hydrophobic treatment.

3.2 Water penetration into the Gothic pinnacle samples

The surface of the Gothic pinnacles has natural water repellent characteristics that are much higher than those of fresh stone. Some complementary tests were carried out in our laboratories, where the water sorption and wettability were measured by means of Karsten tubes. According to the assumptions, the water absorptiveness of the treated pinnacles was zero during 5 minute measurements. The wetting property investigation proved that the water repellent treatment is not continuous and some parts have water-receptive (hydrophilic) features. This was well apparent on the thermograms after rain or on the pictures with rain water visibility agents. This explains the small measured weight increase which also appeared after rain in the case of the treated pinnacle. During the wettability tests, the amount of water adhering to the surface after rain in the form of drops was also estimated, in order to be able to correct the weight measurements in the wind tunnel.

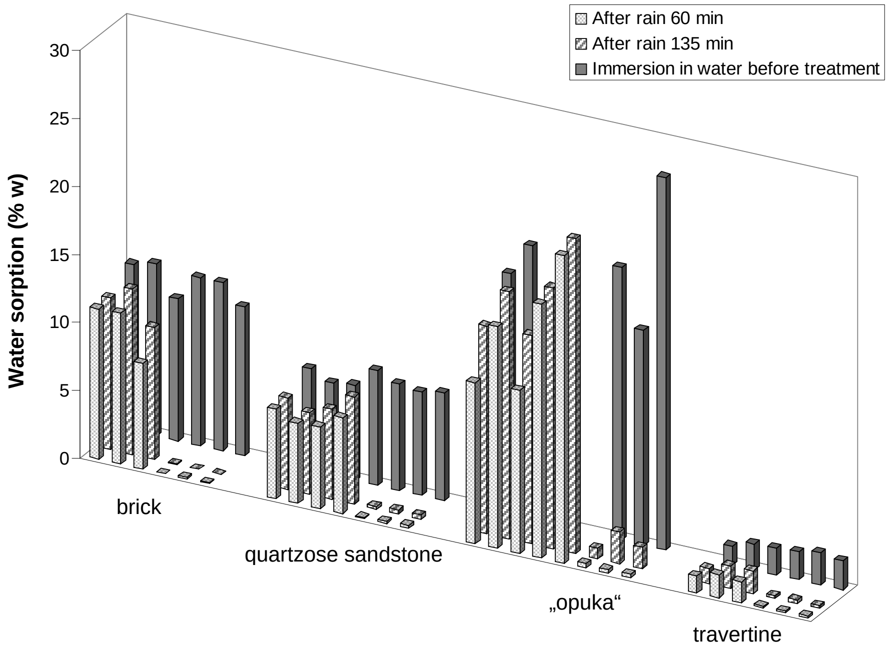

Figure 4 : Windy rain impact on brick and stone samples protected by water repellent and unprotected

On the other hand, the untreated pinnacles also had quite low water absorption measured by means of Karsten tubes. The water absorption coefficient measured after 18 minutes was equal to 0.93 $kgm^{-2}h^{-1}$. This phenomenon explains the relatively low water penetration when winds drives the rain into the untreated pinnacle, and the subsequent small difference between the treated and untreated elements. Of course, the wettability of the untreated pinnacle was much higher than the wettability with hydrophobic paint, Table 1.

Table 1 : Effect of a hydrophobic coating on the original Gothic pinnacles.

Rain driven wind speed of 10 ms^{-1}	**Increase of the weight due to rain (% w)**			Unprotected pinnacle after 115 minutes of rain driven by wind with velocity of 10 ms^{-1} (highly wet parts have light colour).
Rain duration	Unprotected surface	Water repellent protected surface		
60 min	0.92	0.20		
+135 min	1.86	0.82		
+ 60 min	-	0.93		
+ 60 min		0.98		

On a small sample of the historic calcareous sandstone the rate of capillarity was measured, and the value was about 50 mmh^{-1}.

The effect of hydrophobic protection can be well compared in Table 1, which summarizes the weight gains after wind driven rain on treated and untreated pinnacles. The rate of water penetration decreases with the rain duration, due to partial saturation of the pores. It was further observed that water flow along the vertical surface probably has a drag effect, which decreases the capillarity and reduces the wind effect.

It follows that hydrophobic treatment on fresh stone samples (with more open pores) and brick leads to a higher protective effect than the effect on old weathered stone. The ancient stone elements have an apparently “natural” protective layer on their surface, at least in some areas.

The changes in relative humidity measured inside the stone reacted to temperature variations of ± 5 °C, rather than to the moisture content in the stone, and the values were about 3%.

3.3 Surface temperature measurements

Surface temperature changes of the pinnacles were recorded by means of an infrared camera. One example of a sequence of measurements during cyclic change of climatic parameters is given in Fig. 6. This case aimed to study the effects of wind on temperature and moisture content changes in the treated pinnacle after 2 hours of intensive rain.

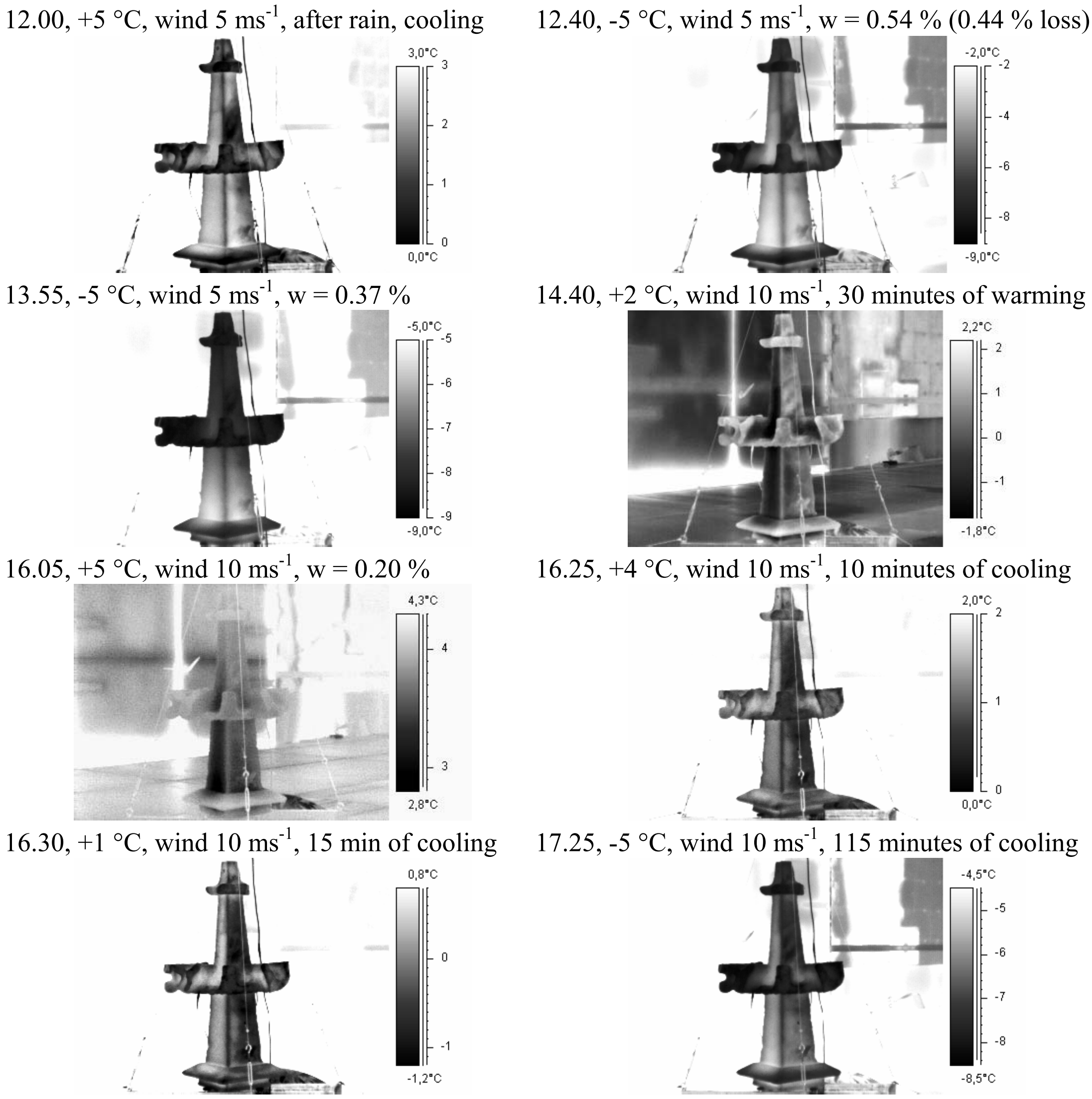

Figure 6 : Surface temperature changes on a previously wetted pinnacle with a hydrophobic coating subjected to cyclic temperature change and simultaneous wind flow.

It follows from Fig. 6 that wind substantially influences both the distribution of surface temperature and the absolute temperature compared to the ambient temperature. Of course, the decrease in the temperature beneath the level of the surrounding air temperature is significantly influenced by the evaporation of water from the wet stone. The mass volume dependent inertia and heat accumulation effects are also clearly shown. These experiments proved that subtle parts of stone elements, especially when wetted, are subjected to more severe temperature differences and related temperature gradients than massive parts, which might lead to the initiation and opening of fissures and cracks, resulting in material damage and degradation.

Infrared measurements of surface temperature can be further utilized for a study of the flows and eddies around complex architectural shapes. Wetting the surface intensifies the measured effect.

3.4 Temperature inside the pinnacles during cyclic climatic loading

An example of temperature variations inside the pinnacles is presented in Fig. 7 for the same cyclic loading as used in Fig. 6. The temperature changes are apparently significantly delayed, dependent on the depth as well as the heat accumulation capacity of the investigated part of the element. Again the temperature inside the subtle cross flower quite rapidly follows the surrounding air temperature.

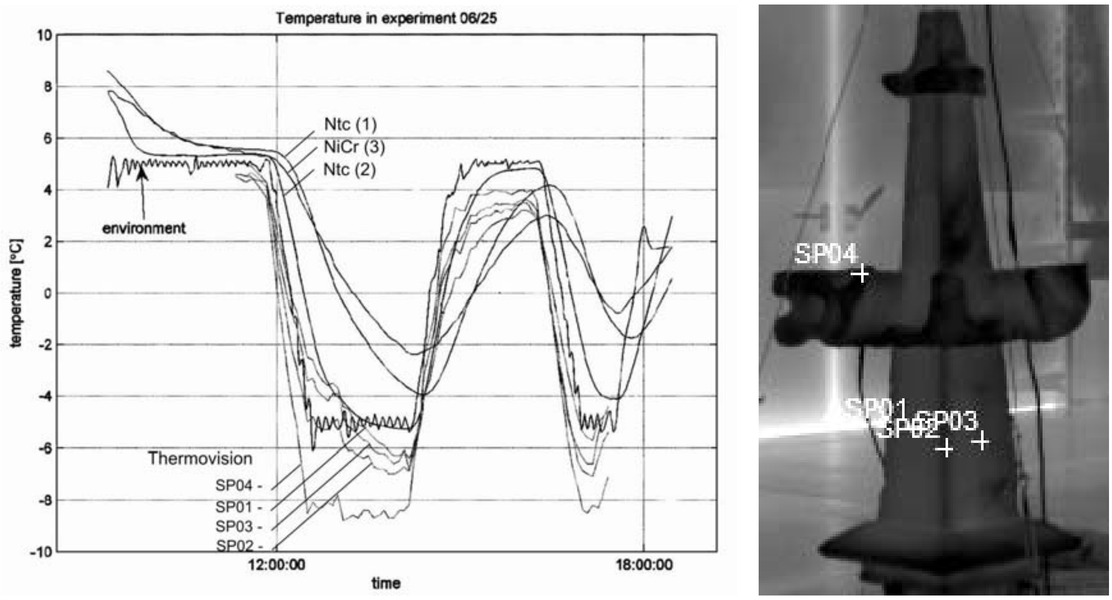

Figure 7 : Differences in surface temperature in the course of surrounding temperature cycle.

When compared to the surface temperature, a much more significant difference and related temperature gradients were identified, Fig. 7 (left). The surface data is taken from the thermovision measurements in the areas near to the sensor measurements, Fig. 7 (right). The real temperature gradients in structures are dependent on the long term conditions of the surroundings of a building. The greatest danger is posed by sudden changes, in many cases accompanied by precipitation, which further increases the damaging mechanisms, especially in stones with moisture-dependent volumetric stability (namely some sandstones).

The Figs. above illustrate the complexity of the problem and the need for more detailed studies on simpler shapes, which can be better mathematically modelled.

The wind tunnel measurements were supplemented by some laboratory tests, in which the temperature change inside a small cube of dry and wet sandstone was investigated during a loading cycle in the range of ± 20 °C. Similar curves and dependencies were measured.

4 CONCLUSIONS

The pilot tests described in the paper were mainly focused on study of temperature and moisture distribution response of a real historical architectural object to climatic action variations. Therefore simple climatic load cycles with limited variation of parameters were applied at the tests. However, the selected temperature and wind variations are quite common in the area from where the tests samples originated. The acquired results will be further used for calibration of a FEM representation of the problem using a geometrical model created on a base of 3D laser measurements, which is beyond the scope of this paper.

The experiments have shown the importance of using a climatic wind tunnel for historically valuable structures, especially concerning „accelerated“ climatic changes, which can be used for calibrating and developing models for numerical calculation.

Temperature changes are very sensitive to the shape of particular details of complex architectural forms. In addition, cooling and evaporation are highly influenced by the wind flow, especially cold wind flow.

Driven rain probably increases the water penetration into the stone only at the beginning of the rain period, and after a certain saturation the surface water flow tends to take away the water that would penetrate the stone.

The moisture content grows by means of infiltration through the stone surface when the ambient temperature increases (high humidity and cold stone surface).

In the case under the discussion, the specimens were treated by IMESTA®IW 290 (water repellent based on oligomeric siloxanes) following a suggestion of the restorers according to their experience with both the type of stone and the protective material. No other material has been tested. The hydrophobic surface coating protects fresh stones very well, if applied compactly on a sufficiently large area of interest. However, protection of the stone surface by applying a water repellent product has a temporary effect only, which is influenced by the qualities of the treated surface, its performance conditions as well as the selected protective product. Moreover, according to the described results, it seems that protecting weathered surfaces does not exhibit significant efficiency, (the weathered surfaces performed low water absorbency even before impregnation by water repellent agent), and therefore its application in the discussed project might be questionable. Further, some coatings even significantly change the deformability and permeability of surface layers, which can lead to severe material and structural damage.

Surface stone temperatures in wind flow can be measured with appropriate accuracy using thermovision, for both dry and wet surfaces. This is because the emissivity of most stone surfaces (0.85 to 0.95) is not very different from the emissivity of water (0.96). Our technique can be advantageously applied for studying the air flow and eddies around complex shapes and forms.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from a European ARI grant, which provided access to the Climatic Tunnel, and the help of colleagues from the Jules Verne Climatic Tunnel in Nantes, especially Dr. Philippe Delpech. The work was further supported by the EC 6th FP grants CULTSTRAT and NOAH’S ARK and the project GACR No.103/06/1609. The evaluation of the sensors was carefully prepared by Jan Bryscejn.

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