MECHANICAL AND ACOUSTIC EMISSION CHARACTERIZATION OF LIME-BASED MASONRY

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Abstract:

This paper deals with an improved representation of the progression of damage in lime-based masonry under cyclic loads using the Acoustic Emission (AE) technique. Stress-strain relations are a familiar concept in engineering which detail the elastic-plastic behaviour of the material. During AE monitoring, AE activates with the increase of stress and initiation of micro fracture due to local changes in the material structure. The population of AE events registered at an increasing stress levels provides information on the structure’s integrity. In the present study, masonry couplets and walls were built with clay bricks in combination with two different mortar types: hybrid lime-cement (LC) and lime hydrate mortar (LH). One set of experiments focuses on masonry couplets and another set of experiments focuses on masonry walls, both under compression. The AE-based damage quantification is validated by a comparative analysis with strain measurements from Linear Variable Differential Transformers (LVDTs). In conclusion, results indicated that at initial stages the AE trend was closely related to axial strain for LC specimens and lateral strain for LH specimens. Regardless of size effects with respect to masonry couplets and walls, there was no significant difference in damage progress.

1. Introduction

Over many centuries, the traditional binder in historical monuments is found to be lime. Even today, lime mortar is primarily used in most repair and restoration work of historic buildings [1-3]. Lately, the combination of lime with cement is used because it is quick to set and has high compressive strength. Mortars are bound with the bricks to form masonry and behave in a complex manner. Mechanical properties are well documented for lime-based masonry in literature [4-6] but there continues to be a gap in understanding the behaviour of masonry under compression more precisely. This leads to a search for a non-destructive technique (NDT) to monitor the structure in real-time analysis.
Acoustic emission (AE) is an NDT which detects the release of high frequency elastic waves from a localized source generated by a crack within a material [7]. AE has been recognized for its ability in monitoring the damage progression in materials [8-10] and masonry structures [11,12]. Quantification of damage in lime-based masonry due to time-dependent progressive deterioration has been addressed in [13].

This paper contributes to the understanding of the mechanical behaviour of lime-cement and lime hydrate masonry under cyclic compressive loads using AE technique. From the literature [14], it is important to know whether the effect of size has an impact on the mechanical behaviour and progression of damage in masonry. Hence, in this study, we analyze the size effects of masonry couplets (combination of two bricks and one mortar layer) and masonry walls (seven bricks in height with running bond). This study shows how the degradation process in lime-based masonry will effectively be assessed by strain measurements and by AE data.

2. Methods and materials

2.1 Materials

Red clay bricks were used with dimensions 188x88x63 mm$^3$ having an average compressive strength of 11.8 N/mm$^2$ (Standard deviation SD = 2.41 N/mm$^2$) and average Young’s modulus of 1238 N/mm$^2$ (SD = 208 N/mm$^2$). Two different types of mortar were chosen, the composition of the mortar is as shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Lime-cement$^1$</th>
<th>Lime hydrate$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>70 %</td>
<td>74 %</td>
</tr>
<tr>
<td>Binder</td>
<td>15 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Water</td>
<td>15 %</td>
<td>17 %</td>
</tr>
</tbody>
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The binder for the preparation of:
$^1$ hybrid lime-cement mortar is a mixture of 66.7 mass-% of calcic lime [CL90S] and 33.3 mass-% of cement [CEM1 42.5R]
$^2$ lime hydrate mortar is calcic lime, CL90S

2.2 Methods and equipment

Two types of masonry specimens (couplets and walls) were tested under cyclic compressive loads to investigate the progressive damage by means of AE. Couplets were built out of two stacked bricks with overall dimensions 188x88x138 mm$^3$, see Figure 1(a). Walls were built with seven courses in height with overall dimensions 388x88x515 mm$^3$, see Figure 1(b). In all the specimens, an average mortar joint thickness of 12 mm was maintained. Two samples for each type of masonry were tested at the age of 28 days. The lime hydrate (LH) specimens were too ‘young’ at the time of testing as hardening relies solely on carbonation.

Cyclic compression tests were performed on the specimens using a hydraulic press testing machine ‘Instron’ with a capacity of 2,500 kN. The loading rate was 0.25 kN/sec. A thin layer of gypsum was applied on top and bottom of the specimens and slightly pressed under the platens of the hydraulic press to make it a flat surface for an equal distribution of load. Up to
7-9 loading and unloading cycles were done. In every new loading phase, a higher peak load value was reached. The peak load was maintained by 1.5 minutes and the successive cycles were separated by a time of approximately 1.5 minutes. In the final loading step, the load was increased until the ultimate failure of the specimen. Linear Variable Differential Transformers (LVDT) were used to measure the deformations. For masonry walls, the displacement was recorded across two mortar joints in vertical direction at three locations (3A-3B; 4A-4B; 2A-2B) and one mortar joint in horizontal direction (1A-1B). For masonry couplets, the displacement was recorded across only one mortar joint in vertical direction (1A-1B).

For masonry walls, AE data was recorded by a Vallen AMSY-6 system with six channels in an ASIP-2 board connected to a PC, with a sampling rate of 10 MHz. For masonry couplets, AE data was recorded by a Vallen AMSY-4 system with four channels. In both cases, piezoelectric sensors with a frequency bandwidth 100-450 kHz were attached to the specimens by means of a hot-melt glue. The set-up of the sensors was symmetrical with respect to the mid-section of the specimens as shown in Figure 1. The built-in band pass filter had a frequency range from 50-850 kHz for signal processing. Pre-amplifiers AEP5 with 34 dB gain were used. A threshold of 38.5 dB was set to eliminate the background noise.

![Figure 1. Test setup for compression test on masonry (a) couplet and (b) wall.](image)

During the fracture process, AE hits exceeding the threshold are registered and subsequently grouped into AE events. For progressive damage evaluation in masonry, the Japanese Society for Non-Destructive Inspection proposed two AE indices in order to estimate the critical damage levels [15,16]. The first parameter is called the ‘Load ratio’. It is calculated as the ratio between the load at the onset of AE activity in the subsequent loading step to the maximal load reached at the previous cycle. When the Load ratio is above 1, Kaiser effect is present, which indicates ‘stress’ memory in a material for the previously applied maximum load level. When the Load ratio is below 1, Felicity effect is present, which evidences the occurrence of micro-structural damage before previous maximum load. In this study, to calculate the Load ratio, the onset of AE activity is determined by the occurrence of at least 10 events in a time interval of 10 seconds. The second parameter is called the ‘Calm ratio’. It is calculated as the ratio of AE
events registered during unloading to the AE events registered during the whole loading-unloading cycle.

3. Results and discussion

3.1 Stress-strain

Figure 2 shows representative stress-strain curves from the compression tests on masonry couplets and masonry walls. Two interesting observations can be made by comparing the type and size of masonry. Firstly, the lime-cement masonry has higher compressive strength than the lime hydrate masonry. Secondly, masonry couplets present a higher compressive strength compared to masonry walls.

3.2 Mechanical behaviour and AE trends

AE data obtained for cyclic compressive tests on both masonry types with different size (couplet and wall) are analysed. For this analysis, AE events generated in each cycle and localized all over the specimen were considered. The normalised cumulative AE events in relation to the normalised load and time is shown in Figure 3(a) and (b). The cumulative AE events is the total number of AE events received from the beginning of the test to a certain moment.

In Figure 3(a), the load levels for the LC wall are very low compared to the LC couplet, which results from an underestimation of the strength of the LC walls prior to testing. In Figure 3(b), for the LH couplet and wall, a good agreement between the load levels can be observed. In general, AE events registered for LC specimen are much higher than LH specimen. The reason for such a behaviour in AE activity is due to two reasons. Firstly, the LH specimen has lower mechanical strength and less brittle nature of cracking compared to LC specimen. Secondly, at higher load levels the formation of micro fracture in LH specimen largely increases AE attenuation. As can be seen in Figure 3(a) and (b), the AE activity increased progressively for successive load cycles. In both cases, irrespective of size effects, the cumulative AE events
remain similar apart from some scatter in the trend. Vertical dotted lines in Figure 3(a) and (b) are drawn at those moments when the macro-crack was visually observed.

In Figure 3(a) and (b), the measured stiffness (E) for each load cycle normalised by the initial stiffness (E₀) of the first load cycle vs. the number of AE events is shown. The stiffness reduction with the increase in AE events for the successive load steps is observed. In this study, the elastic modulus (E) was calculated at the stress level in a current cycle that exceeds the previously applied maximum stress, and corresponding AE events were considered. For the correlation, a logarithmic fitting function is used.

In Figure 4(a), for the first load cycles, the number of AE events is less than 5,000. In the last load cycles, the number of AE events is reaching almost 15,000 to 20,000 for the LC wall and couplet with the stiffness modulus decreasing by approximately 30 to 40%. Similarly, in Figure 4(b), the number of AE events is reaching almost 8,000 to 11,000 for the LH wall and couplet with the stiffness modulus decreasing by approximately 20 to 30%. In both cases, as the stress approaches the ultimate strength of the masonry, an increase in AE activity at the cycle (norm. load = 80%) prior to failure is observed. This is due to the signals registered from spalling of the mortar. In the last loading cycle (norm. load = 95%), the macro-cracks followed by crushing of masonry leads to a huge drop in stiffness and an increased number of AE events.

In general, as observed from these results for couplets and walls, LH specimen quickly deteriorates compared to LC specimen, which is dependent on the stiffness characteristics of the masonry constituents. However, in recent studies [17,18] this hypothesis has been highly investigated in different combinations of lime-based masonry. From the stress-strain graph (see Figure 2), LH specimen has low stiffness and large deformability compared to LC specimen. As can be seen in Figure 4, LC specimen has a better correlation between the stiffness and AE events compared to LH specimen. Another observation indicates that the couplet have high stiffness and large number of AE events compared to the walls. However, the masonry couplets and walls of the same mortar type have the same shape of trend irrespective of size effect.

In Figure 5(a) and (b), the normalised load vs. the number of AE events is shown. The increasing load values leads to higher AE activity which is due to more damage induced by
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crack initiation and propagation. These trends illustrate that the correlation between the normalised load and number of AE events is slightly better than the correlation between the stiffness loss and the AE events.

3.3 AE activity during cyclic loading

In Figure 6(a) and (b), the trend represents the AE events accumulated during the loading and unloading phase of each loading cycle. The number of AE events is shown with respect to the normalised load during each loading step. Here, AE activities are grouped into two categories namely ‘primary AE activity’ and ‘secondary AE activity’. As can be seen from the results, AE events were registered during the loading phase of subsequent loading cycles due to crack formation under compressive loading referred to as primary AE activity. Similarly, AE events were registered during the unloading phase of subsequent loading cycles due to friction between the existing crack surfaces referred to as secondary AE activity.
For LC specimen and LH specimen, the loading phase of the first cycles has higher AE activity which indicates the nucleation phases of micro-cracking in masonry. Upon continuing of the test, a sudden increase in secondary AE activity is observed by the change of slope in the trend (arrows in Figure 6). On approaching the ultimate strength of the masonry, the secondary AE activity is found to be dominant as a consequence of deterioration of the material's microstructure. Hence, the AE activity during the unloading phase appears to be an interesting characteristic to further investigate the fracture growth.

![Figure 6. AE activity during loading and unloading phase for (a) lime-cement masonry and (b) lime hydrate masonry.](image)

3.4 AE and strain-based damage quantification

Load ratio and Calm ratio are applied to quantify the damage progress in masonry under cyclic compressive loading. Load ratio characterizes the damage based on the stress level at the onset of AE activity. Calm ratio is applied to assess the damage during unloading due to crack closure and rubbing. As previously explained, these two AE indices are important as they characterize the progression of damage during the loading and unloading phases. By combining both AE indices, Load and Calm ratio, this scheme classifies the damage into three zones: minor, intermediate and heavy damage [15,16]. The damage quantification limits for Load ratio (0.9) and Calm ratio (0.05) were developed from AE evaluation criterion in bending load for RC beams [16]. However, the same limits are used here to investigate their applicability for identifying the progress of damage from sub critical to critical stage in masonry under compression.

In this study, two different research questions are addressed. Firstly, the accuracy of AE-based damage quantification has to be validated. Secondly, most recorded AE signals during unloading are attributed to the damage development. These questions are addressed by comparing AE-based damage quantification with deformation measurements. A comparative analysis was performed with the measured deformation from LVDTs in terms of strain values with the Calm ratios, as shown in Figure 7(a) and (b). The axial strains are obtained from one
LVDT in couplets and the average of three LVDTs in walls. The lateral strains are obtained from one LVDT in walls. Results from AE and LVDTs present a clear trend representing the damage progress. Irrespective of masonry type and size effects, the trend shifts from the sound zone (phase I) to the heavy damage zone (phase III) with little or no accumulation at the intermediate damage zone (phase II). There is no major difference observed in the trajectories to reach the heavy damage region.

![Graphs showing AE and strain-based damage quantification for lime-cement masonry and lime hydrate masonry.](image)

(a) Figure 7. AE and strain-based damage quantification for (a) lime-cement masonry and (b) lime hydrate masonry.

From the comparative analysis of the results of the lime-cement masonry, following observations are made, see Figure 7(a):
- For the LC couplet, AE is in good correlation with the axial strain throughout the experiment, except the last load cycle.
- For the LC wall, in the initial stage, AE is in good correlation with the axial strain. As the test continues, AE shifts apart from the axial strain. Nevertheless, AE is more close to axial strain rather than lateral strain.

For lime hydrate masonry, following observations are made, see Figure 7(b):
- For the LH couplet, from the initial to final stage, the AE-based trend line remains lower than the axial strain.
- For the LH wall, in the initial stage, AE is in good correlation with the lateral strain. In the last two load cycles, AE shifts apart from the lateral strain. Nevertheless, AE is in between lateral and axial strain.

The horizontal LVDTs were not installed in the couplets and therefore AE was not compared with lateral strains. In general, the interesting observation from these results is the shifting behaviour of AE in different masonry types. It can be seen that the AE trend either follows the axial strain or lateral strain or remains intermediate. Such behaviour is likely to be related with the AE activity in connection to the mode of cracking in the specimen. Usually, tensile type of cracks (mode I) are generated during the nucleation of cracks upon stress increase. Upon approaching the failure, the frictional activities in the crack surfaces generate shear type of AE
signals (mode II). The shifting behaviour of AE may be related to the change in the fracture mode of cracking from the tensile type to shear type of fracture. However, a further analysis is needed to confirm this hypothesis. On the other hand, the damage quantification limits seem to be too low and overestimate the damage grade for masonry under axial compression. Hence, in future, the Load-Calm ratio critical limits have to be calibrated with other NDT techniques. In this way, it provides the basis for damage quantification in masonry for laboratory and on-site applications.

4. Conclusion

In this study, the mechanical and acoustic emission behaviour of two different types of masonry with lime-based mortar is examined under cyclic compression. Walls as well as couplets are studied to investigate size effects. Firstly, the study focuses on comparing the AE and mechanical trends for lime-cement and lime hydrate masonry types. AE activity is strongly related to successive load levels, and a good correlation to the stiffness degradation of the material is observed. Secondly, the study focuses on the AE activity during cyclic loading. The presence of secondary activity has been indicated by the registered AE events during the unloading phase of a loading cycle.

Furthermore, the Load-Calm ratio in relation to strain values from LVDTs are applied to quantify damage. Irrespective of masonry type and size effects, the trend indicates similar trajectories to reach the heavy damage state. Comparison with strain measurements indicates that the damage quantification limits are to be revised. The trends of Load-Calm ratio from AE were in a reasonable agreement with the strain values from LVDTs. In general, AE is closely related to axial strain for LC specimens and lateral strain for LH specimens. Results demonstrate some interesting findings and raise questions about the mode of cracking for the two different types of masonry. A detailed study of the crack classification using the RA value and average frequency is a part of further work to investigate this hypothesis. Lastly, for masonry couplets and walls with respect to size effects, there was no significant difference in AE damage progress, apart from the registered number of AE events.

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