DAMAGE ACCUMULATION IN MASONRY UNDER PERSISTENT LOADING EVALUATED BY ACOUSTIC EMISSION TECHNIQUE

[1]ELS VERSTRYNGE, [1]SVEN IGNOUL, [2]LUC SCHUEREMANS, [2]DIONYS VAN GEMERT

[1]Ph. D. researcher
[2]Prof. dr. ir
Department of Civil Engineering
Katholieke Universiteit Leuven
Heverlee, Belgium

MARTINE WEVERS

Prof. dr. ir
Department of Metallurgy and Materials Engineering
Katholieke Universiteit Leuven
Heverlee, Belgium

SUMMARY

An extensive test program has been set up to evaluate the mechanical behaviour of masonry under long-term monotonic and sustained loading. The laboratory tests include short-term monotonic compressive tests, accelerated creep tests and long-term creep tests on three types of masonry wallets with different mortar composition. Besides stress-strain and crack-opening monitoring, the acoustic emission technique is proposed as a non-destructive technique to assess the damage evolution within the masonry. This contribution presents the first test results, gives a critical appraisal on the applicability of acoustic emission for damage monitoring and suggests further improvements.

INTRODUCTION

Despite substantial efforts to describe the mechanical behaviour of masonry, many questions remain, particularly considering its long-term behaviour. Especially the alteration of its mechanical features when damage accumulates under a persistent load requires notice. Attention was drawn to this research area as a consequence of several collapses of historical masonry buildings during the past decades (Civic Tower of Pavia, Italy, 1989; Church of Kerksken, Belgium, 1990; St. Magdalena at Goch, Germany, 1992; Cathedral of Noto, Italy, 1996). In general, these collapses took place without warning or a specific identifiable cause such as an earthquake or a fire. In many cases, these collapses concern tall masonry structures with a non-negligible self weight which acts as a high sustained compressive loading. This was also the case at very recent collapses, for example, the medieval tower “Maagdentoren” at Zichem, Belgium, which collapsed in June 2006 or the bell tower of the St. Willibrordus church at Meldert, Belgium, which collapsed in July 2006 (Figure 1).

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

Figure 1. Bell tower of Church St Willibrordus at Meldert (a and b);
Maagdentoren at Zichem (c and d)

The modelling of long-term behaviour of historical masonry is a complex matter, as masonry is a very heterogeneous material. It can be modeled as an orthogonal network of two different components in the case of new masonry, but historical masonry is often build up as a totally disordered network of bricks, mortar and voids, such as the core of three-leaf masonry. As a consequence, to model the time-dependent behaviour of masonry, the material is often approached on an abstract macro-scale, as a homogeneous, continuous material. What is lost in accuracy is gained in overall applicability of the formulation, computational simplicity and efficiency.

The time-dependent behaviour of historical masonry, which at high sustained stresses can lead to collapse of the structure, is a combined action of creep in the material layers, deterioration of the material and additional mechanical loading effects, which lead to stress redistributions and the development of “hot spots” where damage is initiated. Time dependent behaviour of cementitious materials is likely to be caused by the effects of moisture migration within the material and carbonation of the mortar (Ferretti & Bazant 2006). As often massive walls are concerned, these phenomena occur very slowly in time. But, in general, it can be stated that not all physical processes which influence creep in masonry are known and/or the contributions of these processes to the creep phenomenon are uncertain (Lenczner 1986). Therefore, a phenomenological approach is often followed, based on the results of creep tests at different sustained stress levels.

A rheological model was proposed by Papa and Taliercio (Papa and Talierco 2005) to describe time-dependent behaviour of brittle materials under monotonic and sustained stresses. The theoretical evolution of strain in time under sustained stresses, the “creep curve”, exhibits three creep phases; a primary phase during which the strain rate decreases in time, a secondary phase or steady-state creep, with a constant strain rate and a tertiary phase with an increasing strain rate, which leads to a sudden failure of the specimen (Boukharov 1995; Anzani 2000; Challamel 2005). In order to describe the accumulation of damage in time, damage variables were introduced in the rheological model.

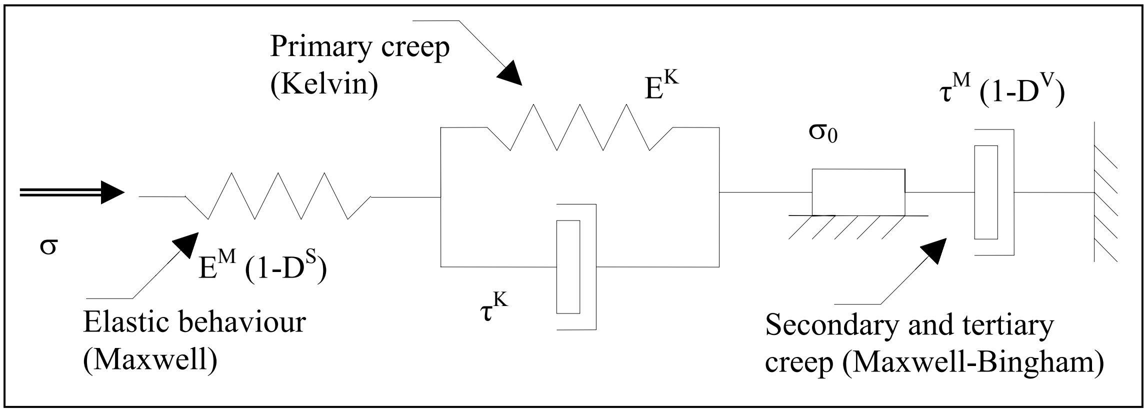


Figure 2. Schematic representation of the rheological model including damage variables (adopted from Papa and Talierco 2005)

The model parameters have to be estimated from experimental creep test data. At this moment in time, no elaborated data sets are available in literature. The ability of the model to simulate the strain evolution due to sustained loading and predict the failure time of a structure, which is subjected to specific conditions, depends on the accuracy of the predicted parameters, but also on the spread regarding these calculated parameters. In order to reduce the spread on the predicted values and to perform a reliable risk analysis, the elaboration of reliable data sets is a prerequisite. Therefore, an extensive test programme was set up to evaluate and model the mechanical behaviour of masonry under monotonic and sustained loading (Ignoul 2006). These laboratory tests included monotonic compression tests, accelerated creep test and long term test on small masonry wallets, with 4 different mortar compositions.

Besides stress-strain and crack-opening monitoring, the acoustic emission (AE) technique is proposed as a non-destructive technique to monitor the damage accumulation in masonry. The acoustic emission technique records and locates active (initiating and growing) damage when elastic energy is being released by the material. In this sense, the technique is exceptional as it emerges from energy release supplied by the damage process itself while it occurs and micro-defects are registered even long before visible macro-cracking might occur. The results of these first tests from the ongoing test campaign are presented, the applicability of AE for damage monitoring is discussed and suggestions for further improvements are outlined.

LONG-TERM BEHAVIOUR OF MASONRY – EXPERIMENTAL RESEARCH PROGRAM

In order to expand our knowledge on the long-term behaviour of masonry and gather data for the fitting of the model parameters, a test program has been set up, including three types of tests; the necessary data are gathered by means of monotonic compressive tests, as well as by accelerated creep tests on masonry wallets. Additionally, long-term creep tests were started up to enable the validation of the calculated strain and damage evolution in time, simulated by means of the rheological model, as the parameters used in the simulation are based on the short-term test data. The implementation and results of the different creep tests will be discussed here, the model calibration can be found elsewhere (Ignoul 2006).

In the ongoing experimental program one single type of brick is combined with 4 different types of mortar: cement mortar, hydraulic lime mortar, air hardening lime mortar and a cement-lime mortar. The purpose is to investigate the effect of differences in stiffness between brick and mortar on the long-term creep behaviour. The brick type and mortar composition were chosen to be representative for historical masonry encountered in Belgium. For each type of mortar, 9 wallets 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 an uniaxial stress distribution in the middle of the specimens. For the monotonic compressive tests (3 tests per mortar type) as well as for the accelerated creep tests (3 tests per mortar type), a hydraulic test device was used in combination with one horizontal and one vertical strain gauge (LVDT) on each side of the specimen. For the real creep tests (3 tests per mortar type), 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.

Monotonic Compressive Tests

Compressive tests were performed in strain-controlled conditions to gather information on the compressive strength of the different masonry types. Based on these ultimate strengths, the stress path to be followed during accelerated and long-term creep tests can be calculated. The results of these tests on the masonry and on the different materials are summarized in Table 1.

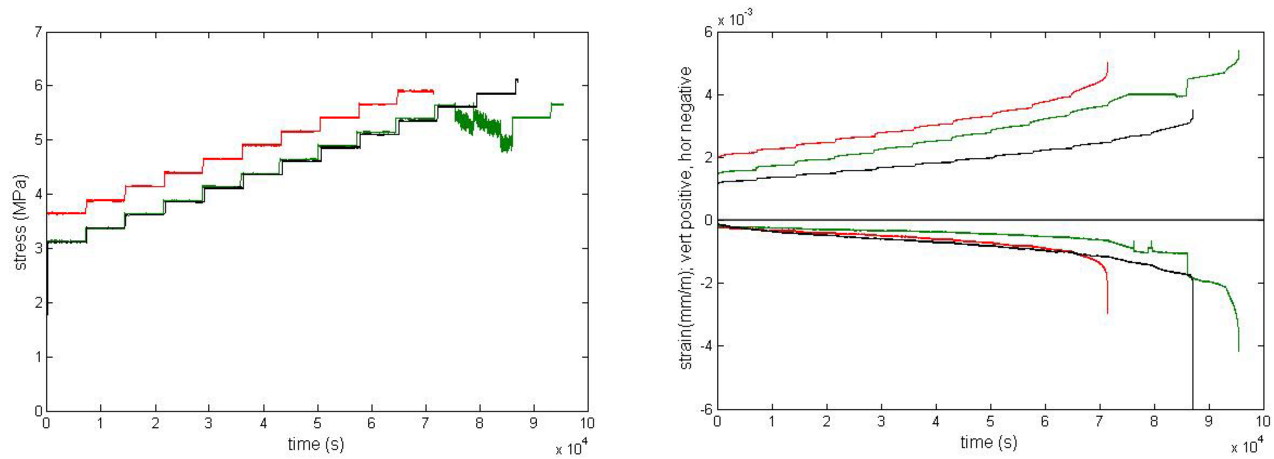
Table 1. Results of monotonic compressive tests on brick, mortars and masonry columns

Samples	Compressive tests (f_c) [MPa]	3-point bending test (f_t) [MPa]	Young's modulus (E) [MPa]
Brick (module 50)	9.97±2.24 (20)	3.12±0.47 (10)	1314
Mortar:			
-air hardening lime	0.79±0.09 (10)	0.52±0.03 (5)	100 (2)
-hydraulic lime	4.47±0.28 (10)	1.34±0.11 (5)	532 (2)
-cement	34.5±3.02 (10)	5.82±0.24 (5)	3325±1643 (10)
-hybrid lime/cem.	4.20±0.90 (12)	1.13±0.24 (6)	235±190 (10)
	Compressive tests (f_c) [MPa]	Young's modulus (E) [MPa]	Vertical strain ($\varepsilon_{vert,max}$) [mm/m]
Masonry columns:			
-air hardening lime	4.76 (2)	1374 (2)	-
-hydraulic lime	6.3±0.9 (3)	2136±45 (3)	4.17±0.80 (3)
-cement	5.7±0.2 (3)	2601±160 (3)	3.90±0.36 (3)
-hybrid lime/cem.	7.3±0.3 (3)	2902±320 (3)	3.83±0.87 (3)
Legend: presentation of test results: *average value±standard deviation* (*no. of samples*)			

Accelerated Creep Tests

As proposed in literature (Binda 1993), accelerated creep tests were performed to assess the damage accumulation in masonry under sustained stresses. The aim is to obtain data during a

short-term test, which can be used to deduce the parameters, necessary to simulate and assess the strain and damage evolution on the long term, for example during the life-time of a masonry structure. Three accelerated creep tests were performed for each type of mortar, starting at a stress level of 50-60 % of the compressive strength and increasing with stress increments of 5% until failure of the specimen. In between two stress increments, a constant stress level was maintained during a period of at least 2 hours, but even then, failure often occurred during the stress increment and no tertiary creep phase was reached. The stress-time and strain-time graphs of the accelerated creep tests on the lime mortar columns are presented in Figure 3. During one of the tests, the stress level could not be kept constant at the end of the testing period. The data presented in table 2, indicate that lower stresses were reached at failure, but no remarkable strain increase can be noticed in comparison with the compressive tests.



(a) (b)

Figure 3. Stress-time (a) and strain-time (b) evolution for three accelerated creep tests on masonry columns with hydraulic lime mortar

Table 2. Results of accelerated creep tests

	Accelerated creep tests ($f_{c,creep}$) [MPa]	Time to failure (t) [min]	Vertical strain ($\varepsilon_{vert,max}$) [mm/m]
Masonry columns:			
-hydraulic lime	5.9±0.2 (3)	1000-4500	4.77±0.55 (3)
-cement	5.2±0.4 (3)	1000-4500	4.07±0.40 (3)
-hybrid lime/cem.	6.8±0.3 (3)	1000-4500	2.60 (2)
Legend: presentation of test results: *average value±standard deviation* (*no. of samples*)			

Long-term Creep Tests

In order to assess the long-term behaviour of masonry under persistent loading, 9 long-term creep tests were set up. For each mortar type, respectively lime mortar, cement mortar and lime-cement mortar, three masonry wallets were tested. These three wallets were initially loaded at 50, 65 and 80 % of the compressive strength, obtained by averaging the results of the monotonic compressive tests. The evolution of the vertical strain is indicated in Figure 4.

The preliminary results of the long-term creep tests clearly show the different phases of the creep curve. At initial loading, an elastic deformation is measured, which depends on the load level, except for the cement mortar at 80% of its compressive strength. This sample has been built in a former test program, clearly demonstrating deviating stiffness properties. The graph also shows a primary creep phase with decreasing strain rate, which had a duration of approximately 3-4 months. At the current phase, all wallets still have a linear increasing deformation (vertical as well as horizontal) as a function of time. This means that all wallets still are in the secondary creep phase, except for the lime mortar column at 80% which failed at 855 days, at a few hours after a small stress increase.

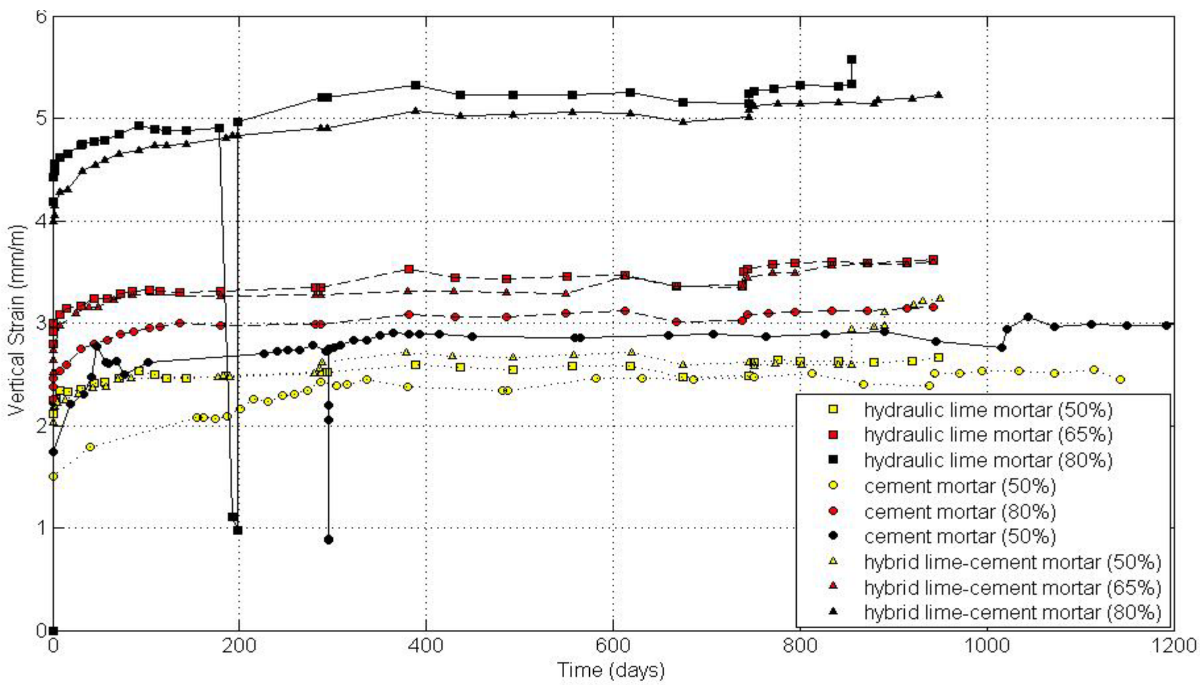


Figure 4. Vertical deformations as a function of time during long-term creep testing

For two wallets an unloading and reloading cycle was included. The unloading revealed a significant portion of non-reversible deformation. After reloading, the strains reached the original level again. In relation with the different types of mortar used, it can be stated that the behaviour of the different samples is quite similar. Also in the secondary creep phase, a difference in speed of vertical deformations is hardly noticeable. One could even state that the lower stress levels only exhibit a very limited creep behaviour. The latter demonstrates that probably higher stress levels are required to enforce creep behaviour within an acceptable test period. Therefore, a small increase in stress level of 5 % of the compressive strength was applied after a measuring period of 750 days. After this stress increase, a new equilibrium with constant strain rate was reached. The primary creep phase at this stress increment is shorter than at the initial loading. Although a higher constant stress level is maintained from that point, no marked difference in strain rate is noticeable yet.

Concluding from previous remarks and regarding the aim to complete this type of creep testing within an acceptable period, it is not possible to perform long-term creep testing on masonry maintaining a constant stress level throughout the duration of the test. In order to determine the

time step during which the stress level has to be kept constant in between two stress increments, the duration of the primary creep phase has to be considered. Figure 4 shows a duration of the primary creep phase of 3-4 months after the first loading step, which is slightly higher than the 70-80 days for longitudinal strains, proposed during previous creep tests (Pina-Henriques 2005). This can be explained by the observation that the length of the primary creep phase depends on the magnitude of the load increment. Here, the 50-60 % load step is much higher than the 10 % load increment considered by Pina-Henriques, and therefore a longer time period is needed before a constant strain rate is reached. Concerning these remarks, the results of the previously discussed accelerated creep tests have to be processed carefully, as no constant strain rate has been reached yet.

ACOUSTIC EMISSION TESTING PROGRAM

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. The technique is proposed here as a monitoring technique for the detection of damage initiation and the assessment of the rate of damage evolution during creep deformation. As masonry is a highly heterogenic material, with different speeds of propagation of the energy waves in different directions, localization of damage is very difficult. The main features of an AE signal (burst type) are schematically indicated in Figure 5.

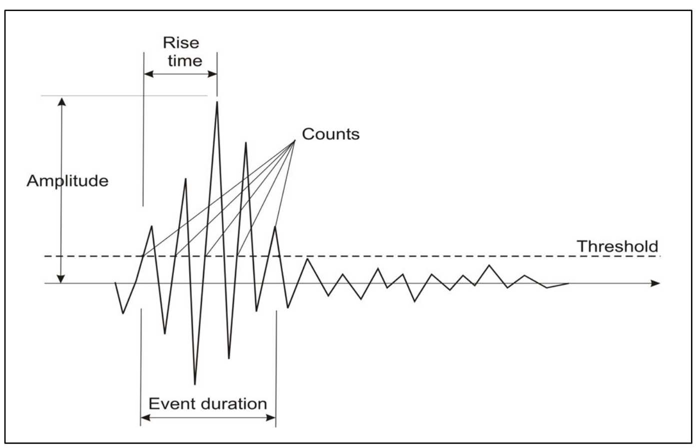


Figure 5. Main features of an AE signal (burst type)

Examples of damage assessment by AE monitoring in brittle materials under mechanical loading can be found in literature (Grossi 1996; Eberhardt 1997; Colombo 2003). References describing the use of this technique on masonry on the other hand are to a much smaller degree available in literature, especially regarding the monitoring of damage evolution in masonry as a consequence of long-term creep deformation. A practical study of the creep phenomenon in masonry towers combined with acoustic emission monitoring was performed by Carpinteri (Carpinteri 2007).

In order to evaluate the stability of the creep deformation at a certain stress level, acoustic emission monitoring was performed before, during and after the small stress increases on the masonry wallets, subjected to the long-term creep testing, as discussed above. Simultaneously

with the acoustic emission monitoring, the vertical and horizontal strains resulting from the stress increase were measured as indicated in Table 3.

Table 3. Stress increase, resulting stress level and deformations during AE monitoring

Test column	Test nr.	Stress increase	Constant end stress	Δε vert	Δε hor	ΔAE counts
		(% f_c)	(% f_c)	(mm/m)	(mm/m)	(counts)
9 – hydraulic lime mortar	1A	5	90	0.24	0.175	18300
30 – lime/cement mortar	2A	2	87	0.03	-0.035	300
28 – lime/cement mortar	2B	5	65	0.12	0.02	4030
28 – lime/cement mortar	1B	10	60	0.34	0.18	21970

The stress increments were performed stress controlled by manually increasing the pressure in the hydraulic jacks. The transient sound waves were detected by means of two AE sensors with a frequency range from 250-700 kHz, one on each side of the specimen at a distance of 19 cm from each other. The sensors are attached to the masonry by means of a thin metal plate which is carefully glued on the leveled surface. A vacuum grease is used as a couplant in between the sensor and the metal plate. The preamplifier is set to 49 dB and a threshold level of 34.5 dB is applied. As the number of detected counts is proportional to the total emitted energy, the elastic strain during stress increase, which is related to the total damage, will be compared to the total amount of counts detected during stress increase (Eberhardt 1997). As indicated in Figure 6, a linear relation between these parameters is found when the instant, elastic deformation is considered.

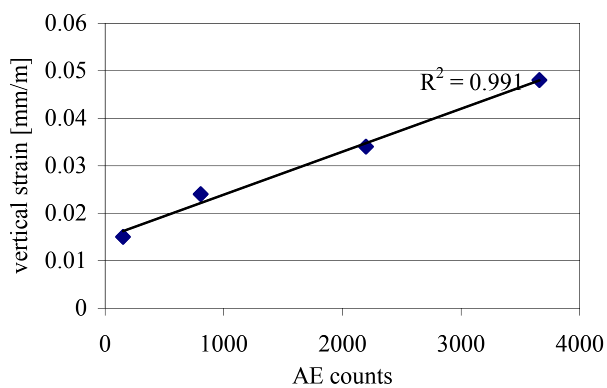


Figure 6. Relation between elastic deformation and total amount of counts during stress increase

After the stress increment, the acoustic emission activity was monitored for a period of several hours up to a period of 7 days. Figure 7 presents the detected events during a period of 2 hours after the stress increase. The first test specimen, column 30, shows very little damage during and after the stress increase, which corresponds to the very small strain increments. Column 28, test 2B, shows higher levels of damage during and after the stress increase, corresponding to the higher strain increments indicated in Table 3. After this monitoring period of two hours, the level of AE bursts decreases and the inclination of the cumulative curve fades away. The monitoring of column 9, test 1A, displays a very different behaviour. The large amount of AE hits decreases rapidly after the stress increment, which only lasts for a few minutes, but within the following monitoring period, a persistent damage detection is present and the cumulative curve shows no

significant decrease in damage rate near the end of the monitoring period. This observation was a premonition for a failure within the next 6-10 hours of the wallet. Unfortunately, no data are available for the acoustic emission monitoring at the moment of failure as the collapse occurred during the night.

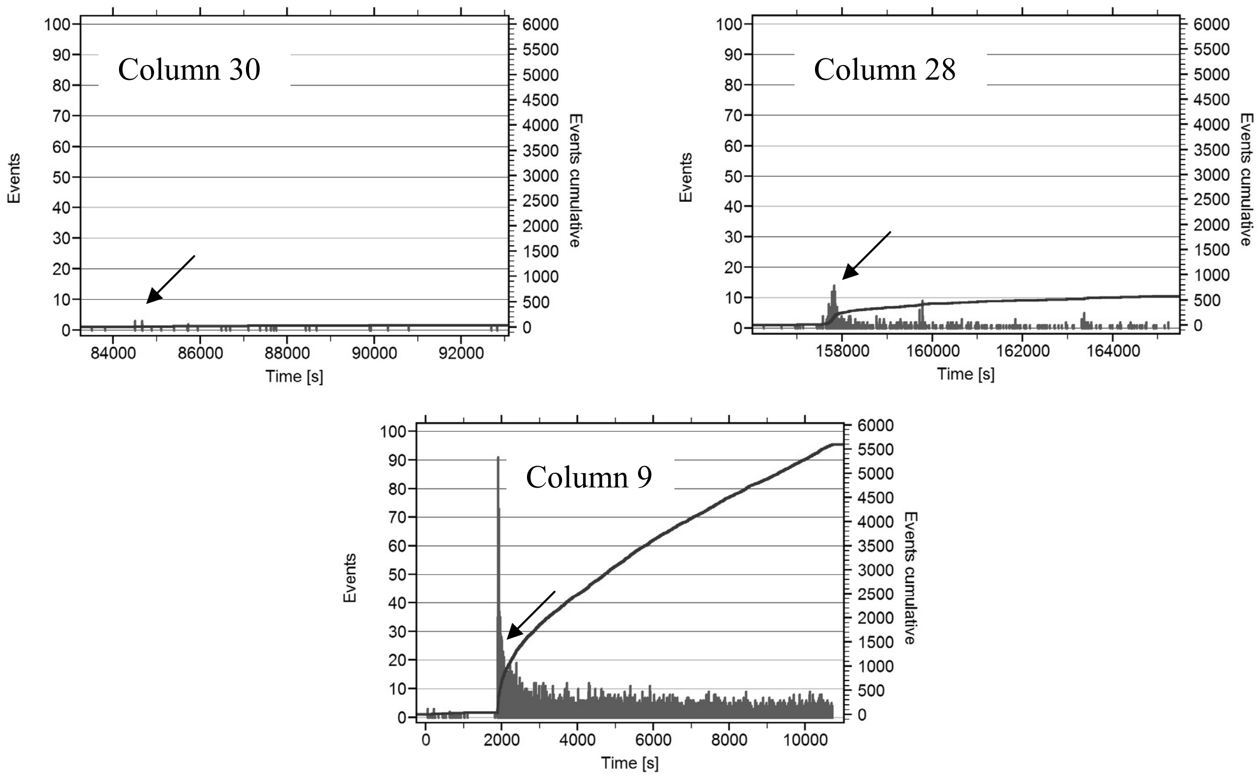


Figure 7. Monitoring of acoustic emission events over a period of 2 hours after stress increase (left axis), cumulative acoustic emission events (right axis). The stress increase is indicated

From these tests can be concluded that AE monitoring appears to be a promising technique, able to monitor the unstable damage-accumulation in masonry, but there are certain drawbacks present. During the test program discussed above, the moment of critical behaviour was known in advance as the strain increment was triggered by means of an externally imposed stress increment. Even then the question remains which threshold level of event rate has to be considered in order to evaluate at which point the creep deformation becomes critical. Secondly, as continuous monitoring over large periods of time is not always possible, an optimal time interval and time duration for the monitoring campaigns has to be established. To encounter these problems, further research will be performed, including periodical acoustic emission monitoring of masonry columns with different compositions, during long-term creep tests. During these tests, the constant stress level will be increased in periods of three months from very low stress levels at which no damage is expected up till high stress levels where the creep failure mode is active.

CONCLUSIONS

An extensive test program was set up to evaluate the long term behaviour of masonry under monotonic and sustained loading. This test program involved short-term monotonic compressive and accelerated creep tests and long-term creep tests on masonry wallets with three types of mortar compositions. An extension of this test program, including an additional air-hardening lime mortar, is put in prospective and therefore, present lacks and possible improvements of the current test program were indicated. In addition, some recent collapses in Belgium indicated that monitoring our monumental masonry buildings is an urgent task. Therefore, a reliable monitoring system is required to perform repetitive health-monitoring of historical masonry structures where safety is in doubt, thereby transferring the knowledge gained by performing masonry creep tests into practice. The acoustic emission technique is proposed as a non-destructive technique for the assessment of damage evolution in masonry and some first test results were presented. These results showed a persistent damage detection by means of acoustic emission when failure was at hand, indicating a positive evaluation towards the applicability of this technique for the monitoring of long-term damage accumulation in masonry.

ACKNOWLEDGEMENTS

The authors express their thanks to the Flemish Fund for Scientific Research (FWO) for the doctoral grant, offered to Els Verstrynge.

REFERENCES

Anzani A., Binda L., Mirabella Roberti G., “The effect of heavy persistent actions into the behaviour of ancient masonry”, Materials and structures, Vol 33, nr. 228, pp. 251-261, 2000

Binda L., Anzani A., “The time-dependent behaviour of masonry prisms: an interpretation”, The masonry society journal, Vol 11, nr. 2, 1993

Boukharov G.N., Chanda M.W., Boukharov N.G., “The three processes of brittle crystalline rock creep”, Int. J. Rock Mech. Min. Sci. & Geomech., Vol 32, nr. 4, pp. 325-335, 1995

Carpinteri A., Lacidogna G., “Damage evolution of three masonry towers by acoustic emission”, Engineering structures 29, pp. 1569-1579, 2007

Challamel N., Lanos C., Casandjian C., “Creep damage modelling for quasi-brittle materials”, European Journal of Mechanics A/solids 24, pp. 593-613, 2005

Colombo S., Main I.G., Forde M.C., “Assessing damage of reinforced concrete beams using b-value analysis of acoustic emission signals”, Journal of materials in civil engineering, 15:3, pp. 280-286, 2003

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

Ferretti D., Bazant Z.P., “Stability of ancient masonry towers: Moisture diffusion, carbonation and size effect”, Cement and Concrete research, Vol 36, pp. 1379-1388, 2006

Grossi C.M., Esbert R.M., Suarez del Rio L.M., et al., “Acoustic emission monitoring to study sodium sulphate crystallization in monumental porous carbonate stones”, Studies in conservation, Vol 42, pp. 115-125, 1997

Ignoul S., Schueremans L., Binda L., et al., “Creep behavior of masonry structures – failure prediction based on a rheological model and laboratory tests”, Proc. Of the 5th int. seminar on structural analysis of historical constructions, Vol 2, pp. 913-920, 2006

Lenczner D., “Creep and prestress losses in brick masonry”, The structural engineer, Vol 64B, nr. 3, 1986

Papa E., Talierco A., “A visco-damage model for brittle materials under monotonic and sustained stresses”, International journal for numerical and analytical methods in geomechanics, Vol 29, nr.3, pp. 287-310, 2005.

Pina-Henriques J.L., “Masonry under compression: failure analysis and long-term effects”, Dissertation, University of Minho, Guimaraes, Portugal, 2005