# Application of the acoustic emission technique for assessment of damage-accumulation in masonry.

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**Abstract**

The interest in acoustic emission (AE) as a monitoring technique to assess the damage evolution in masonry structures is recently gaining field. The AE technique detects transient energy waves emitted by a material as a result of stress redistributions. Energy waves are excited by external loads as well as by internal movements in the structure or the materials. In this paper, the focus is on long-term monitoring and the use of AE-monitoring to assess damage evolution under sustained stresses, such as damage-accumulation during creep phenomena in masonry.

A laboratory test campaign is set up, during which long-term creep tests are performed on masonry specimens at different stress levels. The latter are increased at specific time intervals. In addition to stress-strain and crack monitoring, AE-monitoring is performed at discrete moments in time. Both sources of data are used to validate the AE-monitoring technique to assess the damage accumulation. Hereby, both damage initiation due to load increment and the damage accumulation due to time-dependent deformation under sustained loading are addressed. In this paper, focus is both on the added value and limitations of the AE for damage assessment. The results indicate that the acoustic emission technique is able to detect the damage-accumulation in the masonry, in particular the instable damage increase during the tertiary creep phase, thereby predicting the failure of the test specimen.

Keywords
Masonry, damage-accumulation, acoustic emission, elastic response, creep testing

## 1. Introduction

Since the sudden collapse of a number of historical buildings (Civic Tower of Pavia, 1989; Noto Cathedral, 1996, both in Italy; Sint-Willibrordus church in Meldert, July 2006; Maagdentoren in Zichem, June 2006, both in Belgium), much effort has been made in order to analyse and describe the long-term behaviour of historical masonry [1, 9]. Long-term behaviour is a general descriptive term for the combined behaviour of deterioration of the material in time and the time-dependent deformations of masonry under high sustained stresses (creep phenomenon). The time-dependent behaviour which eventuates in failure of a structure, partly or in total, is being described by means of rheological models [4, 5]. These models aim to describe the three phases of a typical creep process in masonry, including phases with decreasing, constant and increasing creep rate. Based on these phenomenological models, attempts are made to predict the time to failure of the masonry, taking into account the material characteristics and the evolution of the stresses within the masonry over time. In order to evaluate creep behaviour, the time-dependent deformations are monitored within a structural element. In some cases, this monitoring period extends over a long period of time [2], but more often, the monitoring of cracks and deformations is started when stability problems arise. In some very critical cases, only a short monitoring period is enough in order to draw conclusions and take action. A typical example is the case of the bell tower of the Sint-Willibrordus church in Meldert, which collapsed on July 7, 2006. The three-leaf masonry of the tower was composed of two outer leafs in sandstone and an inner core with rubble masonry of smaller sandstone chunks and large amounts of lime mortar. The red-brown, rather porous sandstone contains iron oxide, which is responsible for its colour. The sandstone is known for having a large scatter on its strength characteristics and easy absorption of water, making it rather vulnerable for weathering influences.
A visual inspection of the supporting corner pillars of the church tower, carried out before collapse, showed a large amount of vertical cracks, indicating that the masonry was heavily loaded and in bad condition, figure 1.

Fig. 1: Large vertical cracks in the supporting corner pillars of the church tower

This crack pattern was found on several of the supporting elements of the tower and a monitoring campaign was set up, including the monitoring of a number of cracks by means of a mechanical strain gauge. Within a period of two weeks, some crack openings showed an increase of 1mm and more and the advice was given to close the church and to start immediate strengthening and repair actions. Two weeks later, while the technical staff (who was removing valuable sculptures before the restoration) was having a lunch break, the tower collapsed. Fortunately, making no casualties [6].

Fig. 2: Bell tower of the Sint-Willibrordus church in Meldert, before and after collapse on July 7, 2006

Comparable critical conditions were found at the bell tower of the Sint-Eustachius church in Zichem, Belgium. The crack pattern of one of the corner pillars is presented in figure 3. Again, typical vertical cracks were noticed after removal of the plasterwork. Urgent stabilization measures were taken, by wrapping the pillars with CFRP sheets in order to increase their load bearing capacity, figure 4.

Fig. 3: Crack pattern of corner pillar

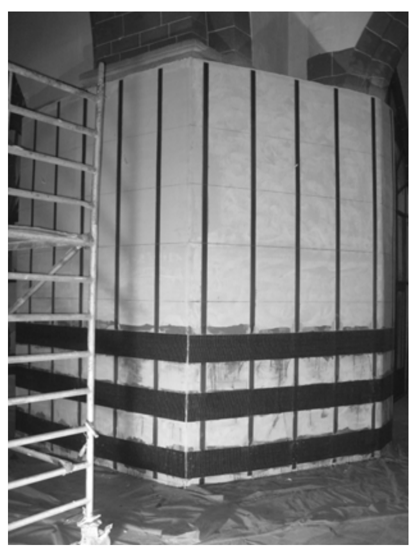

Fig. 4: Wrapping with CFRP sheets

Creep effects, if not critical at a certain moment in time, involve very small deformation rates, which are difficult to monitor (think of the combined action of deformations due to moist and temperature). Long-time and very accurate monitoring campaigns are necessary in order to draw conclusions regarding the damage-accumulation within the masonry. Therefore, a combination of non-destructive techniques is generally used on site in order to assess a structure. These will result, in combination with stress analysis and historical data, in a more reliable diagnosis, from which more efficient measures can be taken. Within the test program described here, the acoustic emission technique is used as a complementary technique in order to assess the damage evolution during creep tests on masonry.

## 2. The 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 several sensors is applied for the acoustic emission measurement, localisation of the source of the emissions is possible by taking into consideration the geometrical arrangement of the sensors and the moment of arrival of a wave at each individual sensor. This technique is frequently used for detection of the location of damage within isotropic materials. As masonry is a highly heterogenic material, with a different propagation speed of the energy waves in different directions, localization of damage is very difficult and, as it is of minor importance for the described application, 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. Two or more hits, captured by different sensors and originating from the same event are simply referred to as only one “event”. Hits are grouped into events by means of an “event builder” software tool, which takes into account the configuration of the sensors and the time criteria, related to the speed of sound and the maximum distance between the sensors. During the described experiments, only two sensors are used for each specimen, placed in a linear arrangement. Here, also sources producing only one hit are referred to as an “event”.

Examples of damage assessment in masonry by AE monitoring are not frequent in literature, especially regarding the monitoring of damage evolution in masonry as a consequence of long-term creep deformation. Acoustic emission monitoring has been used during fatigue testing on masonry arch bridges [7]. A practical study of the creep phenomenon in masonry towers combined with AE monitoring was performed by Carpinteri [2].

The amount of hits, detected during a certain time interval, depends on various specific boundary conditions of the test setup, such as the threshold level, the quality of the coupling between the sensor and the test specimen, the type of sensor, the density and coherence of the material, which are related to the attenuation of the material and the interference of surrounding test equipment to name a few. Therefore, the necessary precautions have to be taken in order to keep these boundary conditions constant as much as possible. The specific conditions used during the described

experiments are discussed below. 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. Within the described research, the parameter-based technique is adopted, using event-counting and parameter-analyses to assess the damage accumulation within the masonry specimens. This technique enables a fast and on-line assessment of the test-results. Other techniques involve a more complex signal-based analysis [10].
Another issue is the placement of the sensors. During the experimental tests, the sensors are placed on each side of the specimen in an area where the highest damage is expected. For in situ measurements, the placement of the sensors should be considered carefully as large cracks in the structure (see figure 1) disable damage detection from the zone behind the voids. Especially in case of multi-leaf masonry, the different layers could be detached, disabling the area behind the void to be monitored by the acoustic emission technique.

## 3. Acoustic emission and creep testing

The acoustic emission technique is generally used during short-term compressive tests, tensile tests and fatigue testing, as the large amount of material damage during these tests can easily be detected. Additionally, the amount of detected events originating from cracks within the material is large in comparison with the detected events coming from background noise and interference of other equipment. As creep test are long-term tests where very little damage is detected during the first stages of the tests, the measurements will include relatively more “false events” from background noise. Another difficulty which has to be taken into account is that creep tests are long-term tests, and require several months. During the presented test program, the measurements were performed periodically, with each measurement lasting for 5-8 days.

### 3.1 Creep tests on masonry columns

Two masonry columns (column nr. 28 and 30) were chosen out of a larger test program for masonry creep testing and for these specimens, both the deformations and the acoustic emission were monitored during the test. The masonry specimens were made with a base of 29 by 19 cm and a height of approximately 85 cm, which corresponds to 14 brick layers and a joint thickness of 1 cm. The height of the masonry wallets is at least three times larger than the thickness to assure a uniaxial stress distribution in the middle of the specimens. The masonry specimens are constructed with a blended cement-lime mortar. Separate steel frames were constructed and hydraulic jacks were used, in combination with a mechanical strain gauge to measure the deformations periodically. On each side of the test wallet, four horizontal and six vertical measuring bases were installed, from which the average value was calculated to describe the strain evolution in time. A more extended description of the full test program is given in [4], [8].

Table 1: Successive stress increase steps during long-term creep test

| Specimen | Successive stress increase steps (in % of average compressive strength $f_c$) | | | | Days to failure after last stress increase |
|---|---|---|---|---|---|
| | (0) | (1) | (2) | (3) | |
| 28 | 50 → 60 % | 60 → 65 % | 65 → 70 % | 70 → 75 % | 8 days |
| 30 | - | 85 → 87 % | 87 → 90 % | 90 → 93 % | 5 days |

The evolution of the stress level during the test for the two selected columns is indicated in figure 5 and table 1. Both columns were initially kept at a constant stress level of 50% (column 28) and 80% (column 30) of the compressive strength, which was calculated as the average compressive strength during compression tests on three masonry columns with the same composition. Then, the stress level is increased in steps and kept again constant for a period of at least one month. This schedule is followed until failure of the specimen. Aim is to detect the different creep rates related to the different stress levels and obtain creep failure during a constant stress interval.

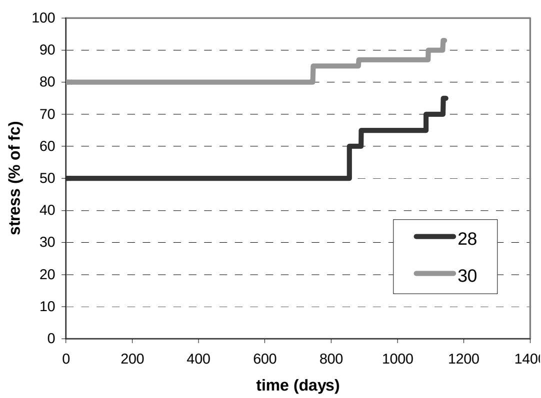


Fig. 5: Stress evolution during last stages of creep test on column 28 and 30

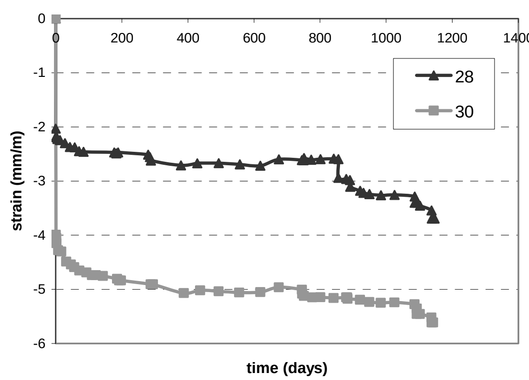


Fig. 6: Vertical strain evolution during creep test on column 28 and 30

Although both masonry specimens are constructed with the same brick and mortar, their composition is not alike. Column 28 has failed during a previous stress increase. A vertical crack on the small sides runs all the way through the specimen, splitting it in two layers. The specimen has been repaired by grout injection. The creep test for this specimen is started at a low stress level of 50%. Measurement show that even at this level, there is already a large amount of damage and the specimen will not be able to withstand the same stresses as will column 30.

Fig. 7: Masonry specimens for creep test

Fig. 8: Coupling of AE-sensor on masonry

The acoustic emission monitoring is performed before, during and about a week after the small stress increase steps, in order to capture the different phenomena of creep failure:
- the elastic deformation during stress increase;
- the decrease of the AE event rate after the stress increase;
- the AE events emission level during a constant stress interval;
- the accelerated damage-accumulation during the tertiary creep phase.

Aim is to assess whether AE monitoring would be applicable to detect the unstable damage growth during the tertiary creep phase of a creep test on masonry.

## 4. Experimental tests and results

The tests were carried out following the stress path as described above. Deformations were measured every month, using fixed measuring points and a removable strain gauge. 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 in between the sensor and the metal plate. Between two measurements, the sensors were removed, while the metal plates stayed attached to the structure. The preamplifier gain is set to 34 dB and a threshold level of 34 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 the two specimens simultaneously. With the AMS-3 system, only two channels could be measured and this two-channel configuration was sustained during the monitoring with the AMSY-5 equipment. The used sensors have a frequency range of 250-700 kHz, with a resonance at 375 kHz.
The results of the AE detection are presented in figure 10.The hits detected by the two sensors are grouped into events as described above. The moment of stress increase is indicated with an arrow, for both specimens the three final stress increases before failure are presented. The numbers in brackets are related to the stress levels in table 1. The amount of acoustic emission events is indicated per hour, this is a non-fixed time interval chosen by the author as it enables to clearly distinct between the

different phenomena. The gaps in the graphs, when no AE is detected, originate from a technical problem in case of the large gaps and a temporary shut-down of the system in case of the small gaps in order to enable the deformation measurement. This temporary break of the monitoring during deformation measurement is not necessary, but was made to avoid false events being originated while touching the specimens.

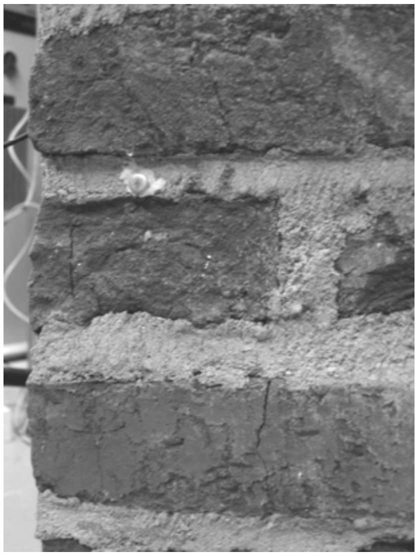

Fig. 9: Vertical cracks in the brick due to creep deformations before failure of the specimen; column 30 after failure

A higher damage increase is clearly detected during the stress increases, except for increase (1) of column 30 (see figure 10) where only a small damage increase is measured. After the stress increase, a decrease of AE events is noticeable, even at the last measurement, during which failure occurred. Although a constant stress level was maintained, column 30 failed five days after the stress increase at a level of 93% of the average compressive strength, column 28 failed 7 days after the stress increase at 75%. It is clear from comparison of the last two graphs with the previous ones that collapse of the specimens could be predicted hours in advance, due to the increasing damage-rate measured by the AE technique. This increasing damage-rate indicated that the tertiary creep phase was reached and an unstable damage accumulation occurred, which eventually lead to failure of the specimen. It is not possible yet from these results to give an accurate prediction of the failure time; therefore, a more elaborate research program will be set up in order to quantify the reliability of the failure time prediction.

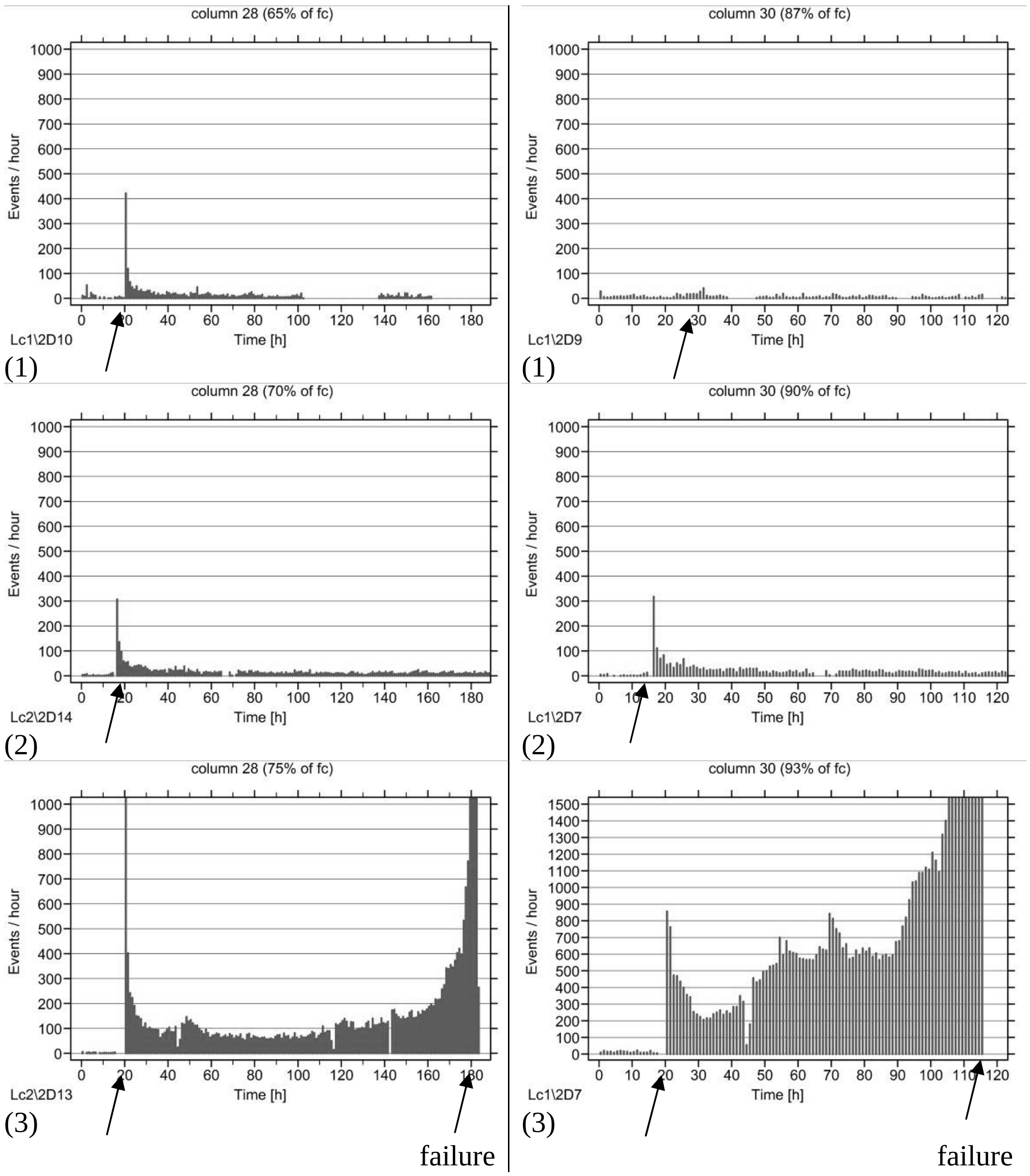


Fig. 10: Results of periodic AE measurement of column 28 (left) and 30 (right), the stress increases indicated with an arrow correspond to the values presented in table 1.

## 5. Discussion of results

The resulting graphs indicated a different intensity of acoustic emission during the different phases of the creep tests. These different phases are further analyzed below.

### 5.1 AE during stress increase

A distinction is made between the data acquired during the stress increase and the detected AE events during the constant stress level interval. The acoustic emission during stress increase can be linked to the elastic deformation of the masonry. In figure 11, the elastic strain is compared with the total number of detected counts. Counts are used here instead of events, as the number of counts is proportional to the total emitted energy, and thereby related to the total deformation [3]. Because not all stress increases were equally high, the vertical strain and the amount of counts are presented per percentage of stress increase. As indicated in figure 11, a linear relation between these parameters is found when the instant, elastic deformation is considered.

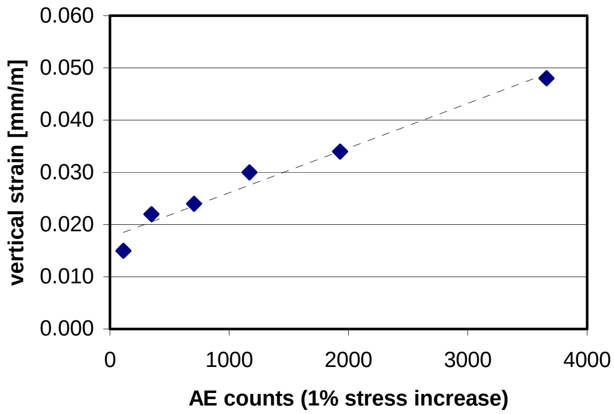


Fig. 11: Relation between the elastic strain and the total number of counts during different stress increases

5.2 AE during interval of constant stress

To distinguish between the different phases, the number of AE events are presented as a cumulative curve (see figure 12). The cumulative curve shows a behaviour which is very similar to the form of a typical creep curve:

- a primary phase, with a decreasing slope. This indicates a decrease in strain rate for the creep curve and a decrease in AE-rate for the cumulative AE-curve;
- a secondary phase or steady-state phase, during which a constant slope is shown;
- a tertiary phase, with an increasing slope. Considering a creep curve, this indicates an increasing strain rate and thus an unstable damage-accumulation up to failure. This increasing slope is also clearly noticeable for the cumulative AE-curve.

These three regions are indicated in figure 12. The increasing slope during the last stage of the test made it possible to indicate the unstable damage growth and predict the possible failure of the specimens over fifty hours before the actual collapse occurred.

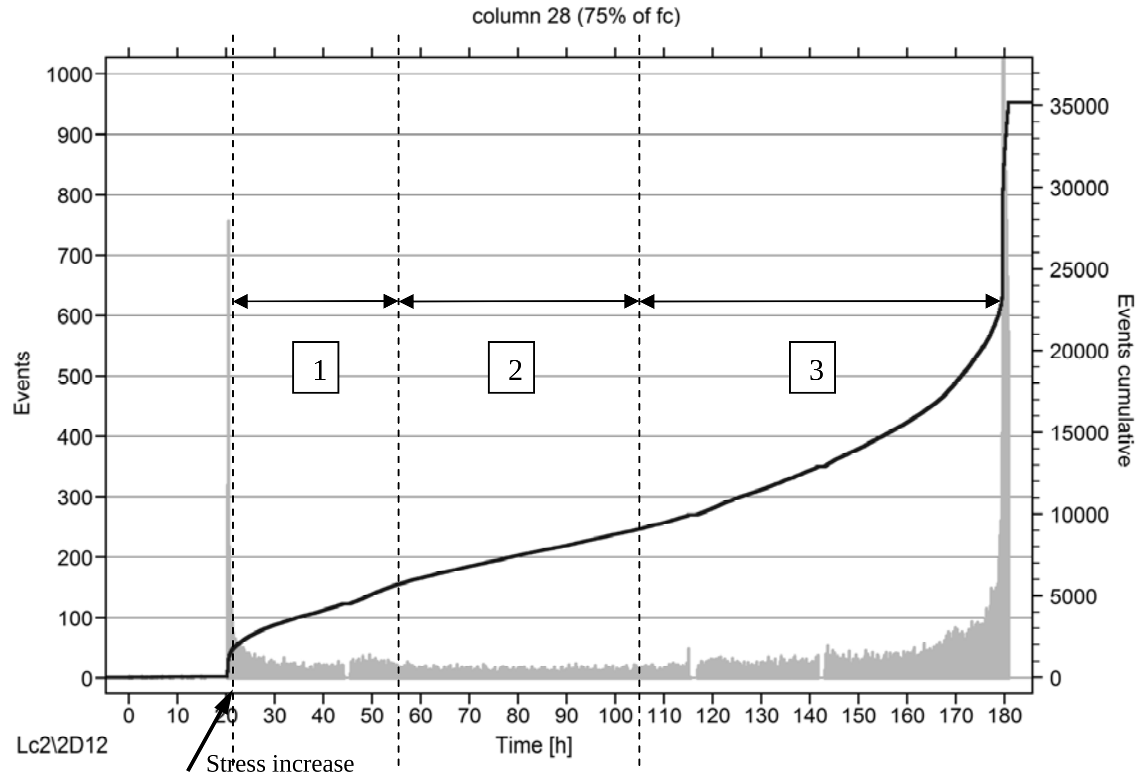


Fig. 12: Cumulative graphs of AE-events, with an indication of the different phases of a creep curve

## 6. Conclusion

The sudden collapse of a number of historical buildings has boosted the research effort regarding the analysis and mathematical description of the long-term behaviour of historical masonry. In order to evaluate creep behaviour, the time-dependent deformations are monitored within a structural element, but other non-destructive techniques are valuable to obtain a more reliable diagnosis, from which more efficient measures can be taken.

The use of the acoustic emission technique is proposed as a non-destructive monitoring technique to assess damage evolution in masonry under sustained stresses. The technique is applied during creep tests on masonry columns and its applicability for detecting the damage evolution within masonry is demonstrated as well during the small stress increase steps as during the intervals with constant stress level.

Considering the elastic deformation during stress increase, a relation has been found between the vertical strain increase and the amount of AE counts detected during stress increase. The results of the acoustic emission monitoring during constant stresses indicated persistent damage detection, with a cumulative curve which can be compared to the phases of a creep curve. A sequence of decreasing, constant and increasing damage-accumulation rate has been found. These results illustrate the advantages and potential of AE monitoring towards the applicability of this technique for the monitoring of long-term damage accumulation in masonry. However, the application of AE measurements on site will acquire more detailed investigations as well in laboratory conditions as on site in order to establish an optimum monitoring frame, related to the monitoring period in case of periodic monitoring, the boundary conditions and the sensor configuration. During the experiments described, the critical moment was known in advance, as the small stress increase was externally imposed on the masonry. In order to further analyze the application of this promising technique, a research program has been set up, including AE monitoring during short- and long-term creep testing and on-site measurements.

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## References

[1] Binda, L., Gatti, G., Mangano, G., Poggi, C. & Landriani, G.S. 1992. The Collapse of the Civic tower of Pavia: A survey of the materials and structure. Masonry Int. Vol 6 (1): 633-642

[2] Carpinteri A., Lacidogna G. 2007. Damage evolution of three masonry towers by acoustic emission. Engineering structures 29: 1569-1579.

[3] Eberhardt E., Stead D., Stimpson B., Read R.S. 1997. Changes in acoustic event properties with progressive fracture damage. Int. J. Rock Mech. & Min. Sci. Vol 34 (3-4), paper nr. 071B.

[4] Ignoul, S., Schueremans L., Binda L., et al. 2006. Creep behavior of masonry structures – failure prediction based on a rheological model and laboratory tests. In P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.) Proc. Of the 5th int. seminar on structural analysis of historical constructions. Vol 2: 913-920. New Delhi 2006.

[5] Papa E. & Talierco A. 2005. A visco-damage model for brittle materials under monotonic and sustained stresses. International journal for numerical and analytical methods in geomechanics, Vol 29 (3):287-310.

[6] Schueremans L., Ignoul S., Figeys W.,Verstrynge E., Depickere W., Van Gemert D., Van Balen K. 2007. Pre- and post collapse emergency interventions on historic load-bearing structures – case studies in Belgium, Historic Structures 11th International Scientific Conference, Cluj Napoca, 25-27 October 2007, “Emergency Interventions on Load Bearing Structures”, pp. 25-55.

[7] Tomor, A.K. & Melbourne C. 2007. Monitoring masonry arch bridge response to traffic loading using acoustic emission techniques. Proc. of the 5th int. conference on arch bridges, Madeira, Portugal, 12-14 september 2007: 281-288

[8] Verstrynge, E., Ignoul, S., Schueremans, L., Van Gemert, D. & Wevers, M. 2008. Damage accumulation in masonry under persistent loading evaluated by acoustic emission technique. Proc. 14th Int. Brick & Block Masonry Conference, Sydney, 17-20 February 2008.

[9] Verstrynge, E., Ignoul, S., Schueremans, L., Van Gemert, D, Wevers M. 2008. Long-term behaviour of historical masonry - a quantitative acquisition of the damage evolution. Proc. of the 6th int. seminar on structural analysis of historical constructions. Bath 2-4 July 2008.

[10] Grosse CU, Finck F., 2006. Quantitative evaluation of fracture processes in concrete using signal-based acoustic emission techniques. Cement & Concrete Composites 28 (2006): 330-336.