Advanced Materials Research Vols. 133-134 (2010) pp 331-336
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doi:10.4028/www.scientific.net/AMR.133-134.331

Long-term Reliability of Historical Monuments Built with Low Quality Sandstone

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Abstract The presented research concerns the long-term stability of a series of historical monuments, which were constructed with low-strength, ferrous sandstone. The main issues are the overall low compressive strength of the sandstone, the large scatter on these strength values, the sensitivity of its characteristics to water absorption and the lack of new original sandstone to replace the damaged zones. The sandstone reacts poorly under sustained high load levels, a situation which typically occurs at the base of bell towers and medieval city towers, as the dead load is considerably high compared to the compressive strength of the sandstone material. To assess the long-term behaviour of the sandstone, a test program has been set up to obtain information on its strength characteristics under monotonic and sustained loading. Therefore, test specimens were taken from the original material of a collapsed church tower. The results of these laboratory tests were used to adapt the parameters of an existing creep model to simulate the long-term behaviour of the sandstone under specific stress levels. Additionally, a number of strengthening solutions are discussed.

Keywords: Masonry, long-term behaviour, collapse, creep modelling, ferrous sandstone.

Introduction

The presented research concerns the long-term stability of a series of historical monuments, situated in Hageland, a region north-east of Brussels in Belgium. The conservation of historical monuments, constructed with lower quality natural stone, often poses a difficult problem, especially if new original material of the considered type of natural stone is lacking to replace damaged zones. Although this paper focuses on problems encountered when dealing with a particular type of ferrous sandstone, the addressed issues, methods and conclusions can be extrapolated to many examples of soft natural stone masonry.

Firstly, a description of the sandstone and its characteristics will be given. A short overview will be presented of typical historical monuments which are built with this type of sandstone, and special attention will be given to two cases studies which suffered partial or full collapse. As it will be clear from these case studies that the strength characteristics of the sandstone are often inadequate to guarantee structural safety, the compressive strength and behaviour under long-term sustained loading will be addressed next. Finally, a number of possible strengthening actions are discussed and illustrated.

Description of Ferrous Sandstone

The ferrous sandstone (in Dutch: ijzerzandsteen) which will be discussed in this paper was frequently used for monumental buildings in the 14th-16th century in the central regions of Belgium. The regions where it was used correspond largely with the areas of local exploitation. However, at this moment, exploitation sites with good quality stone in adequate quantities are lacking and restorations are often done with debris material from other monuments. In the late 19th and 20th century, it was even common practice to replace damaged stone material with infill brickwork. (Fig. 1b and c)

The sandstone contains iron fragments, which cause its typical brown-red colour. The sandstone has rather poor mechanical characteristics: it has a low overall compressive strength and there is a large scatter on these strength values. Additionally, the sandstone easily absorbs water, which reduces the strength even further. According to common practice, the structural elements built with ferrous sandstone are often composed as three-leaf masonry, consisting of two outer layers with better quality stonework and an inner core with sandstone chunks and large amounts of lime mortar (Fig. 1a and d).

Figure 1: Cross section of a wall built with ferrous sandstone (a). Restorations with brickwork (b) and cement mortar (c): both only visible after removal of the plaster, however, large cracks in the plasterwork indicated these anomalies. Samples obtained by core drilling in three-leaf masonry (d), the outer leaf (right parts) and part of the inner rubble masonry (left parts) are visible

Collapses of Historical Monuments

Several collapses of monumental masonry constructions, not only in the past but also recently, have demonstrated the vulnerability of our built heritage. Some of these collapses occurred rather sudden and unexpected, without any warning of the structure being on the edge of its load bearing capacity. These phenomena generally occur in tall constructions, such as bell towers or medieval city towers, as rather high stress levels are present at the base of these constructions due to the dead weight. Damage accumulations which occur during creep deformation are usually within limits, but at high stress levels, they can result into partial or total failure of the material. Two recent examples are the

complete collapse of the Bell tower of the Sint-Willibrordus Church at Meldert (Fig. 2a and b) and the partial collapse of the Medieval Maagden tower at Zichem (Fig. 2c and d), in Belgium. Both collapses occurred in 2006.

The bell tower of the church at Meldert consisted of three-leaf masonry, which was composed of two outer leafs in ferrous sandstone and an inner core with rubble masonry of smaller sandstone chunks and large amounts of lime mortar. A visual inspection of the supporting corner pillars of the church tower revealed a large amount of vertical cracks, indicating that the tower was heavily loaded and suffering from time-dependent creep deformations. Adaptations carried out in the past, such as the increase of entrance openings and the removal of sandstone from the outer leaf for rectification had increased the stress level at the base of the tower and reduced the inner coherence of the masonry (Verstrynge et al. 2010b). The tower collapsed at 6th of July 2006.

The Maagden tower partially collapsed at 1st of June 2006 under comparable circumstances. Again, no sudden disturbance of the acting forces could be pointed out as having caused the collapse. The tower was also composed of three-leaf masonry in ferrous sandstone, which appeared to be in bad condition. A high dead load acted on the base of the tower, especially in the area where the cross section of the wall had been reduced by a staircase opening. It was at this point that the wall collapse was triggered.

(a) (b) (c) (d)

Figure 2: Examples of recent collapses: Bell tower of the Sint-Willibrordus Church at Meldert, Belgium (a and b) and Maagdentoren at Zichem, Belgium (c and d), both collapsed in 2006

Compressive Strength

Alarmed by the collapse of the bell tower of the church at Meldert and the collapse of the Maagden tower at Zichem, the bell tower of the Sint-Eustachius church at Zichem was investigated, as this tower was built with the same sandstone material and showed a comparable damage pattern. From this monument, core samples were taken to measure the compressive strength of the ferrous sandstone. A total of 33 core samples were taken, with diameters of 45mm and 133 mm. A histogram of the results of the compressive tests is given in Fig. 3. The results are fitted with a normal and a lognormal distribution function to enable the calculation of a characteristic value, f_k, as indicated in the Eurocode (EN 1990: 2002 (NL)). The characteristic value is the compressive strength which is exceeded by 95% of the experimental results. The normal distribution does not show a good fit to the experimental values. The characteristic value of the normal distribution ($f_{k,N}$) is even negative and therefore physically impossible and not suited to be used for stability calculations. The lognormal distribution clearly shows a much better fit to the results and has been proven in literature to be adequate for modelling the low compressive strength values of masonry (Schueremans 2001). The mean compressive strength of the sandstone, according to the lognormal distribution function, is 2.47 MPa and the characteristic strength ($f_{k,LN}$) is 0.85 MPa.

It can be concluded that the ferrous sandstone has a very low compressive strength and a large scatter on the average strength value. This complicates stability calculations and it would therefore be a good option to incorporate this scatter in the assessment by means of a probabilistic analysis.

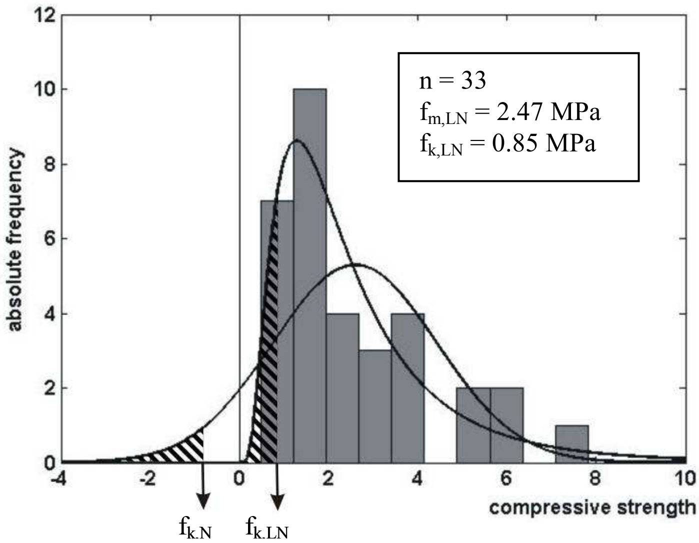

Figure 3: Experimental results of compressive tests on sandstone samples, together with normal and lognormal distribution and indication of characteristic strength f_k

Behaviour under Sustained Loading

An experimental program has been set up to characterise and model the long-term behaviour of ferrous sandstone, which is subjected to high sustained stress levels. A creep model, which has been developed in a previous study to model long-term behaviour of historical masonry, has been applied for this analysis. Details and applications of this model can be found elsewhere (Verstrynge et al. 2009, Verstrynge et al. 2010a). The creep model is a viscoelastic model with damage and has been extended to an orthotropic damage model for finite element analysis.

A total amount of eight accelerated creep tests have been performed, according to a procedure which was established during the previous study. The loading scheme and set up of the accelerated creep tests are indicated in Fig. 4a and b. The tests are performed on cylindrical sandstone samples with a diameter of 113 mm and height of 100 mm. The material originates from the collapsed bell tower of the church at Meldert. The samples consist of ferrous sandstone from the outer leaf, which was gathered after the collapse of the tower. Attempts were made to obtain samples for creep tests from the inner core of the masonry, but this was not possible due to the low coherence of the masonry and bad quality of the lime mortar. Although the used samples consisted solely of ferrous sandstone, they exhibited considerable creep during the tests and their behaviour was taken as representative for the masonry. It should however be clear that tests on the composite material (sandstone and mortar) are necessary to obtain a full description of the masonry's behaviour.

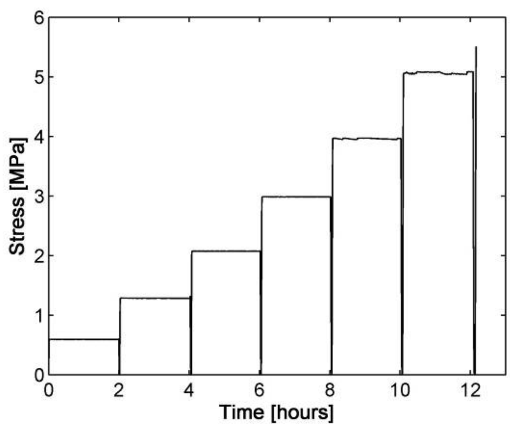

Figure 4: Set-up and loading scheme of accelerated creep tests on cylindrical sandstone samples

In Fig. 5, the creep model is used to simulate the experimental creep results. The input values for the model variables are calculated as the average values of all tests (Bourel 2010). Therefore, the model indicates the "average" creep behaviour and deviations on this behaviour can be incorporated in the analysis as the scatter on the input variables is known. This is illustrated with the dotted lines in Fig. 5, which are model simulations made with the 0.05 and 0.95 quantile values of the compressive strength, f_c, and the Young's modulus, E^M. The compressive strength largely influences the time to failure, while the Young's modulus has a major influence on the strain prediction.

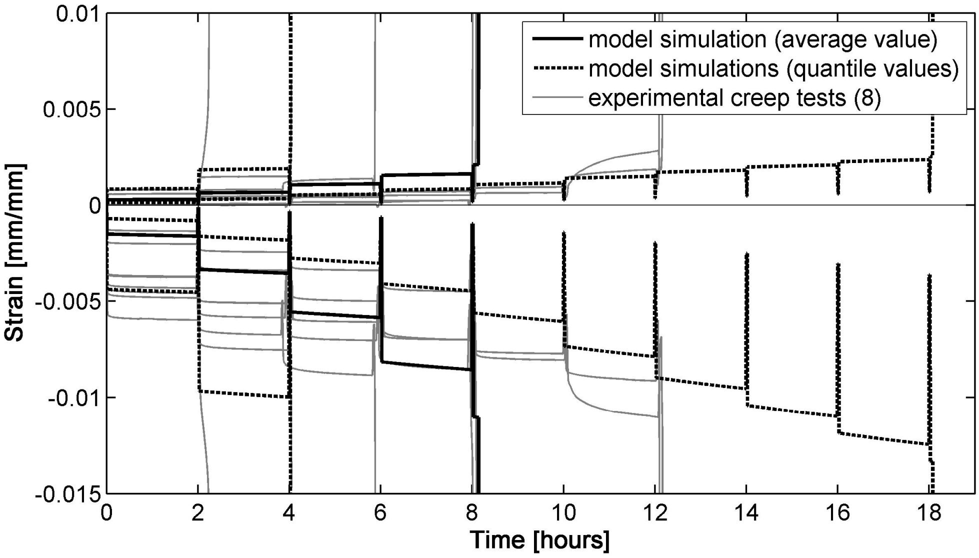

Figure 5: Experimental results and simulation of accelerated creep tests. Dotted lines indicate the upper and lower bounds of the simulation, made with the 5 % and 95 % quantile values of model variables f_c and E^M

Additionally, the model can be used to predict the time to failure under a sustained stress level, due to creep damage accumulation. It has to be remarked that this analysis does not include additional deterioration effects or cyclic loadings. The failure time in function of the stress level in the masonry is indicated for a range of compressive strength values in Fig. 6. A stress level of 50-60 % of the compressive strength, f_c, should not be exceeded to prevent creep damage accumulations. This level is not often exceeded in masonry constructions, however, stress concentrations or deterioration can cause local spots where creep deformations lead to stress redistributions and damage accumulations.

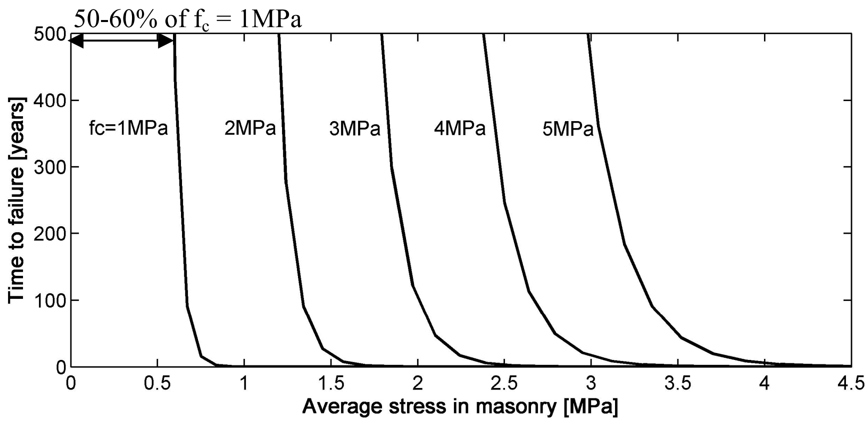

Figure 6: Failure time in function of the stress level in the masonry, indicated for a range of compressive strength values

Strengthening Actions

Different strengthening actions were tested and performed, but at this point, no general solution exists to deal with sandstone monuments in bad conditions. Investigations are in progress to (re)open possible quarries, but in many cases, quality or quantity is lacking to get a return on the investment. When dealing with a stability and/or deterioration problem, the solution chosen should take into account the specific problems and conditions present on site. In many cases, aim of the intervention is to increase the compressive strength of the masonry or (partially) unload the overstressed structural members. As it was concluded from the analysis discussed above, this is a major issue which causes a great deal of stability problems. Possible interventions are:

- Grout injections: this is a general solution to increase the masonry's strength and coherence. Main issues are the compatibility between the grout and the original material and the fact that a lot of water is injected in the masonry, which has a temporarily negative effect on the masonry's stability. If no precautions are taken during the hardening period, this can cause instabilities and (local) collapse.
- Confinement of the masonry: this intervention is easily applicable for columns and can be executed as a temporary measure (for example during grout injections). The lateral forces of the confinement increase the bearing capacity of the column. This type of intervention was opted for during the strengthening of the supporting columns of the church at Zichem (Verstrynge et al. 2010b).
- Stone consolidants: have most effect on good quality stones and are only effective for a restricted depth. They could be a solution for weathering influences, but not for creep damage.

Conclusions

The stability assessment of historical structures, built with lower quality natural stones remains a complex problem. For the case of ferrous sandstone, detailed studies were carried out to specify the material behaviour and to describe the long-term effects of high sustained loading. For many monuments, case specific solutions are necessary which demand a thorough investigation of the damage patterns.

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