The presence of secondary creep in historic masonry constructions: A hidden problem

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Abstract

Top-ranked European research groups have been working for years on the problem of identifying the behaviour of load-bearing elements due to creep in historic masonry structures. All analyses carried out were performed in unexpected structural collapses, related with earthquakes or not, in several regions all around Europe. These collapses are related with the presence of appreciable size cracks, which appear more or less vertically in towers, vaults and pillars. These cracks can be easy detected through mortar before the collapse but it has been detected in previous works the presence of another crack typology in stonework masonry blocks, which has not yet been taken into consideration. This second type of cracks are difficult to detect owing to their reduced size and because they are under surface patina. In this sense, several real cases are presented where these cracks were found. In the laboratory work little sandstone samples were subjected to a cyclic load to generate cracks, with the aim to propose a method to evaluate them in situ. The proposed methodology is based on the procedures employed in the field of the quantitative metallography. This work aims to point out the probable existence of these cracks hidden under stonework masonry blocks surface, in a great number of historical constructions.

Keywords *Quantitative metallographic; historical failures; stonework masonry; secondary creep*

1. Introduction

Historical constructions constitute an important part of our historical memory. Accordingly, our obligation is to maintain them in adequate state of conservation. The analysis of the integrity of the structure is an interesting field to be studied as it allows, sometimes, applying elegant criteria about their long-term behavior.

Masonry is an assemblage of stones, placed upon one on another, forming a stable structure. Mortar may be used to fill interstices but it does not add strength to the assembly. The stability of the whole masonry structure is ensured by the compaction under gravity. A general state of compressive stress exists in the elements and also in the structure as a whole. The average stresses in a masonry structure of a historical construction are low. [1 to 4]. In the majority of the cases, anomalous situations in structures arise from the application of long-term (several centuries long) loads, which are combined with fatigue. There are three "rules of thumb" for the structural integrity of a stonework masonry construction [5 to 7]: the 5-minute rule, the 20-year rule and the 500-year rule. If the structure remains standing 5 minutes after removing the formwork, it will not collapse. When the formwork is removed, the structure adjusts and re-distributes stresses while absorbing the load and undergoing small displacements in its supports. If the geometry of the structure can endure small dimensional variations in the supports, the construction will remain standing. In this period new cracks appear through the mortar, due to the general geometric adaptation of the masonry upon its supports, by generating hinges. The 20-year rule states that if the structure remains standing for 20 years, it can be assumed that the supporting soil has been compacted and consolidated adequately and has settled evenly; i.e., there were no excessive geometric changes caused by differential settling that could cause the structure to collapse. In this period can be generated other type of cracks through the mortar after differential settlements. The 500-year rule refers to the material deterioration. This concept of “deterioration” is not well explained in the literature. It should include creep, which can cause the collapse of the structure. In this phase another type of cracks can occur due to some new differential settlements, this time caused by near constructions or new urban services works. They also can be caused by long-term loads application, associated with fatigue phenomena nearby traffic and earthquakes. In religious temples, sometimes can be included the vibrations induced in belfries because of the ringing of the bells. The stress state is not uniform not constant. Additionally, a stress concentration can take place in particular zones of the structure and alterations in load level can occur due to reparations or modifications in the historical construction. Therefore, almost all masonry structures show a picture of diverse cracks originated by many reasons [8] and frequently those reasons or origins are unknown. This is a stochastic problem that appears over the building's lifetime (Fig. 1). Currently, numerous structural integrity conservation projects are being conducted on historic structures all over the world without any creep analysis. In fact, many professionals ignore the presence, the importance and the influence of creep on structural integrity.

Figure 1. Cracks through the mortar in the Church of Markina and the Tower-House of Espinosa de los Monteros, in Spain.

Creep is associated with the application of constant and cyclical long-term loads. Several top-ranked European research groups have been working for years on the problem of identifying the behavior of load-bearing elements due to creep in historic masonry structures [9 to 27]. The analysis is being performed through laboratory simulations, after the building collapse, not before. Additionally, it must be pointed out that creep has been detected both in high and low seismic activity areas. Examples of documented unexpected failures, attributed to earthquakes or long-term loads are the collapse of the tower of Chichester Cathedral in the United Kingdom (1861), the San Marco bell tower in Venice, Italy (1902), the Civic Tower in Pavia, Italy (1989), the St. Martinus Church in Kerksken, Belgium (1990), the St. Magdalena Church in Goch, Germany (1992), the Cathedral of Noto in Italy (1996), the bell tower of the St. Willibrordus Church in Meldert (2006), the Medieval Maagden tower in Zichem (2006), the Gesù Church in Mirandola (2012) and most recently the Church of Roselló in Lleida, Spain (2016). Attempts to establish a fracture criterion against a creep-fatigue interaction in all these cases, collide with the stochastic nature of the appearance of cracks and the great number of variables that affect its inception. It is almost impossible to reproduce at the laboratory the real conditions affecting to a real structure in service. Even developing representative samples of masonry of reality is extremely difficult.

The analysis of the integrity of a historic building must contain fracture criteria to identify their residual life (the 500-year rule). The problem to be solved, in all the cases, is the onsite quantification of the level of the damage affecting stonework masonries. Comparison between damage level and the fracture criterion, would allow addressing the appropriate solutions for the structural consolidation in each case.

Damages by creep-fatigue interaction in masonry stonework are related to the amount of cracks, stability, morphology and size. Taking into consideration the variety of crack typologies that can appear in a masonry stonework, a test set has been carried out with the aim of developing a simple methodology, which can be easily be utilized in historical constructions. The proposed methodology is based on the procedures employed in the field of the quantitative metallography [28].

2. Brief description of rock mechanics

According to previous laboratory works on masonry blocks, the phenomenon of creep has three phases [14]. The same way, creep phenomenon is described on a unitary stone block [29]. The primary creep has reversible visco-elastic behavior, the secondary creep has viscoplastic behavior and the tertiary creep causes the early failure (Fig. 2). Assume an initial load that on a stone block produces an instantaneous deformation which value is $\boldsymbol{\varepsilon_0}$. If during primary creep the block is discharged, the deformation follows the path “a b c”. The section “ab” coincides with the initial strain $\boldsymbol{\varepsilon_0}$. Strain in the stone block will continue decreasing asymptotically till its complete disappearance (visco-elastic behavior). In the secondary creep, the deformation follows the path “d e f“. In this case, the discharge reaches a remaining value of plastic deformation $\boldsymbol{\varepsilon_R}$. The tertiary creep quickly leads to collapse. The integrity of a historical construction will depend on the detection of the presence of secondary creep. After that, adopted models would be applied for estimating the residual life of the masonry.

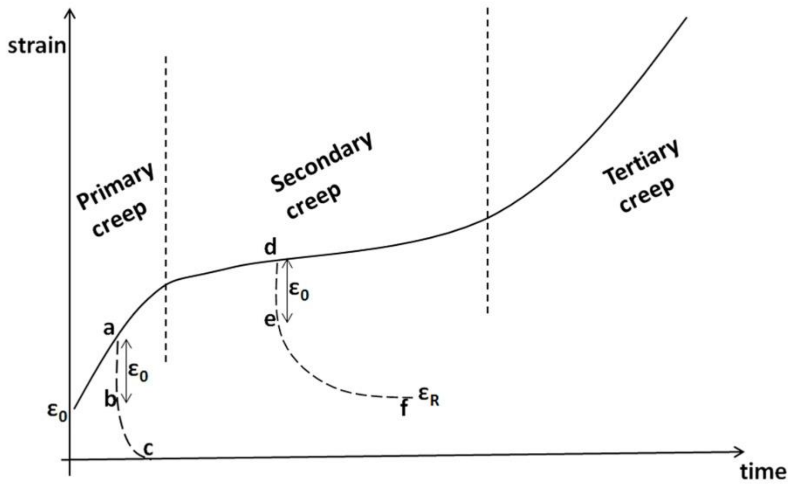

Figure 2. The vertical creep strain under uniaxial compression in a stone block.

Rupture processes in a stone block involve fracture mechanisms of generation and growth of cracks in a pseudo-continuous medium. However, friction between the surfaces of the microcracks, where the onset of the fracture occurs, makes the resistance of the block very dependent on the confining stresses. In this paper sandstone blocks are analyzed. Usually this material has an appreciable resistance, with a fragile behavior for low confinement pressures with respect to the values of the vertical compression (Fig. 3). Pores and microcracks in a discharged rock can lead, under a given stress state, to new cracks. If they reach the surface of a stone block by interaction with other cracks, the fracture of the whole block may occur. Microcracks´

propagation starts under compression loads (**$\sigma_{uniaxial}$**) which levels are below the half of the breaking load of the rock [29]. Under a low confining pressure (**σ_3**) the crack growth is unstable: inclined cracks, related with shear strain (Fig. 3b). When the confining pressure (**σ_3**) is high, microcracks growth turns more difficult, the block behaves as a pseudo ductile high deformation due to the contribution of a large number of microcracks (Fig. 3). Therefore, depending on the confining pressure, a stone block varies from a fragile behavior to a pseudo ductile one.

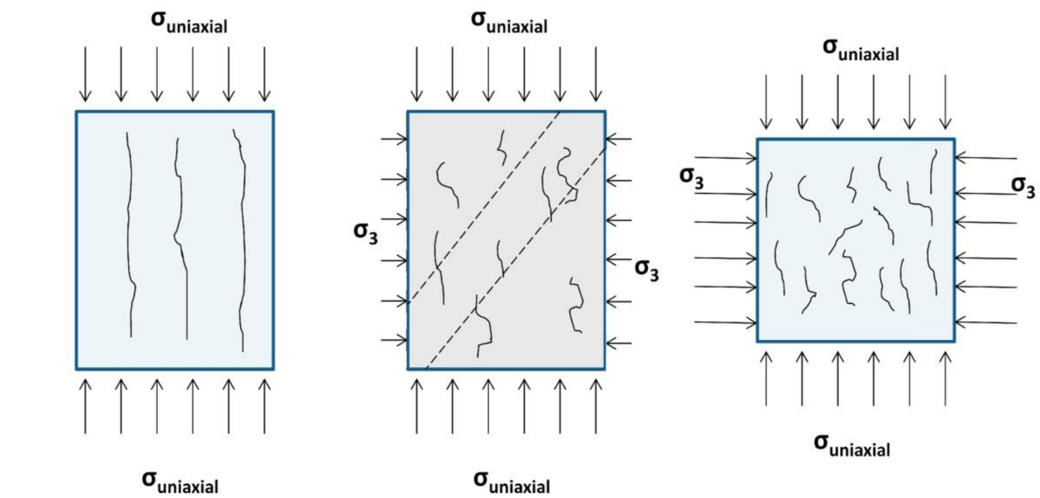

Figure 3 Crack types according to the confining stress value (**σ_3**).

3. Hidden cracking processes observed in stonework masonry

As described in sections 1 and 2, the phenomenon of creep can be detected in a single block or in stonework masonry. Both phenomena should be complementary since both individual block and the masonry of which it is a part, are subjected to a long-term loading process and to the same fatigue phenomena. The heterogeneity of the masonry and the possible presence of stress concentration, induced to believe that the stress state of a block and masonry as a whole is not the same. Reaching this point it is possible to consider that cracking creep in a single block is the beginning of the large cracks. Possibly, cracking in a given block is the beginning of cracking through the mortar when a crack in a block reaches its edges. Obviously, mortar can be considered the weaker area of the masonry. In a historic building, before considering a fissure through the mortar in stonework masonry is originated by creep, it should be analyzed that it has not been originated by other phenomena (mainly differential settlements).

Moreover, it can be considered that the stone blocks of a stonework masonry wall have a weak or a null confining stress due to the presence of mortar or because of belonging to an isolated element like a buttress, pier or a flying buttress. Consequently, the cracks detected in a stone block should be nearly vertical according to Figure 3. Since 1992, the authors have conducted structural analyses, not about of creep analysis, on the following historic structures [1 to 3]: the Santa María cathedral in Vitoria (Spain), the Botines Building in León (Spain), the Asunción church in the Yuso Monastery (Spain), the Hondarribia City Walls (Spain), the Soultan el Ghouri aqueduct in Cairo city (Egypt), the Monumental Asembly in Sasiola (Spain), the Colegiata church in Toro (Spain), the Fortress-church in Turegano (Spain), several palaces in Granada (Spain), the Altes Museum in Berlín (Germany), the Barcelona cathedral (Spain), the Santa María del Mar cathedral in Barcelona (Spain), the church of Pi in Barcelona (Spain), the Saint Jakobs church in Leuven (Belgium), the Seminario Mayor in Comillas (Spain), the Tarazona cathedral (Spain), the Palma de Mallorca cathedral (Spain) and the Oporto cathedral (Portugal). All of these cases involve structural elements composed of stonework masonry. To experimentally determine the in situ structural states, the first author used the technique of Hole Drilling. The first step in this technique is to lightly polish the surface of the masonry element to be measured to provide adequate adhesion of the strain gages that will subsequently measure the relaxed strains (Fig. 4). The presence of fissures or cracks studied in this paper in the material is revealed in this step (the patina is eliminated). Previous similar studies are not known and never before this phenomenon detected by chance was studied. These fissures were not considered relevant by the authors until more recently, when research projects conducted by various European research groups were analyzed. The first author began documenting this problem in the middle of the previous decade, as shown in the following figures (Figs. 5 to 7) where the cracks are previously marked. Figure 6 shows the top and bottom respectively of the same pier in the Colegiata church at Toro city in Spain (Fig. 8). Although fissures were observed in the great majority of cases, graphical results are not available for all of them due to the low resolution of the pictures and because it was not the damage studied in these cases. However, visual inspection under the patina on big historic stonework masonry constructions can be performed anyway.

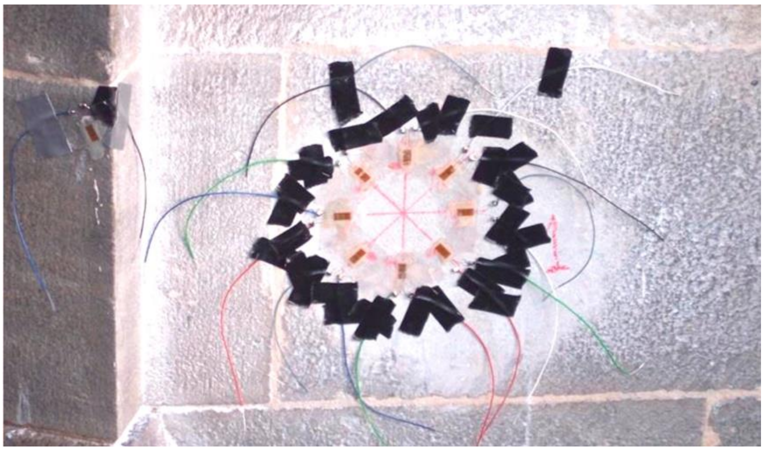

Figure 4. Strain gage rosettes in the Barcelona cathedral (Spain).

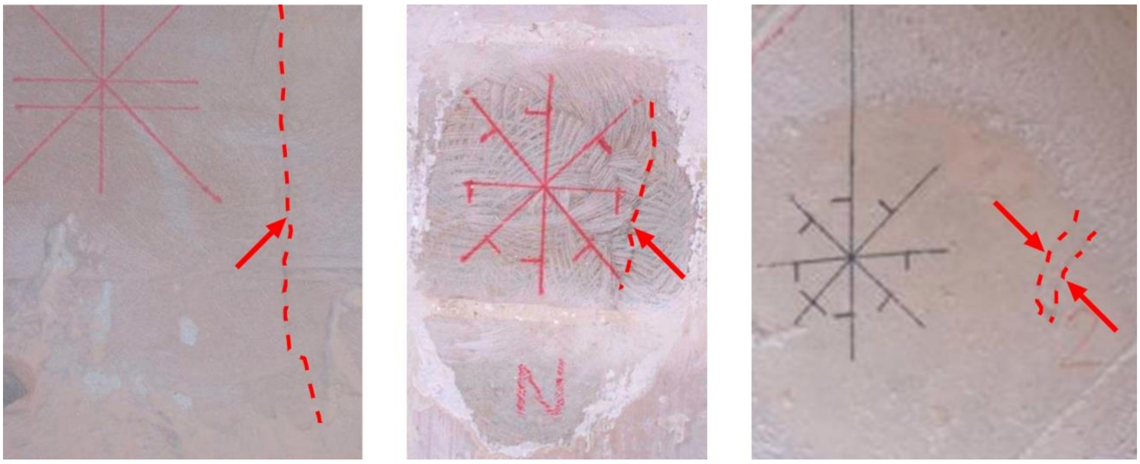

Figure 5. Cracks in Tarazona cathedral (Spain) on the left, Saint Jakobs church in Leuven (Belgium) on the center and Palma de Mallorca cathedral (Spain) on the right.

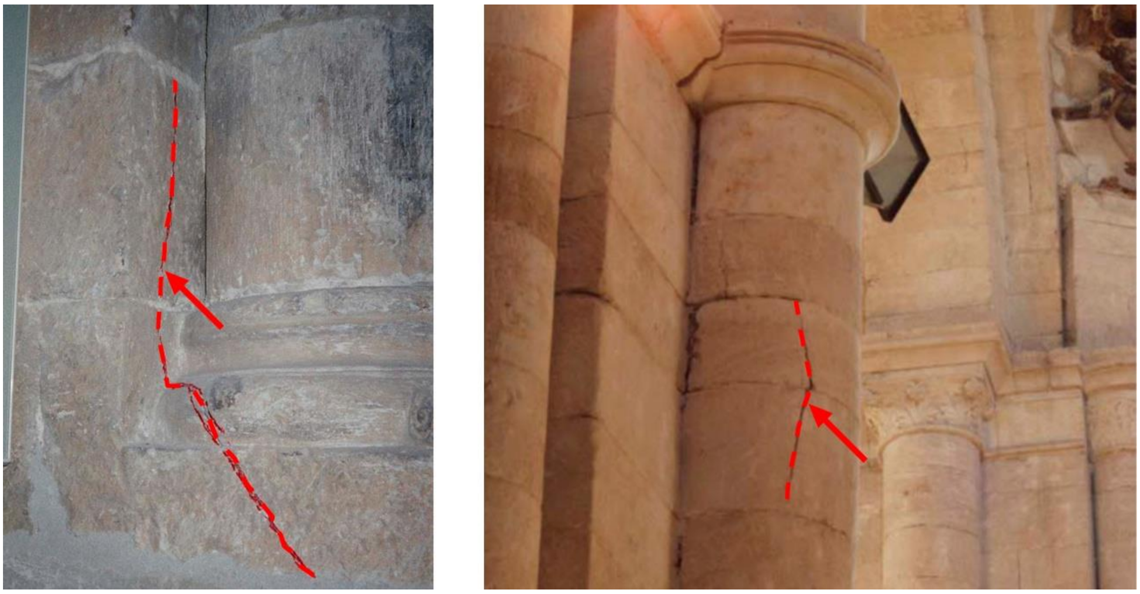

Figure 6. Some cracks in the top part and in the bottom part of a pier in the Colegiata Church in Toro city (Spain).

Figure 7. Some cracks in Turégano Church (Spain) on the left and Santa María del Mar Cathedral in Barcelona (Spain) on the right.

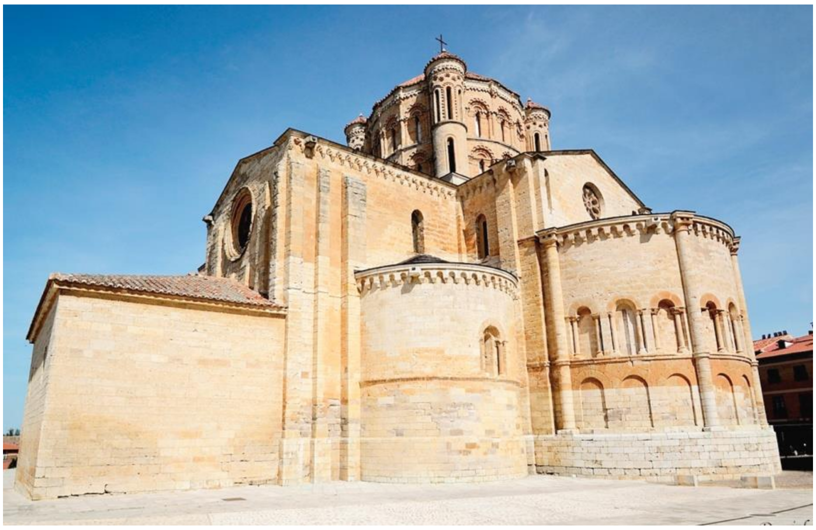

Figure 8. A general view of the Colegiata Church in Toro (Spain).

4. Generation of cracks in laboratory and the quantification method

In the laboratory work sandstone masonry blocks were tested, which were subjected to 25 +/- 2.5 MPa cyclic load at five Hz, at five minute intervals. After each interval, the surfaces of the blocks were examined under different magnifications, with the aim of detecting the number and the size of generated cracks. In this sense, the micrographs did not require a contrast and no computer application was used to count and size these cracks. Both the level of charges and the frequency chosen are arbitrary although the adopted stress level is close to the elastic limit of this kind of sandstone common in Spain (between 30 and 35 MPa). It should be pointed out that the objective of this test was not to check the behavior of the material under creep-fatigue or to reproduce in the laboratory the loads originated in a real stonework masonry construction. The aim of this test was to verify if a cyclic load generates vertical cracks in sandstone masonry blocks and to establish a procedure for its identification. The technique applied in the laboratory was the quantitative metallography, commonly used in laboratories for testing fracture in metallic materials. Figure 9 shows what type of block was tested and the machine used for the tests. In all cases the prisms are 122 mm in length and have 72 mm side square section. Before starting the test, first block´s four vertical faces were photographed at different zooms (between 25X and 36X) in order to distinguish the grains and the pores of this first sample, where compression microcracks will start. Figure 10 shows one of those vertical faces of the block.

After the first 5-minute interval, two cracks were generated on the B side of the first block (Fig. 11). The two cracks could be measured using quantitative metallography, measuring 12 millimeters the longest crack. After the second interval, both cracks increased in length (Fig. 12), the longest crack measured 22 millimeters. The process was repeated for several times until a new crack was generated on other block side (Fig. 13). The new crack was located on the A side and it was 15 millimeters in length. After this interval, the longest crack of the B side increase to 31.4 millimeters. The test was stopped after the eighth interval, to avoid the breakage of the block (Fig. 14).

In the second test, after the first interval, 122 millimeters length crack appeared, which covered all the surface of the block (Fig. 15). Therefore, the length of the longest crack is 122 mm, coinciding with the height of the sample. In the third test, one crack was also detected. This crack progressed in the same way as in the first test. In Figure 16 the final situation of one of the faces in the third block checked can be observed. In that moment the crack coincides with the length of the simple. In this final moment a similar crack developed in the adjacent face. In all cases the number of cracks and their length could be quantified.

Figure 9. Test process and sandstone block type.

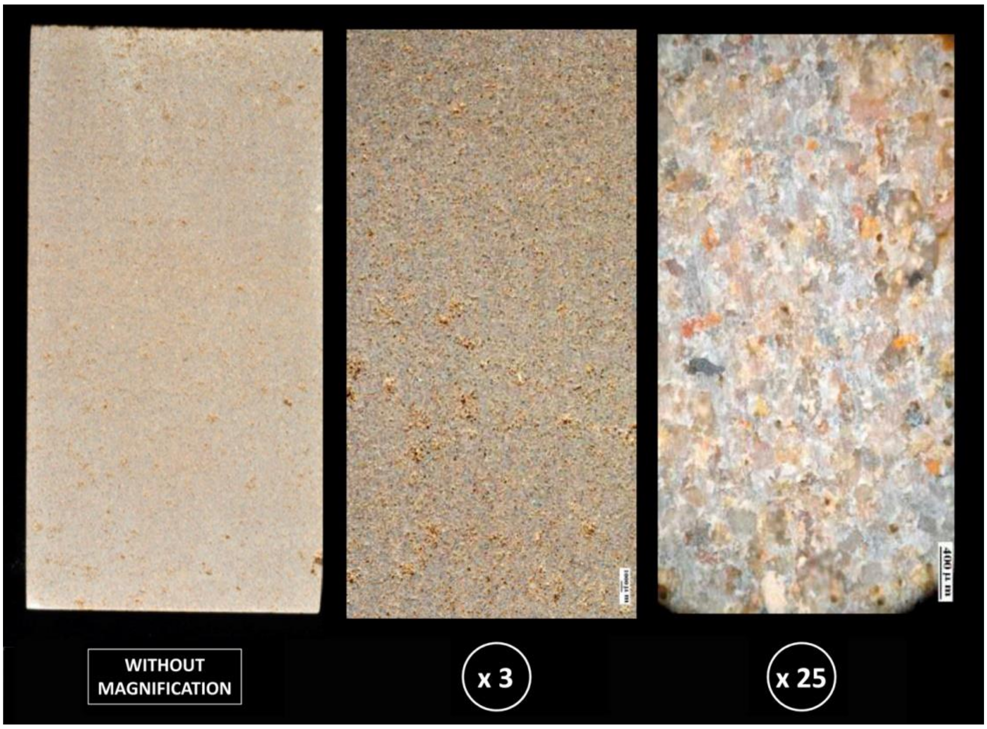

Figure 10. Photographs of the B side of the first block at different magnifications before fatigue test.

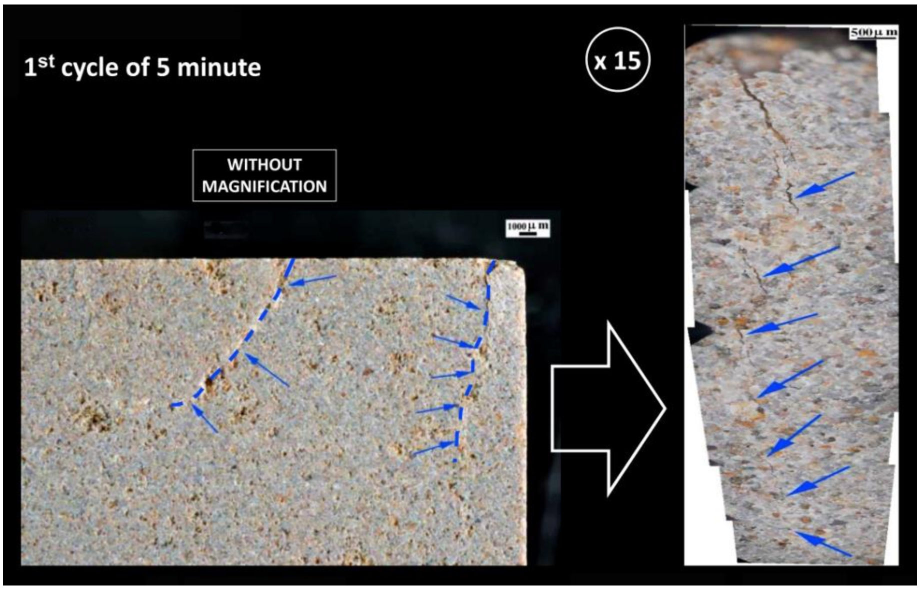

Figure 11. Generated cracks on the top part of the B side of the first block after the first cycle of 5 minutes, with different magnifications.

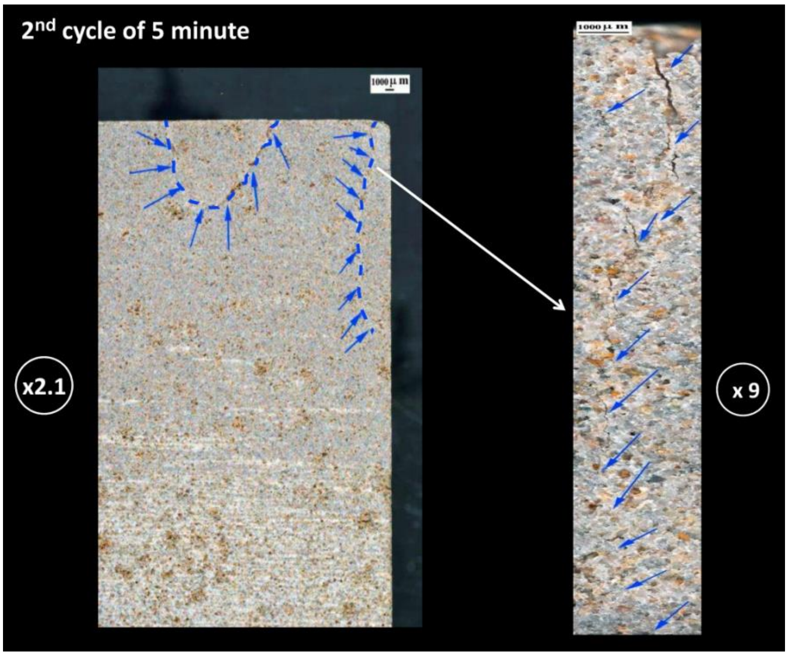

Figure 12. Generated cracks on the B side of the first block after the second cycle of 5 minutes, with different magnifications.

Figure 13. Generated cracks on the A side of the first block after 8 cycles of 5 minutes. The block is rotated 90 degrees.

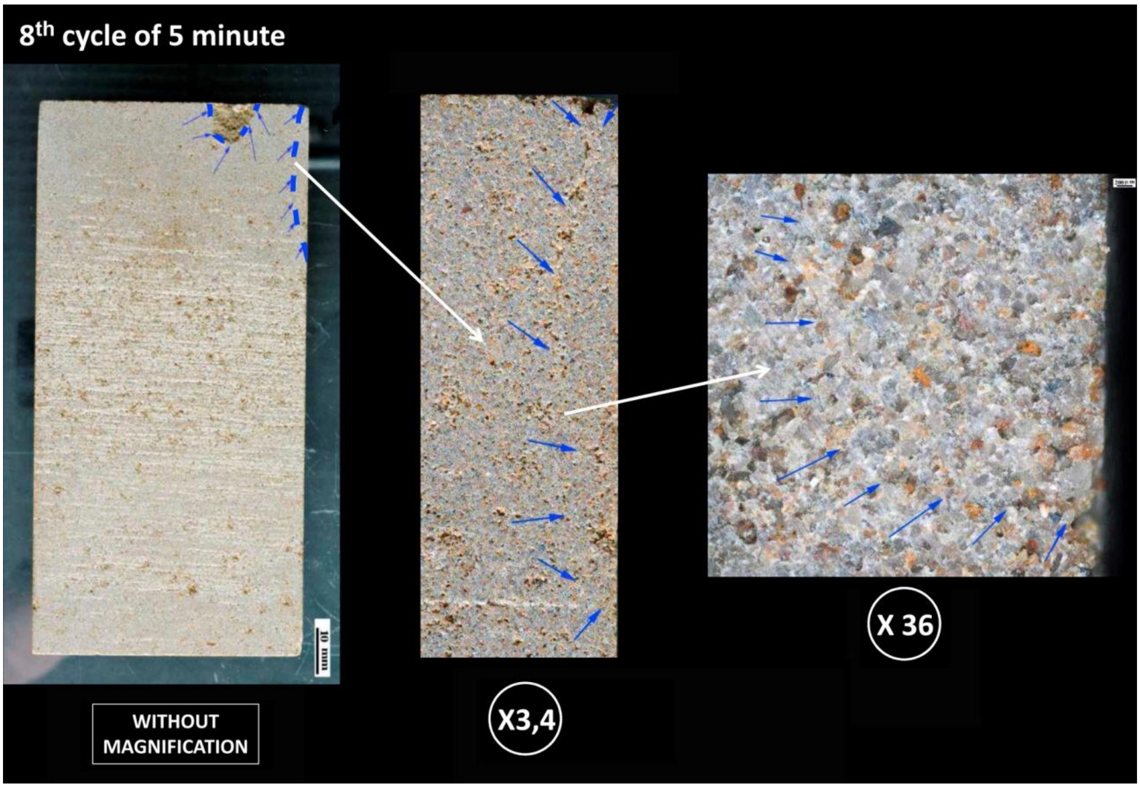

Figure 14. Final cracks on the B side of the first block, with different magnifications.

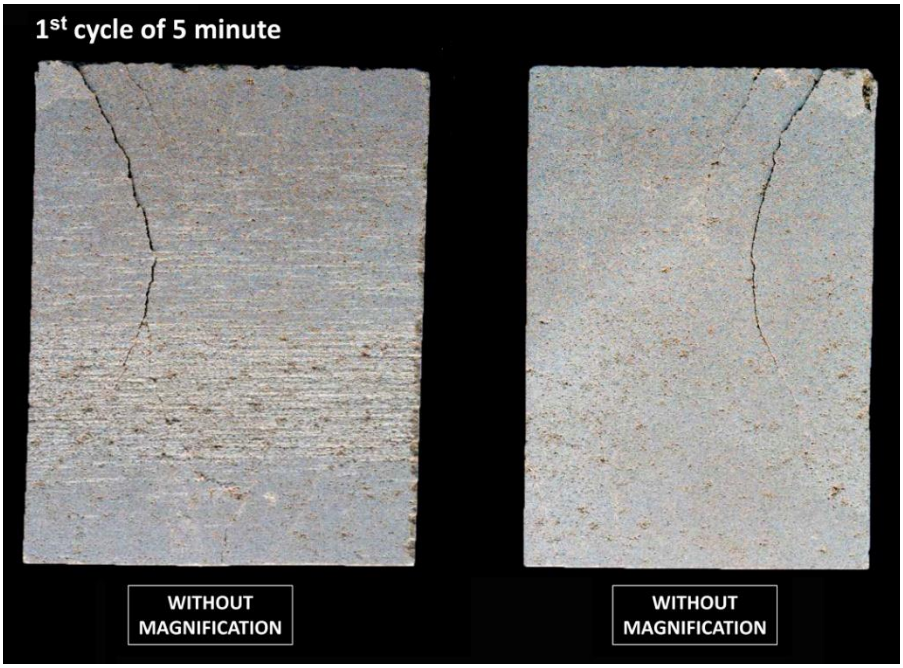

Figure 15. Cracks of the second block tested.

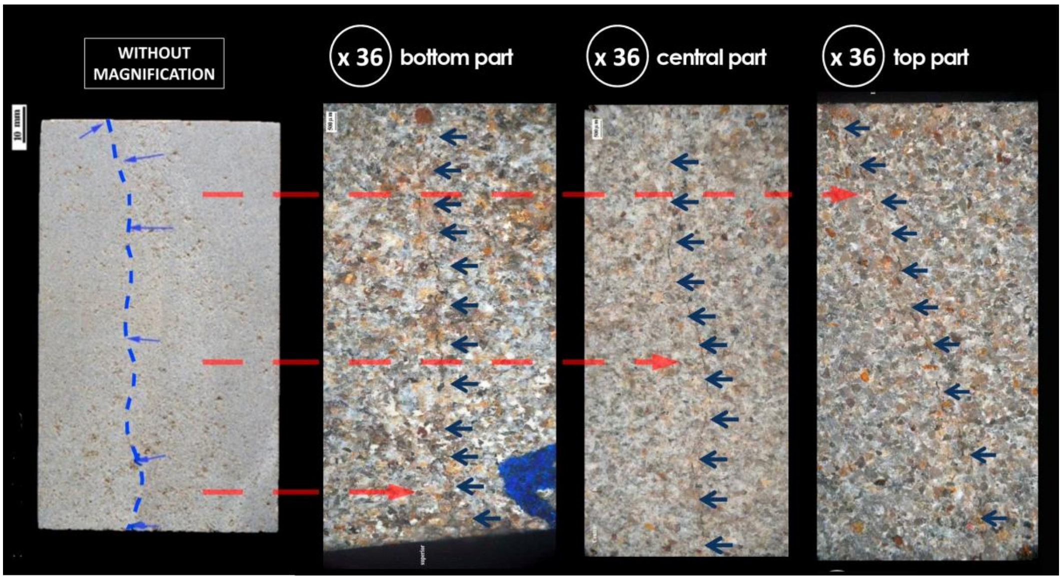

Figure 16. Crack on the B side of the third block tested and the magnification in three parts.

The conditions in the fourth test were different. Each load interval (5 minutes) applied a constant compressive load (25 MPa) during 4 minutes and afterwards a cyclic load of 25 MPa +/- 2.5 MPa with a 5 Hz frequency for a minute. For 16 test intervals (80 minutes test) the appearance of cracks was NOT observed. In order to force the appearance of those cracks, the process was continued increasing the frequency from 5 to 10 Hz. In the first interval, 6160 microns long crack appeared. In the following 17 intervals the same crack reached a length of 7800 microns, being finished the test (Figure 17). No more cracks were observed during the test.

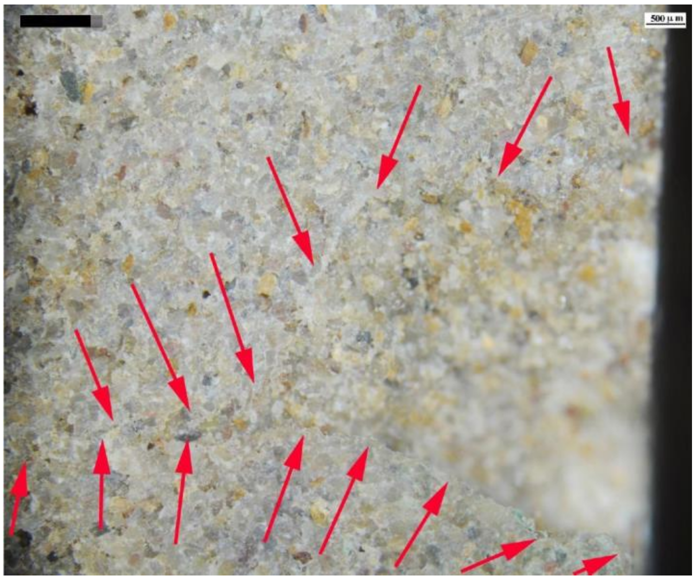

Figure 17. Photomicrograph of 25 magnification of the fourth block tested

5. Discussion and conclusions

No previous published work makes reference about the presence of hidden cracks confined in blocks in stonework masonry. Most of the literature on the interaction creep-fatigue in historic buildings refers to large cracks observed before just before the collapse. However, these large cracks must have an origin and a smaller size sometime before. In this regard, there is no temporal notion about when the cracks are developed in Figure 2 and the problem is reduced to compare the level of the damage under a fracture criterion [15, 16]. It is not clear how can be quantified the level of the damage. It does not exist neither an accepted and agreed criterion of fracture in the international scientific community in this field.

In steel metallography laboratories, there are some standard computer applications available to quantify the number of cracks and their length or the number of inclusions and their size from micrographs and macrographs of polished samples. This method is very useful in the characterization of the quality of heat treatment employed or in fatigue tests on metallic components. This paper shows the possibility of quantifying the cracks and measuring their length in a sandstone block using metallographic techniques. They have been detected maximum 2 cracks in each block, therefore it was not considered necessary to make a statistical analysis of the number of cracks. It is possible to apply this methodology in a pillar of a historic building in order to detect the number of cracks and their length in the sandstone blocks. All the material needed to make these measurements is a photographic-equipment coupled to lenses with different magnifications and a light polishing of the surface before making the picture to remove the patina caused over years hiding the possible cracks. Other authors [18, 30] have alternative techniques based on acoustic emission (AE) for detecting the generation and progress of cracks in stone blocks and masonry at the laboratory. These techniques involve derived quantities (emission energy) and require the cracking process to be active. In this article was decided to use direct methods that not require previous calibration tests in the laboratory.

As mentioned above, a historical construction can have two types of cracks. A detectable crack type when it reaches high lengths and progresses through the mortar and the stone blocks. And a second type of hidden cracks under the patina, which can also be detected, as it was demonstrated (Fig. from 4 to 8) by a light previous polishing. The length of these cracks has not been measured in these real cases because the graphic material available is old and does not permit it. In these cases, the type of crack is more or less vertical according to the solicitation in the block, with low or null confining stress (Fig. 3). In laboratory work conventional method was used to evaluate the size and length of the cracks. Although no conclusion can be drawn, fatigue cracks are generated with similar morphology detected in the historical buildings.

Finally, figure 18 is an assumption in which the graph of strain- time of the Figure 2 with the observed crack in a sandstone block from the Catheral of Santa María del Mar in Barcelona (Spain) and the collapse occurred in Roselló´s church in Lleida (Spain). If this were so, it would have opened here the possibility of detecting onsite the location of a historical building in the process of the creep-fatigue interaction.

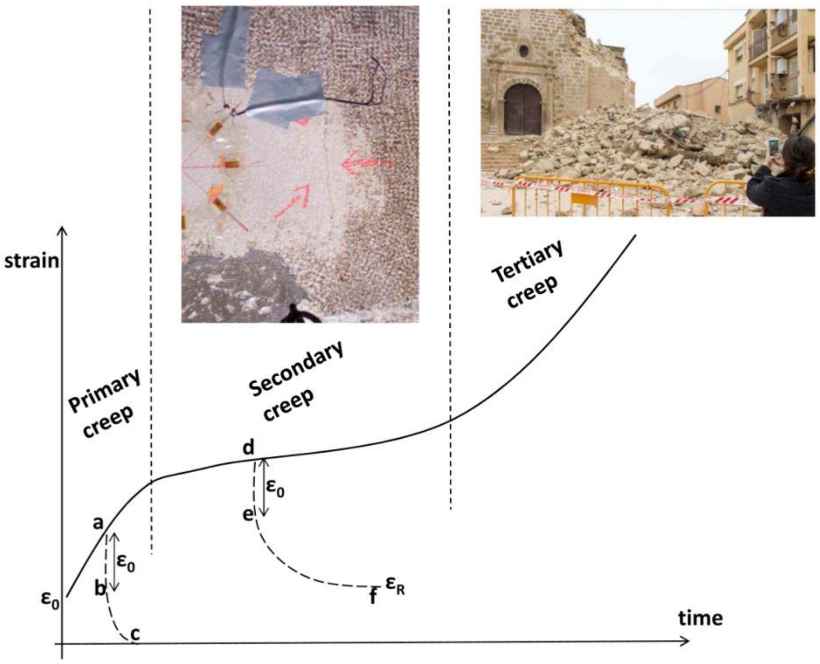

Figure 18. Creep process assumption in a historic construction.

Acknowledgments

The authors wish to thank Mr. Juanjo Añorga Goenaga, skilled metallurgist of Tecnalia Foundation (Inasmet, Parque Miramón s/n, 20018 Donostia-San Sebastián, Spain) for his help in the treatment of micro and macrographs.

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