EVOLUTION OF THE CRACK-PATTERN AS A VISIBLE EFFECT OF LONG TERM DAMAGE

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ABSTRACT

The collapse of some monumental buildings, which have occurred during the last fifteen years, indicate that not only towers, but also particularly slender or heavily loaded elements like columns, pillars, etc., turn out to be greatly influenced by creep deformations, due to their geometry and to the heavy persistent compressive stress which are subjected to. Moreover, the stress distribution within the load-bearing area of these structural elements and buildings is generally non-uniform, due to their non-homogeneous cross section, often made by multiple leaf masonry. A combination of these factors, together with the fatigue effect due to cyclic actions induced by temperature variation, wind and earthquakes action, can well be responsible of very serious structural damage and in some cases even of failure.

Although the collapse of massive buildings (towers, cathedral pillars) happens apparently suddenly, nevertheless crack propagation proved to develop in a relatively long time. This aspect is strictly related to the experimental observation that the volumetric and deviatoric secondary creep strain rate, which is the strain rate during the phase of stable damage growth, proved to be connected with the residual life of the material. This point has important implications on the safety assessment and the reduction of the risks of failure of ancient structures. In fact, the rate of propagation of vertical cracks and the rate of dilation (thickness increase) of load-bearing walls of ancient buildings can be interpreted as significant indicators of the structural conditions and a precocious individuation of their exceeding some limit values is an important index of damage.

INTRODUCTION

The collapse of some monumental buildings, which have occurred during the last fifteen years, enforces the structural analysis for the safety assessment of ancient constructions to take account of specific aspects that were not considered relevant by the traditional stress-strain analysis applied to masonry structures.

Among the factors which are peculiar of ancient masonry structures, there are some that require special attention: the material does not usually respect continuity, homogeneity, isotropy; the wall texture (presence of different layers characterised by different stiffness values) strongly influences the stress and strain distribution. In many cases, the overall dimensions of the structure are considerable; consequently, the stress state due to the dead load has been acting for centuries at high levels, not far from the strength value of the material itself.

In particular, the creep behaviour and the creep-fatigue interaction have proved to strongly influence the mechanical behaviour not only of concrete but also of historic masonry, being responsible of severe damage and often of failure. The failure of monumental buildings is fortunately an exceptional event; nevertheless, when their safety assessment is required, any risk factor that may affect the integrity of the buildings, has to be taken into account. Ancient buildings often show diffused crack patterns, which may be due to different causes in relation to their original function, to their construction technique and to their load history. In many cases it is simply the dead load, usually very high in massive monumental buildings, which plays a major role into the formation and propagation of the crack pattern.

LONG TERM DAMAGE OF ANCIENT MASONRY

The influence of time on the mechanical behaviour of stiff clays, soft rocks, fresh cement mortar, concrete and hardened concrete becomes evident when both uniaxial - triaxial compressive test at different rate of loading and compressive test at vertical constant load are carried out. On the one hand, when testing in compression soft porous materials a decrease of the rate of loading produces a decrease of the vertical peak stress and of the stiffness of the material. On the other hand, if a constant load is applied an increase of deformation develops which is commonly subdivided into three phases: the so-called primary secondary and tertiary creep (Jaeger [1]). The appearance of one or more of these phases and the strain rate of the secondary creep phase depend on the stress level.

After the collapse of the medieval Tower of Pavia, different kinds of uniaxial compressive tests were carried out on the masonry coming from the ruins of the tower, and subsequently also on the masonry sampled from the crypt of the Cathedral of Monza, including monotonic tests, fatigue tests to simulate the effects of the wind (Binda [2]), tests applying unloading reloading cycles (figure 1), creep and pseudo-creep tests.

In figure 1 the results of a pseudo-creep test carried out on the masonry of Monza is shown; creep strain can be clearly observed when the load is kept constant, with the increase of the slope of the strain vs. time diagrams at increasing the stress level (secondary creep strain) and the appearance of tertiary creep during the application of the last load step. In figure 2 the values of the strain rate calculated at the end of each load step, for all prisms tested is shown. An increasing trend is evident after a certain stress level, indicating that the material undergoes mechanical damage; in particular, volumetric strain rate assumes very low values as the stress level approaches failure.

Having assumed positive the vertical deformation corresponding to the shortening of the prism, the horizontal expansions due to fracturing and crack opening are of course negative; a negative volumetric deformation indicates that the effect of the horizontal strains are prevailing on that of the vertical one, therefore an apparent overall dilation is taking place. The creep behaviour is evident since the beginning from the deviatoric strain plots.

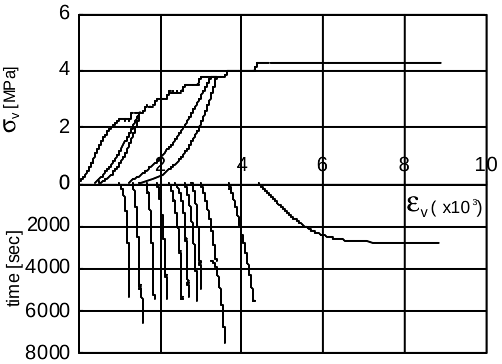


Figure 1: Results of a pseudo-creep test on the masonry of the crypt of Monza

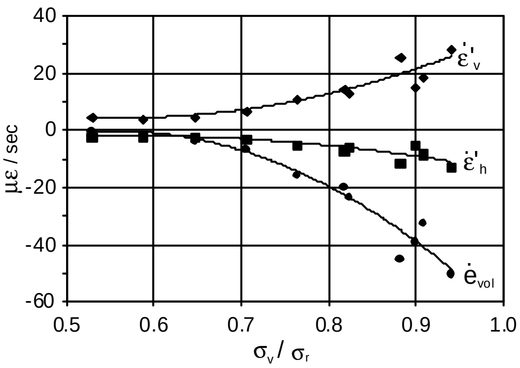


Figure 2: Strain rate of the secondary creep phase in all the samples tested like in fig. 1.

Generally speaking, after a considerable amount of time, and particularly when failure is approached, the decrease of volumetric deformation can only take place through fracturing and crack opening, which appears with great evidence also observing the evolution of the crack pattern. In figure 3 the four faces of a prism subjected to pseudo-creep tests are shown at different stress levels.

The highly irregular texture of the wall is evident, with a great part of the masonry being occupied by mortar. The crack pattern is characterized by the progressive development of vertical and subvertical cracks. In general, the crack pattern is obviously influenced by the stress level, but also by the masonry texture: the presence of rounded stone, like that on face C, forces the crack to go around the stone itself, whereas elsewhere the cracks can more easily cut the bricks.

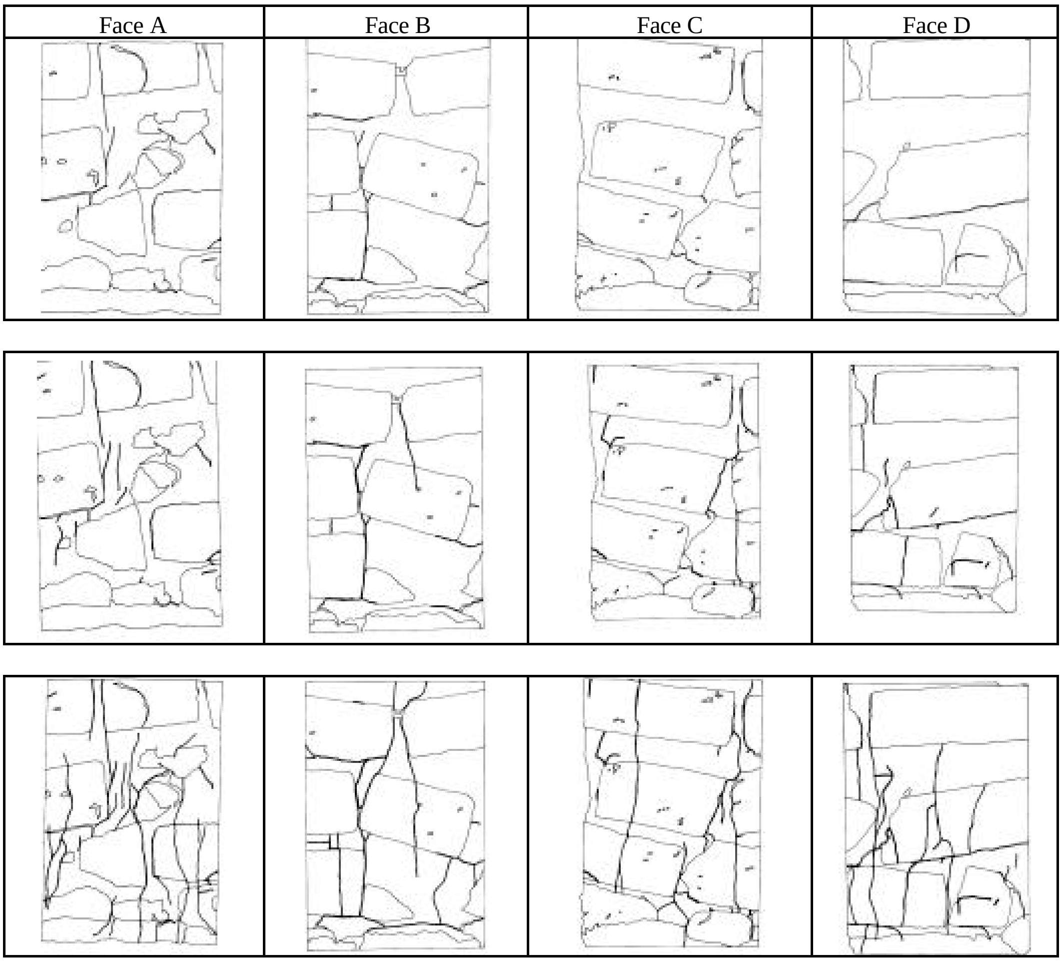


Figure 3; Evolution of the crack pattern during a pseudo-creep compression test on a brickwork masonry specimen sampled from the crypt of the Cathedral of Monza.

Figure 4: Crack pattern through the thickness of the masonry of the Tower of Monza, corresponding to the opening of a door.

The same considerations can be made observing the crack pattern appearing on buildings. The Bell Tower of the Cathedral of Monza is a XVI century building which suffered for an extensive crack pattern, due to compressive stress, and is at present under repair intervention (Binda [3]). Figure 4 shows the crack pattern corresponding to the wall of a passage to the Cathedral, and therefore shows a masonry face on a plane normal to the plane of the tower walls. This corresponds to a severe structural damage indicating the discontinuity of the masonry in its thickness, for a deepness which cannot be known. Again, the crack development follows the weakness zones represented by the mortar joints, and also can cut the bricks vertically.

A different experimental investigation was carried out after the collapse of the Cathedral of Noto, having examined the high non-homogeneity of the pillars, which was one of the weakness factors of the building. Multiple leaf stone specimens were purposely constructed and subjected to shear and compression tests, in order to study the response of the different leaves and of the composite masonry in its complex, again analysing the crack pattern. In figures 5a,b the results of compression tests are shown and in figures 6,7 the crack evolutions recorded during the test are reported, which allow to highlight different aspects of the studied behaviour.

From the diagrams 5a, 5b, in both cases almost coincident vertical strains of both leaves and higher horizontal strains of the inner leaves developed, indicating a good collaboration between the leaves. In the case of the Serena specimen, the peak load could not be attained because it was exceeding the maximum machine capacity. A strength increase was observed in comparison to the strength of the inner leaves tested individually.

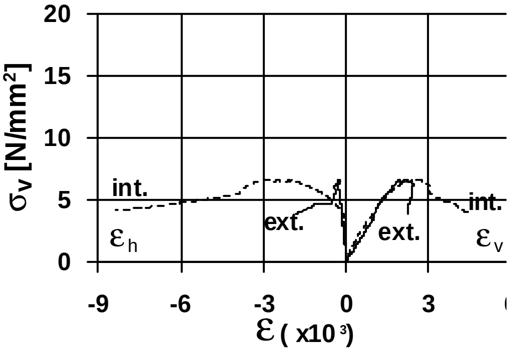


Figure 5a: Results of compression test on a three leaf Noto stone specimen.

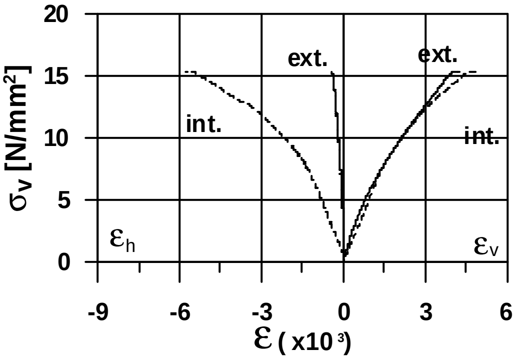


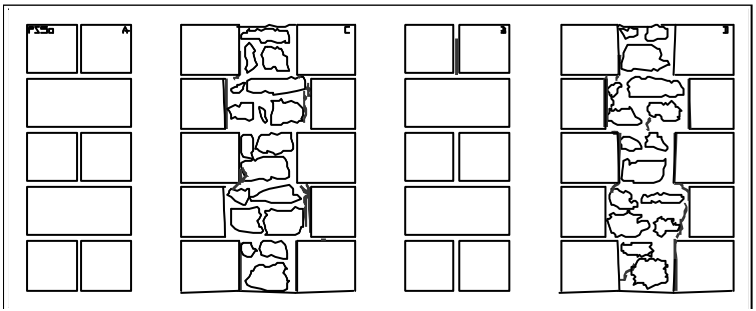
Figure 5b: Results of compression test on a three leaf Serena stone specimen.

In the case of the Serena stone specimens and despite the fact that the peak load was not achieved, the development of some cracks in the inner leaf was observed that, however, went around the stone pebbles without breaking them (see Figure 6). This is due to the fact that the Serena stone presents a higher strength than the Noto stone and also a worse adhesion (due to its lower porosity) toward the mortar.

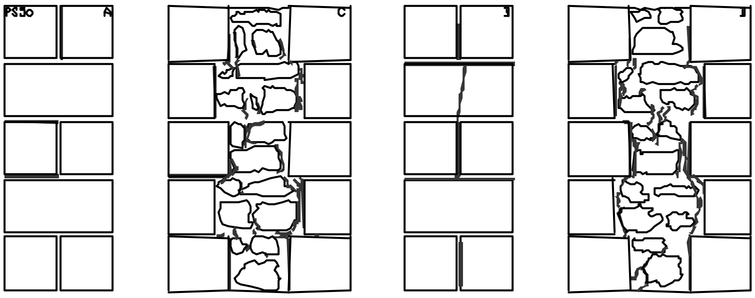
In the case of the Noto stone specimen, the outer leaves presented a severe and diffuse final crack pattern (Figure 7).

Relatively to the inner leaf, several vertical cracks developed near the peak load, some of them splitting the stone pebbles.

An extensive investigation carried out in Sicily allowed to detect other cases of churches, like that of Noto built after the earthquake of 1693, which hit the whole eastern Sicily, presenting similarly serious crack patterns caused by compressive stress states. Figure 8 shows the bases of a pillar of the Church of SS. Crocifisso in Noto, also built in Noto stone, where similar cracks of those shown in figure 7 can be seen (Binda L. [4]).

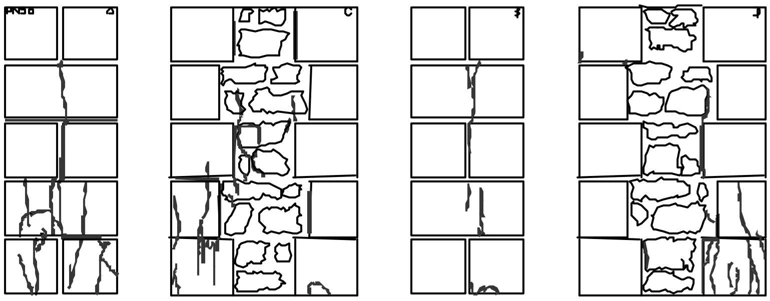


σ_v = 8.5 N/mm^2 55.5 % σ_{max}

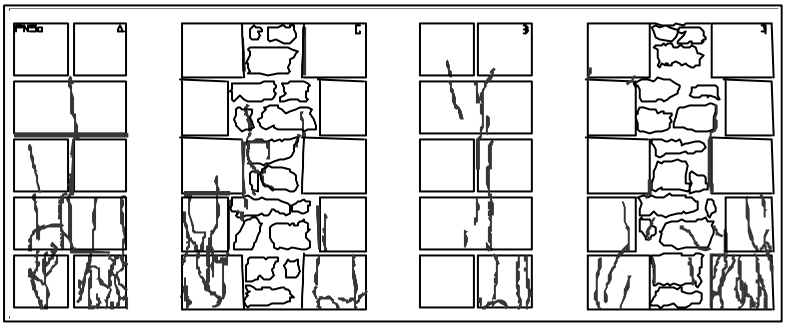


σ_v = 15.32 N/mm^2 100 % σ_{max}

Figure 6: Evolution of the crack pattern during a monotonic compression test on a three leaves masonry specimen built in Serena stone (sandstone).



σ_v = 4 N/mm^2 60 % σ_{max}



σ_v = 6.62 N/mm^2 100 % σ_{max}

Figure 7: Evolution of the crack pattern during a monotonic compression test on a three leaves masonry specimen built in Noto stone (calcarenite).

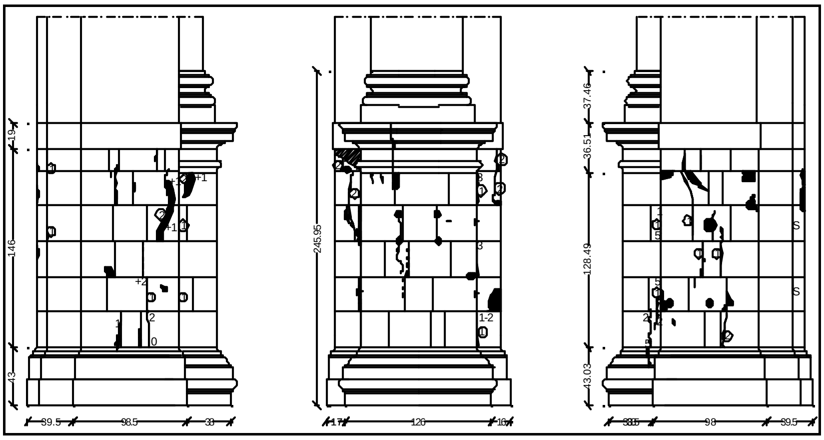


Figure 8: Crack pattern on the basis of the Church of SS. Crocifisso at Noto (Italy).

CONCLUSION

The prevention of collapse of heavy masonry structures subjected to long term damage due to their own weight can only be reached with appropriate repair avoiding the crack propagation caused by the damage evolution. The design for intervention can be prepared only after on site and laboratory investigation on materials and structure. Nevertheless a first step toward prevention is represented by the recognition of the existence of damage through the observation of the crack pattern typical of this phenomenon. As it can be seen from the experimental results and from real structures, the crack pattern consists in a multitude of vertical cracks starting at a certain distance from the base of the structure up to around two third of the structure height. In order to know the possible crack pattern evolution a monitoring system can be applied to the damaged structure.

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