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The effects of temperature on historical stone masonry structures

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ABSTRACT: The effects of the environmental temperature on the stone masonry of ancient structures are often taken into account only as far as the weathering of the surface materials is concerned. Instead, this paper focuses on the structural effects that the stresses induced by the thermal strains can have on ancient buildings or parts of them. Analyzing three case studies, the different possible effects of environmental temperature changes over monuments are presented: temperature changes can produce both global effects, mainly in the case of massive structures, and local effects, especially in the contact areas between materials with different thermal behaviours or with different exposure to environmental thermal actions. The solutions to these problems have therefore to be calibrated on the situation encountered.

1 STONES AND TEMPERATURES

The effects of temperature on the stone masonry structures are often neglected, because they are considered minor, with respects to self weight, earthquakes or settlements. Some studies already exist regarding the structural effects of very high temperatures (typically in the case of fires, Chakrabarti et al. 1996) on the strength of stones. Indeed, also lower temperatures can produce negative effects on the building stone materials, not only for its implications for mechanical rock weathering (Inigo & Vicente-Tavera 2002), but also for the formation of major strains and consequent stresses.

In a material like stone masonry, with low tensile strength, even small tractions can give rise to unexpected (and otherwise unexplained) cracks. There are several situations in which this can happen. The most common is the case in which different materials (with different thermal behaviors) are close together: in this case the connection area is often cracked because of these strains. The other case in which these strains can occur is when there are large thermal differences within the structure: this can happen in elements very exposed to thermal variations, with large differences between one part of the structure and the other, or in the case of massive structures, where the slow thermal diffusion causes the different parts of the same structure to be at very different temperatures. Moreover, the thermal actions on historical structures are naturally cyclic and the older the building is, the larger number of cycles it has been subjected to: the fatigue thus enhances the effects of temperature causing plasticization of the material and crack propagation in a way very similar to the one produced by tensional states.

In this contribution, three examples of this phenomenon are presented, referring to three different situations that are particularly meaningful of the different possible effects, both global and local, that environmental temperature can have over monuments and some possible solutions for the different cases are proposed.

2 THE PONT GRAN DUC ADOLPHE IN LUXEMBOURG

2.1 *The situation*

The Pont Gran Duc Adolphe, designed by Paul Séjourné and built between 1900 and 1903, with its 84.65 m of span, is one of the largest arch stone bridges in the world. It is a milestone in the art of construction and the pictures of the construction phases are particularly impressive (Fig. 1).

Each time the bridge underwent controls and inspections, it showed an exceptional quality and an extremely positive structural behaviour: the compression strength of the stone masonry was estimated in 63 MPa and during some tests the maximum deflection of the keystone under full load was only 1.65 mm (Wirion 1953).

In 1961–62 some modifications were carried out to the frame over the arches, creating thermal joints in the concrete slab.

Figure 1. The construction phases of the Adolphe bridge in Luxembourg.

Only recently, during some maintenance works at the beginning of the 1990s, some cracks were noticed in two symmetrical positions:

- longitudinal cracks on the great arches, approximately from the impost up to one third of the span;
- cracks in the central part of the bridge with an inclined direction, as shown in Figure 2.

The "discovering" of these cracks brought some anxiety to the administration and to the public opinion, thus, due to the importance of the bridge, retrofit interventions were immediately carried out, inserting both horizontal and vertical ties inside the masonry, to keep the different parts of the bridge section together. This choice was based on the hypothesis that the origin of the cracks was a structural one. The level of anxiety was so high that it was also proposed to demolish part of the bridge and rebuild it with a concrete core, although the Service des Sites et Monuments Nationaux had some doubts about this hypothesis.

2.2 *Studies and analysis*

A survey and a more accurate study of the cracks, carried out by a group of experts of the University of Parma in cooperation with the Service des Site et Monuments Nationaux, allowed to understand better the real situation:

- the longitudinal cracks, about 1 mm large, are not new, but they appeared very early after the construction, as the corrosion of the stone edges clearly demonstrates;
- the inclined cracks in the central area correspond to the position of the thermal joints realized in 1962 in the concrete slab over the arches.

Moreover, it was observed that also the severe crack pattern over the stone balustrade was mainly localized in correspondence to these joints.

A non linear finite element analysis on the cross section of one main arch clarified that the longitudinal cracks were caused by a normal phenomenon of differential shrinkage for thermal strains inside the great arches (cross section from 1.44 m × 5.32 m in the keystone to 2.16 m × 6.32 m at the impost): the thermal variations at night, particularly in the summer season (when the inside of the masonry is manly warm, and only the outer part gets momentously cold) produce tensile stresses on the surface up to 5 MPa: these tensions are cyclically repeated and are obviously excessive for the stone.

The thermal analysis on a F.E. model of the whole arch has also underlined that the seasonal thermal variations produce at the impost of the arches variations in stresses which are about ten times larger than the ones produced by the larger accidental loads foreseen, and even inverts the bending moments. Thus, this analysis allowed to comprehend the results of the experimental in situ tests carried out by the University of Bruxelles with flat jacks at the end of the summer of 1998 (Didier et al. 2000). Indeed, the tests had shown a stress pattern at the impost of the arches completely different from the one foreseen in the design calculations and obtainable with a normal analysis. Anyway, all the results remained much lower than the values of compression strength of the masonry, thus confirming the perfect stability of the arches.

As far as the inclined cracks are concerned in correspondence with the thermal joints in the central part of the bridge, it was proved the importance of the thermal effects fostered by the strain concentrations due to the thermal joint that have been introduced in the concrete slab but, obviously, not in the remaining part of the bridge.

In the same way, the cracks on the stone balustrade (with a continuous concrete core also straddle the thermal joints!) have been caused by the thermal variations.

The upgrade and strengthening interventions realized in the past, non considering or wrongly considering the consequences of thermal variations, brought at the end to worsen the situation of this great construction, causing the appearance of many new cracks.

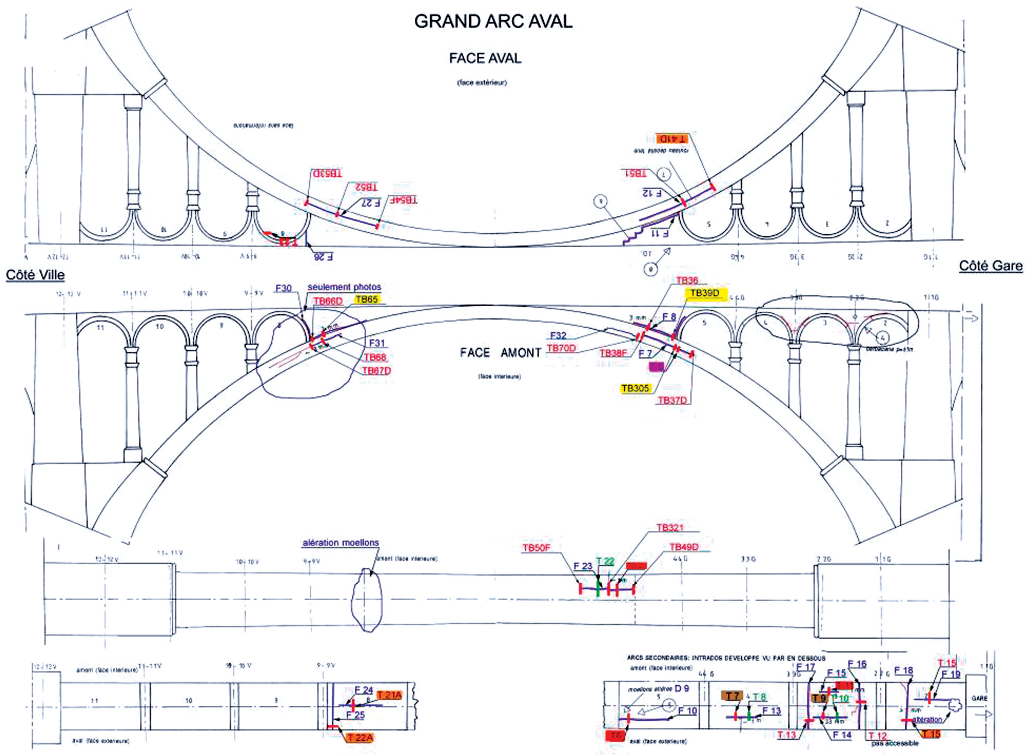

Figure 2. The cracks survey (Adm. des Ponts et Chausses).

3 THE OUTER DOME OF THE FRENCH PANTHEON

3.1 *The situation*

The French Panthéon, designed by Soufflot and completed by Rondelet at the end of the XVIII century, has three superimposed domes (Fig. 3): an inner one, hemispherical and with a central hole, has only a scenographic purpose, an intermediate one, with a catenary section, sustains the lantern, and an outer one for protection. They are all made of stone masonry reinforced with the widespread use of iron clamps.

The outer dome, probably designed looking at the shape of the wooden dome of Saint Paul in London, is very light, as it has the only purpose of protecting and covering the inner space: the thickness is just 25 cm over a diameter of 28 m, with some larger stiffening ribs. Externally, it is covered by a layer of lead.

The area that shows more frequently fractures and detachment of stone fragments is the one at the intersection between the intermediate and the outer dome, where the lantern begins (Fig. 4).

At first, it was thought that the cracks were caused by shear stresses between the two domes, due to the

Figure 3. The model of the three domes of the Panthéon made by Rondelet.

Figure 4. The cracks at the connection between the intermediate and the outer domes.

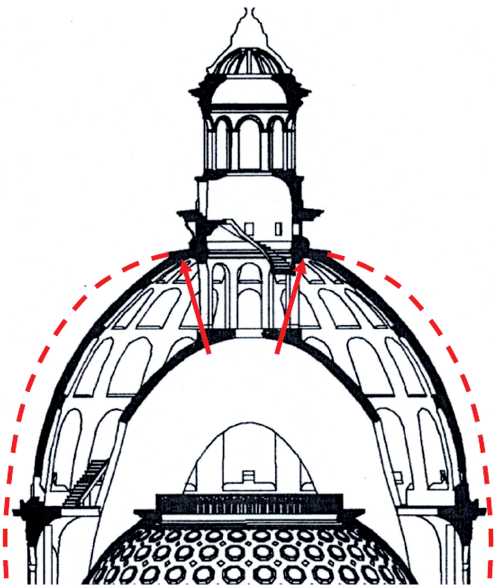

Figure 5. The damage mechanism caused by environmental thermal strains in the domes of the Panthéon.

weight of the lantern that wasn't completely carried by the intermediate dome. It was also proposed to insert a steel structure between the intermediate and the outer dome to sustain the weight of the lantern, but it was never built.

3.2 *Studies and analysis*

Recent measures, carried out under the direction of the architect en chief Daniel Lefèvre, have shown that

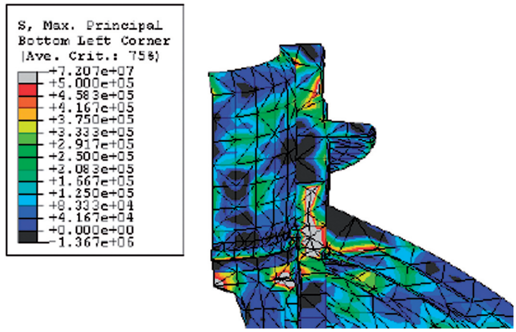

Figure 6. A non linear F.E. analysis evidences the tensile stresses caused by differential thermal deformations between the two domes.

in the gap between lead and stone, temperatures over 60°C can be reached.

It was then clear that these large thermal variations, over both daily and seasonal cycles, can bring to large differential movements between the outer dome and the intermediate one, that is subject to much lower temperature changes than the outer dome, but it is strictly linked to it (Fig. 5).

A thermal analysis on a non linear finite element model in Blasi (2005) has underlined the large tensile stresses that can create in the ring that connects the two domes where the lantern starts, when these large thermal changes occur (Fig. 6). This area is therefore subjected to cyclic tensional stresses, and it corresponds to the areas where regularly new cracks can be seen in the stones, demonstrating the importance of environmental thermal variations on these large monumental buildings.

A first intervention proposed was the insertion of thermal insulation under the lead layer, and the use of more deformable materials in this area subjected to high strains.

The invasive insertion of the new steel structure, at last, was found out to be useless.

4 THE BALUSTRADE ON THE ROOF OF THE CHURCH OF SANTA MARIA DELLA STECCATA IN PARMA

4.1 *The situation*

An interesting local effect due to thermal variations appeared on the stone balustrade built at the end of the XVII century on the crowning of the roof of the Renaissance church of Santa Maria della Steccata in Parma (Fig. 7).

The stones of the upper part of the balustrade showed, indeed, quite surprising upliftings in their central parts, while the lateral pillars on the corners of the balustrade were cracked (Fig. 8).

Figure 7. The church of Santa Maria della Steccata in Parma (Italy) with its balustrade crowning the roof.

Figure 8. One of the statues over the balustrade: notice the iron bar on the back and the gap created between the pillar and the statue base.

Figure 9. The iron bar inserted after the WWII to connect the balustrade and the thick layer of resin inserted after the 1983 earthquake.

4.2 *Studies and analysis*

A very simple thermal analysis, following an attentive in situ inspection, demonstrated that the phenomena were linked to the different thermal strains between the surface stones and a metal bar inserted after the Second World War to retrofit and better connect the structure, hit and damaged by a bomb (Fig. 9).

The restoration intervention, still ongoing, foresees the removal of the metal bar and the creation of joints between the stones, so that the thermal strains will be free, and will not provoke stresses, cracks and disorders on the surrounding elements. Moreover, it is planned to insert connection bars for the statues that hinder the dangerous out of plane movement but allows the in plane movements (Alfieri & Fioretti, 2007).

5 CONCLUSIONS

The three case studies reported exemplify the variety of structural problems that environmental temperature changes can foster in ancient stone masonry buildings. This possible origin for the disorders encountered should always be taken into account.

Particularly, inside massive structures, like the Pont Adolphe in Luxembourg, high differences in temperature caused by slow thermal diffusion can cause unforeseen structural behaviour and crack patterns.

In some other cases, like the French Panthéon, two parts of the same structure, even if made of the same materials, can be exposed to very different environmental temperature, thus causing strains at the interface.

At last, local problems can always be previewed when materials with different thermal behaviours are close together: joints should always be introduced and connections should be designed considering the movements caused by thermal deformations.

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