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Predicting the Time to Failure in Heavily Loaded Masonry Specimens with the Acoustic Emission Technique

VERSTRYNGE Els[1, a], SCHUEREMANS Luc[1,b] and VAN GEMERT Dionys[1,c]

[1]KULeuven, Dep. Civil Eng., Kasteelpark Arenberg 40, 3001 Heverlee, Belgium

[a]els.verstrynge@bwk.kuleuven.be, [b]luc.schueremans@bwk.kuleuven.be, [c]dionys.vangemert@bwk.kuleuven.be

Abstract This paper presents the results of a research project in which the knowledge on testing of creep damage in masonry and acoustic emission (AE) monitoring are combined. Results from different types of creep tests are combined to investigate whether AE monitoring could predict the failure time of the masonry specimens. In previous work, it was observed that the AE event rate is related to the time to failure of the specimen. Processing of the results of new tests enables to update the previously found relation between AE event rate and failure time and to indicate a confidence interval for predictions made with this model. Additionally, the question can be raised whether temporary monitoring could detect unstable damage accumulation and predict failure. Therefore, the results of long-term creep tests are analysed and compared with data from strain monitoring. The results indicate that in most cases, the failure can be predicted.

Keywords: Acoustic emission, masonry, failure prediction, non-destructive testing, creep

Introduction

The acoustic emission (AE) technique is recently gaining interest as a non-destructive monitoring technique to detect damage accumulation in masonry. Acoustic emissions are high frequency energy waves emitted by the material itself when stress redistributions, such as crack initiation and growth, occur within the material (Grosse and Ohtsu 2008). This paper presents the results of a research project in which the knowledge on testing of creep damage in masonry and AE monitoring are combined. Hereby, two questions are addressed. Firstly, can AE monitoring be used on masonry to detect unstable damage accumulation and predict the time to failure during short-term and long-term creep tests? Secondly, can the acoustic emission technique be used as part of a structural health monitoring system to assess damage accumulation in masonry, subjected to high sustained stress levels which cause creep damage?

These questions will be addressed in the last two sections of this paper. Firstly, an introduction is given on creep testing in masonry. Hereby, the specimens and experimental set-up of the different types of creep tests are discussed. Secondly, a description is given of the acoustic emission technique, together with the specific set-up used during the experimental research.

Creep Testing on Masonry

For the research program, masonry specimens with dimensions 19*19*60 cm (l*b*h) were constructed (Fig. 1). The columns were composed of 10 brick layers, with two bricks per layer and a mortar layer thickness of 1cm. The composition of the mortar was chosen to be representative for historical air-hardening lime mortar. A composition of 1 volume part of lime on 2.5 parts of sand was used. Relatively low-strength bricks were chosen, with dimensions 188*88*48 mm. All masonry specimens were stored at a temperature of 20 ± 1 °C and a relative humidity of 65 ± 5 % for three months before testing.

To investigate whether the time-dependent carbonation process would have an influence on the creep behaviour of the masonry, half of the number of specimens was subjected to accelerated carbonation (B-type masonry). The other half of the specimens were enabled to carbonate naturally

and, consequently, were not fully carbonated at the time of testing (A-type masonry). The consequence of this difference is not subject of this paper (see for example (Verstrynge et al. 2008)).

During an initial tests series, the compressive strength of both masonry types was determined. As expected, the fully carbonated specimens had a higher compressive strength, see Table 1. Based on these results, a loading path was calculated which was to be followed during the creep tests. A typical loading scheme is presented in Fig.2. Different types of creep tests were performed (Verstrynge et al. 2008):

- Short-term creep tests: following the scheme presented in Fig. 2, with a time interval of three hours between two stress increases. These tests had a total duration of approximately 24 hours.
- Long-term creep tests: also according to the scheme in Fig. 2, however, the time interval between two stress increase steps had a duration of two months. These tests had a total duration of approximately 2 years. Therefore, a few of these tests are still ongoing.
- 1-step creep tests: the stress is monotonically increases up to a very high percentage of the compressive strength (85-95 %) and kept constant until failure of the specimen.

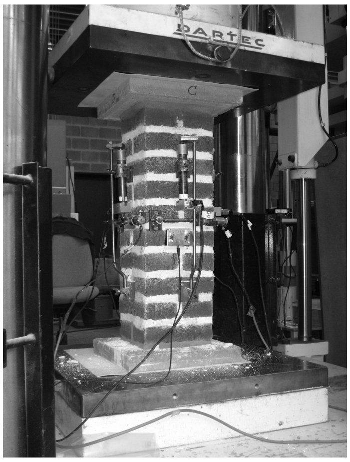

Figure 1: set-up short-term creep tests

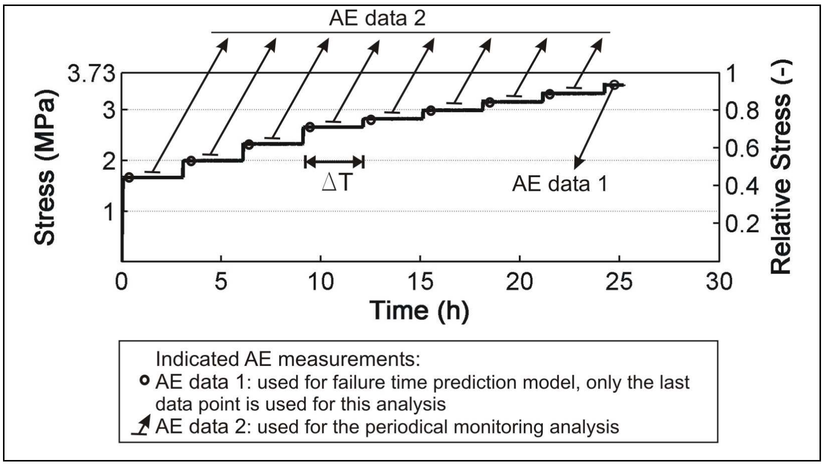

Figure 2: Loading scheme followed during short-term and long-term creep tests, with indication of AE measurements

During all creep tests, the Acoustic Emissions were monitored continuously (during short-term and 1-step creep tests) or periodically (during long-term creep tests). The moments of periodical monitoring are indicated in Fig. 2. The acoustic emissions were monitored at least for one week after each stress increase; these data will be used for the calibration of the failure time prediction model and are referred to as *data 1*. Additionally, the AE data were detected one month after each stress increase, in the middle of the constant stress interval for a period of 24 hours (*data 2*). These latter data will be used for the evaluation of the acoustic emission technique as structural health monitoring technique.

Acoustic Emission Technique

The acoustic emission technique is a non-destructive technique which detects and locates damage at the moment of occurrence. Acoustic emissions (AE) are high frequency transient sound waves, which are emitted during local stress redistributions caused by structural changes, such as crack growth.

When a set of sensors is applied for the AE measurement, location of the emitting source is possible by taking into consideration the geometrical arrangement of the sensors and the moment of arrival of a wave at each individual sensor. As masonry is a highly heterogenic material, with different propagation speed in different directions, location of damage will not be taken into account here.

An AE wave, detected by a sensor, is called a “hit”. In order to filter out the continuous low-amplitude background noise, a threshold is defined and only sound waves passing this amplitude-threshold are detected. Hits, captured by one or more sensors and originating from the same event are simply referred to as only one “event”.

Table 1. Overview of strength values obtained during compressive tests and creep tests on uncarbonated (A-type) and fully carbonated (B-type) masonry.

Type of test	*Number of specimens*	*Max. stress [MPa]*	*Relative max. stress [% of f_c]*
Series A			
Compressive tests	3	2.54 (0.24)	100 (10)
Short-term creep tests	9	2.19 (0.20)	86 (8)
Long-term creep tests	3	ongoing	ongoing
Series B			
Compressive tests	3	3.73 (0.1)	100 (3)
Short-term creep tests	9	3.47 (0.24)	93 (6)
1-step creep tests	6	3.38 (0.16)	91 (4)
Long-term creep tests	3	3.09 (0.25)	83 (7)

Comments: values are indicated with average (standard deviation). The compressive strength, f_c, is the average of the results of the compressive tests.

The amount of events, detected during a certain time interval, depends on various specific boundary conditions of the test set-up, such as the threshold level, the quality of the coupling between the sensor and the test specimen, the density and coherence of the material, the propagation speed of the material and the interference of surrounding test equipment, to name a few. Therefore, necessary precautions have to be taken in order to keep these boundary conditions constant as much as possible. Concerning this remark, it also follows that not the absolute amount of detected events, but rather the change in detection level or event detection rate is a determining factor for the assessment of the damage accumulation.

During the creep tests, the acoustic emission activity was detected by means of two AE sensors, one on each side of the specimen. The sensors are attached to the masonry by means of a thin metal plate which is carefully glued on the surface. A vacuum grease is used as a couplant between the sensor and the metal plate. The preamplifier gain is set to 34 dB and a threshold level of 34.5 dB is applied. The measurements were carried out with equipment from Vallen Systeme, type AMS-3 and AMSY-5. With the latter, four channels could be measured at the same time, enabling the monitoring of two specimens simultaneously.

Failure Time Prediction Model

In previous work, it was observed that the minimum AE event rate, detected during the last step of each creep test, is related to the time to failure of the specimen (Verstrynge et al. 2009). This is comparable with the relation between the strain rate and failure time, which is often observed in literature (Anzani et al. 2009). This idea is illustrated with two representative experimental results (Figs. 3 and 4), which have the typical shape of a bathtub curve (Melchers 1999, Verstrynge et al. 2009). They clearly illustrate that a lower event rate during the 'constant-rate' stage of the bathtub curve is related to a longer duration between stress increase and failure of the specimen.

Processing of the results of the creep tests, mentioned in the previous section (*data 1*), enables to update the previously found power law relation between AE event rate and failure time and to indicate a confidence interval for predictions made with this model. This relation is indicated in Fig. 5 in a double logarithmic presentation, together with the 90 % Confidence Interval (CI) for the regression model and the 90 % Prediction Interval (PI) for new predictions made with the model.

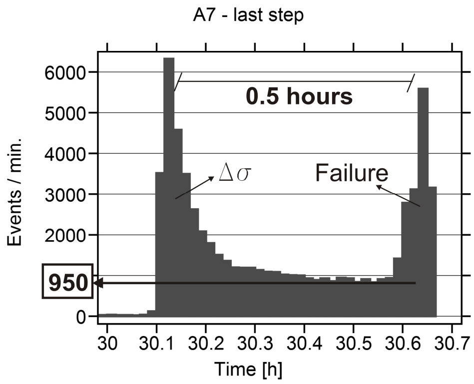

Figure 3: Creep test with high AE rate and little time between stress increase and failure

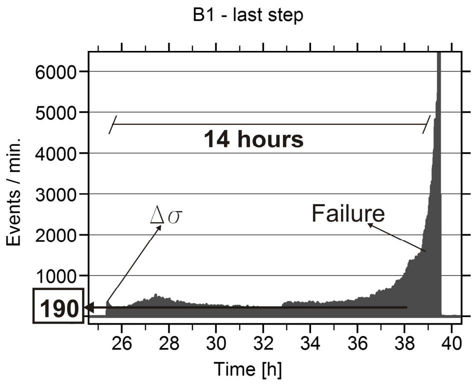

Figure 4: Creep test with lower AE rate and longer time between stress increase and failure

The relationship found here could be extrapolated to longer failure times or, in other words, to masonry subjected to lower stress levels. Unfortunately, two questions rise when this extrapolation would be done in order to assess the failure time while monitoring a structure. The first question is whether this extrapolation is permitted, as well in time (lower stress levels) as in space (larger structures). The latter issue could be addressed by checking the maximum distance between source and sensors and the use of guarding sensors to obtain a comparable monitoring area as during the laboratory tests. Knowledge on the former issue should be obtained with experience from on-site monitoring. The possibility of detecting unstable damage accumulation during periodical monitoring is discussed in the next section. The second question is rather a remark considering the power law relation: if a failure time of 6 months or more is expected, the power law relation predicts an event rate of approx. 50 events or less per day. It is difficult to obtain this accuracy during an on-site monitoring, due to background noise and external excitations of the structure, as the structure can not be isolated and kept under constant environmental conditions as a specimen tested in laboratory conditions. And the event rate will even decrease further when failure times of several years are expected.

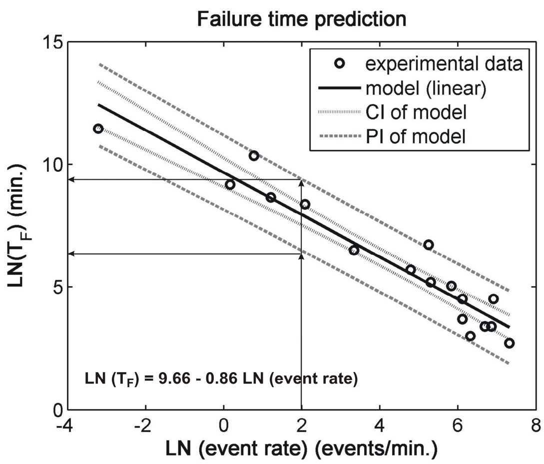

Figure 5: Double logarithmic representation of power law relation between AE event rate and time to failure, with indication of regression model and experimental data

AE as Structural Health Monitoring Technique

The question was raised whether acoustic emission monitoring could be used as part of a Structural Health Monitoring system (SHM) to assess damage accumulation in masonry, subjected to creep damage. Cracks which originate from long-term deformations due to sustained load levels are usually monitored on a periodical basis with crack width measuring devices, such as removable strain gauges. As AE monitoring and periodical strain measurements were performed in parallel during the

long-term creep tests, the results of both monitoring techniques can be compared. To simulate a periodical in-situ monitoring campaign, only data recorded in between two stress increase steps are used for this analysis (referred to as *data 2* in Fig. 2).

The average AE event rates, detected during the intermediate monitoring campaigns, are indicated in Fig. 6. The AE monitoring had a duration of 24 hours, therefore, the indicated results are an average over this time interval. The data are presented for subsequent steps of six long-term creep tests. It should however be noticed that all B-type masonry specimens failed, while the tests on A-type masonry are still ongoing. The horizontal deformations of the six specimens, measured at the same moment as the AE monitoring, are indicated in Fig. 7. To enable the comparison of both types of data, the deformations are indicated as strain rates, or in other words, as the derivative of the usually presented strain-time graphs. In both figures, the measurements are indicated successively up to the previous to last loading step. This means that the step after the last stress increase, in which the specimen fails, is not indicated.

From Fig. 6, it can be observed that a low AE event rate is detected during the successive constant load steps. A rate below 0.15 events/min. corresponds to a failure time larger than two months, according to the failure time prediction model discussed in the previous section. The increased AE level, observed in step 3, is a consequence of the temporary increase of the relative humidity conditions in the laboratory, caused by a defect climatisation system. This indicates that not only the strain measurements, but also the AE measurements are sensitive to the increased deformation rate which originates from moisture cycles in the material. Therefore, higher AE rates can be expected during on-site monitoring, as the environmental conditions can not be controlled and kept constant.

A significant increase in AE event rate is observed during the last measurements of specimens B1 and B3, which indicates an increased damage activity in the previous to last constant load step. Although higher than the other measurements, these data are not critical, which is confirmed by the fact that the specimens did not fail until another stress increase step was imposed. The failure of specimen B2 however, can not be predicted from the presented data as the moment and/or duration of monitoring were inadequate. The lateral strain rates, presented in Fig. 7, show a similar evolution as the AE data. From these monitoring data, one would conclude that specimens B1 and B3 are facing an increased damage accumulation at the measurement of their last data point, while B2 is stabilising.

From these observations, it can be concluded that temporary AE monitoring could predict the failure of two out of three specimens even in the load step previous to the last load increment. In the presented cases, the same conclusion would be drawn from AE monitoring as from deformation measurements. However, AE monitoring has the advantage that the placement of the sensors with regard to the position and direction of the cracks is not of major importance to obtain good data.

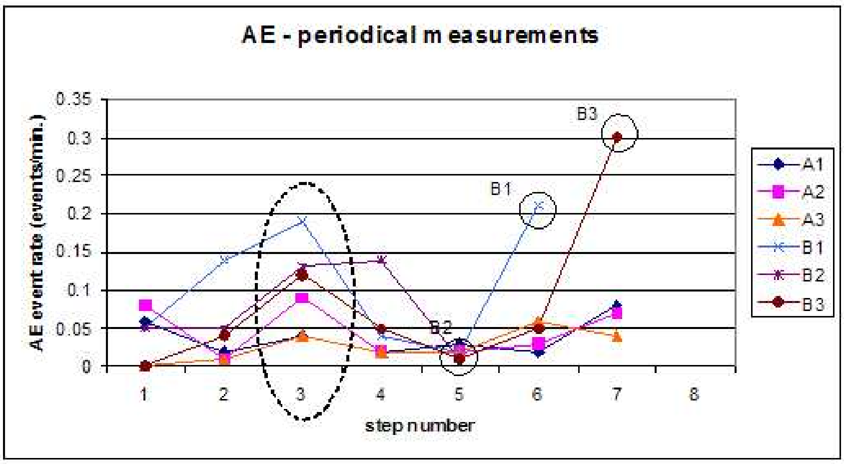

Figure 6: AE event rate measured during periodical monitoring for subsequent steps of long-term creep tests on A- and B-type masonry (The tests on A-type masonry are still ongoing)

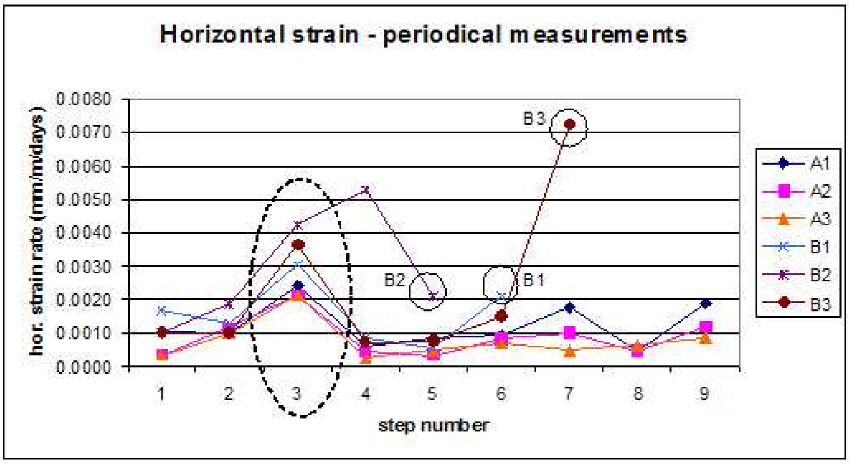

Figure 7: Horizontal strain rate measured during periodical monitoring for subsequent steps of long-term creep tests(The tests on A-type masonry are still ongoing)

Conclusion

Results were presented of a research project in which the knowledge on testing of creep damage in masonry and AE monitoring are combined. The relation between AE event rate and failure time was developed into a promising failure time prediction model. As, for the first time, a data set of adequate size was available from the presented experimental research, a confidence interval could be drawn for the model. It was noted that long failure times can not be predicted with this model as the AE level becomes too low compared with the accuracy of the measurement. Experimental data also indicated that AE monitoring can be an efficient part of a structural health monitoring system for masonry structures, either in a permanent set-up if all damage sources need to be detected, or in a periodical set-up if only time to time damage increase needs to be monitored. Periodical measurements do not always give sufficient information to predict the failure as this will also depend on the moment and duration of the monitoring campaign. The experimental results have shown that even a periodical monitoring of 24 hours was, in this case, sufficient to draw conclusions. Nevertheless, due to changing environmental conditions, an initial permanent monitoring is needed on site in order to have an idea of the normal activity. Additionally, a significant increase in activity due to unstable damage accumulation will always be detected.

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