Numerical simulation of brick-masonry subjected to the double flat-jack test

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ABSTRACT: In the present paper, we describe the results obtained from double flat-jack tests performed varying the size of the masonry prism involved in the test. In addition, not only the deformations have been acquired, but also the acoustic emissions (AE), in order to get information about local cracking during the test. We present a meso-scale numerical model of the test, where every brick of the masonry is modeled in the details. Discrete cracks can arise both in the mortar joints and in the brick units. A good correlation is found between the amount of cracking simulated numerically and the experimental acoustic emissions for different prism sizes. The model is also able to catch the decrease in the compressive strength with increasing size. It is not possible to obtain an easy direct relation between the acoustic emission and the amount of cracking; nevertheless, it is possible to state that the two quantities are proportional to each other when increasing sizes are considered.

1 INTRODUCTION

Nondestructive and instrumental investigation methods are currently employed to measure and check the evolution of adverse structural phenomena, such as damage and cracking, and to predict their subsequent developments. The choice of a technique for controlling and monitoring reinforced concrete and masonry structures is strictly correlated with the kind of structure to be analyzed and the data to be extracted (Carpinteri & Bocca 1991; Anzani et al. 2000). For historical buildings, nondestructive evaluation (NDE) techniques are used for several purposes: (1) detecting hidden structural elements, such as floor structures, arches, piers, etc.; (2) determining masonry characteristics, mapping the nonhomogeneity of the materials used in the walls (e.g., use of different bricks during the life of a building); (3) evaluating the extent of the mechanical damage in cracked structures; (4) detecting voids and flaws; (5) determining moisture content and rising by capillary action; (6) detecting surface decay phenomena; and (7) evaluating the mechanical and physical properties of mortar and brick, or stone.

This study addresses some of the aforementioned problems deemed of special significance. The structural geometry was defined through the customary survey methods. Damage, cracking, and the evolution of these phenomena over time were assessed through a number of nondestructive techniques: tests with flat-jacks were conducted in order to evaluate the range of stresses affecting the structures; and at the same time, the cracking processes taking place in some portions of the masonry structures were monitored using the acoustic emission (AE) technique.

The AE technique has proved particularly effective (Carpinteri & Lacidogna 2002, 2003, 2006), in that it makes it possible to estimate the amount of energy released during the fracture process and to obtain information on the criticality of the process underway. Strictly connected to the energy detected by AE is the energy dissipated by the structure being monitored. The energy dissipated during crack formation in structures made of quasibrittle materials plays a fundamental role in the behavior throughout their life. Strong size effects are clearly observed in the energy density dissipated during fragmentation. Recently, a multiscale energy dissipation process has been shown to take place in fragmentation, from a theoretical and fractal viewpoint (Carpinteri & Pugno 2002a,b, 2003). Based on Griffith's assumption of local energy dissipation being proportional to the newly created crack surface area, fractal theory shows that the energy will be globally dissipated in a fractal domain comprised between a surface and a volume in the Euclidean space. According to fractal concepts, an ad hoc theory is employed to monitor masonry structures by means of the AE technique. The fractal theory takes into account the multiscale character of energy dissipation and the strong size effects associated with it. With this energetic approach it becomes possible to introduce a useful damage parameter for structural assessment based on a correlation between AE activity in a structure and the corresponding activity recorded on masonry elements of different sizes, tested to failure by means of double flat-jacks.

2 NONDESTRUCTIVE EVALUATION TESTS

2.1 *Flat-Jack Tests*

The single flat-jack test concerns the measurements of in-situ compressive stress in existing masonry structures by use of a thin flat-jack device that is installed in a saw cut mortar joint of the masonry wall (ASTM 1991a). The method is relatively non-destructive. After the slot is formed in the masonry, compressive stress at that point causes the masonry above and below the slot to get closer. Inserting the flat-jack into the slot and increasing its internal pressure until the original distance between points above and below the slot is restored, can thus measure the compressive stress in the masonry. The slots in the masonry are prepared by removing the mortar from masonry bed joints, avoiding disturbing the masonry. Care must be taken in order to remove all mortar in the bed joint, so that pressure exerted by the flat-jack can be directly applied against the cleaned surface of the masonry units. The state of compressive stress in the masonry is approximately equal to the flat-jack pressure multiplied by factors which account for the ratio K_a of the bearing area of the jack in contact with the masonry to the bearing area of the slot, and for the physical characteristic of the jack K_m. In fact, the flat-jack has an inherent stiffness which opposes expansion when the jack is pressurized. Therefore, the fluid pressure in the flat-jack is greater than the stress that the flat-jack applies to masonry, and a conversion factor K_m is necessary to relate the internal fluid pressure to the stress really applied. The average compressive stress in the masonry, f_m, can be calculated as:

$$f_m = K_m K_a p \,, \tag{1}$$

where, p is the flat-jack pressure required to restore the gage points to the distance initially measured between them. We performed the tests using rectangular flat-jack 240 mm × 120 mm wide and 7 mm thick (by BOVIAR s.r.l., Italy). Their calibration factor was K_m = 0.90-0.92. The loading procedure was synchronized and the pressure was applied with a manual equipment (pressure range between zero and 60 bar). The usual coefficient of variation of this test method can be estimated equal to 20%; therefore, at least three tests have been carried out on each area of interest.

The double flat-jack test provides a relatively non-destructive method for determining the deformation properties of existing unreinforced solid-unit masonry(ASTM 1991b). The test is carried out inserting two flat-jacks into parallel slots, one above the other, in a solid-unit masonry wall (Fig. 1). By gradually increasing the flat-jack pressure, a compressive stress is induced on the masonry comprised in between. The stress-strain relation can thus be obtained measuring the deformation of the masonry. In addition, the compressive strength can be obtained, if the test is continued to local failure. However, this may also cause damage to the masonry in the area adjacent to the flat-jacks. The tangent stiffness modulus at any stress interval can be obtained as follows:

$$E_t = \frac{\delta\sigma_m}{\delta\varepsilon_m} \,, \tag{2}$$

where, $\delta\sigma_m$ is the increment of stress, and $\delta\varepsilon_m$ is the increment of strain. On the other hand, the secant modulus is given by:

$$E_s = \frac{\sigma_m}{\varepsilon_m} \,, \tag{3}$$

where, σ_m and ε_m are the actual stress and strain in the masonry.

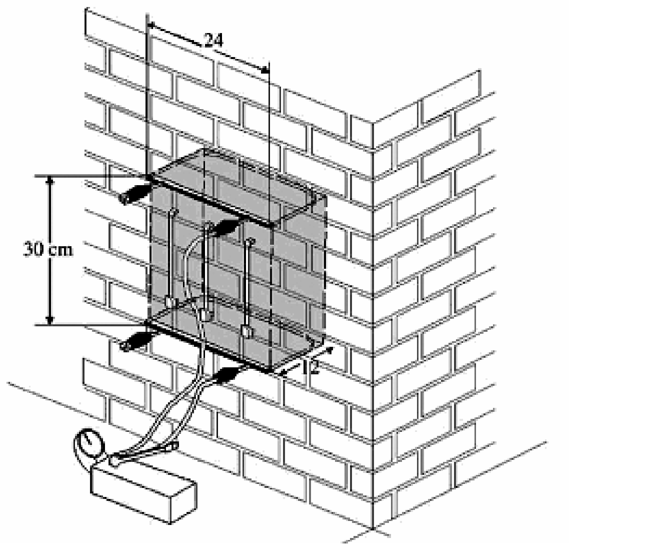


Figure 1. Typical set-up for in situ flat-jack test. The dimensions given are those of the specimen referred to as Vol. 1. (Reprinted from Gregorczyk and Lourenço 2000).

3 ACOUSTIC EMISSION MONITORING

Monitoring a structure by means of the AE technique makes it possible to detect the onset and evolution of stress-induced cracks. Crack opening, in fact, is accompanied by the emission of elastic waves that propagate within the bulk of the material. These waves can be captured and recorded by transducers applied to the surface of the structural elements (Fig. 2). The signal identified by the transducer (Fig. 3) is preamplified and transformed into electric voltage; it is then filtered to eliminate unwanted frequencies, such as the vibrations caused by the mechanical instrumentation, which are generally lower than 100 kHz. The signal is then analyzed by a threshold measuring unit which counts the oscillations exceeding a certain voltage value. This method of analysis is called ring-down counting (Pollock 1973; Brindley et al. 1973).

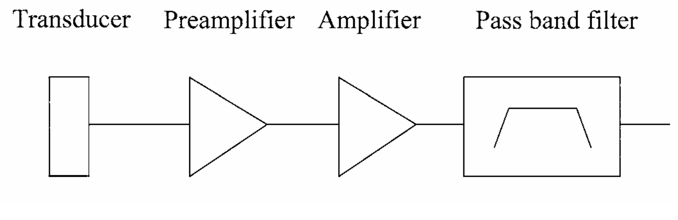


Figure 2. Acoustic emission measurement system.

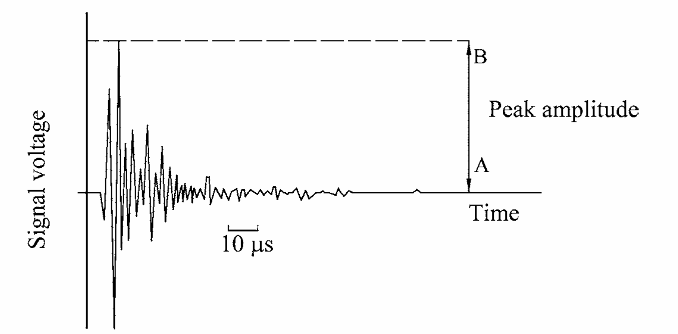


Figure 3. AE signal identified by the transducer.

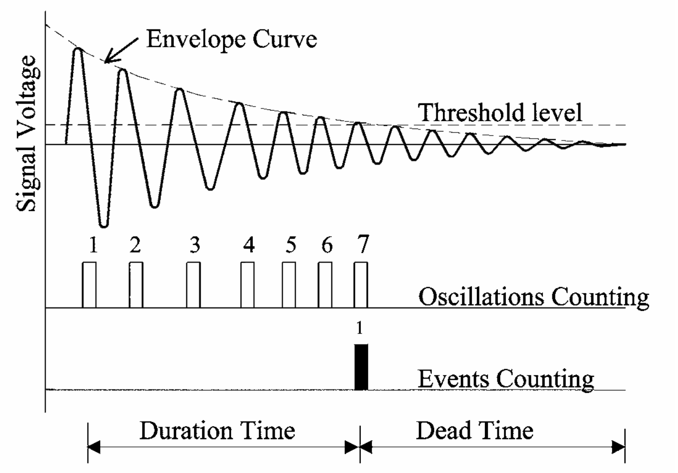


Figure 4. Counting methods in AE technique.

As a first approximation, the counting number, N, can be correlated to the quantity of energy released during the loading process. This technique also considers other procedures. For instance, by keeping track of the characteristics of the transducer and, in particular, of its damping, it is possible to consider all the oscillations produced by a single AE signal as unique events and to replace ring-down counting with the counting of events (Fig. 4).

3.1 *AE Data Acquisition System*

The AE monitoring equipment adopted by the writers consists of piezoelectric transducers fitted with a preamplifier and calibrated on inclusive frequencies between 100 and 400 kHz. The threshold level of the signal recorded by the system, fixed at 100 μV, is amplified up to 100 mV. The oscillation counting capacity is limited to 255 every 120 s of signal recording. In this way a single event is the result of two recorded minutes.

As specified in the literature (Ohtsu 1996), the maximum amplitude of direct non amplified signals is about 100 μV, hence, neglecting the attenuation by reducing to a few cm the distance of the transducer from the signal generation point, it can be assumed that the measuring system is able to detect the most meaningful AE events reflecting cracking phenomena in the masonry. Attenuation properties, in fact, depend on the frequency range: higher frequency components propagate in masonry with greater attenuation (Fig. 5). Based on experimental results, for a measuring area at a distance of 10 m, only AE waves with frequency components lower than 100 kHz are detectable (Carpinteri et al. 2005). With this system, the intensity of a single event is, by definition, proportional to the number N recorded in the time interval (event counting). Clearly, this hypothesis is fully justified only in the case of slow-crack growth (Holroyd 2000).

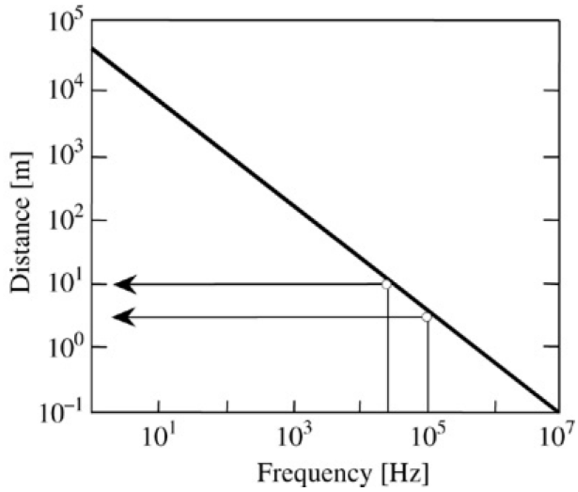


Figure 5. Acoustic emission relationship between signal detection distance and signal frequency.

4 FLAT-JACK AND AE TESTS

Flat-jack testing is a versatile and powerful technique that provides significant information on the mechanical properties of historical constructions. The first applications of this technique on some historical monuments (Rossi 1982) clearly showed its great potential. The test is only slightly destructive, and this is why it is now widely accepted and used by monument monitoring and rehabilitation experts (Binda & Tiraboschi, 1999; Gregorczyk & Lourenço, 2000). When double jacks are used, this test works according to the same principle as a standard compressive test. The difference is that it is performed in situ and the load is applied by means of two flat-jacks instead of the loading platens. The test method is based on the following assumptions: the masonry surrounding the slot notches is homogenous; the stress applied to the masonry by the flat-jacks is uniform and the state of stress in the test prism is uniaxial.

In order to assess the extent of damage in the zone monitored using the AE technique, a compressive test was conducted on the masonry through the combined use of double jacks and AE sensors (Fig. 6). The tests were carried out with flat-jacks measuring 24 × 12 cm^2. The cuts made into the masonry wall to obtain a smaller-sized specimen were made into two horizontal mortar joints spaced about 30 cm apart.

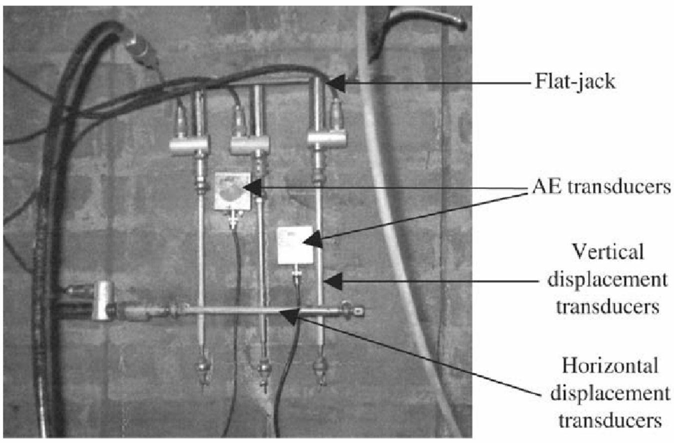
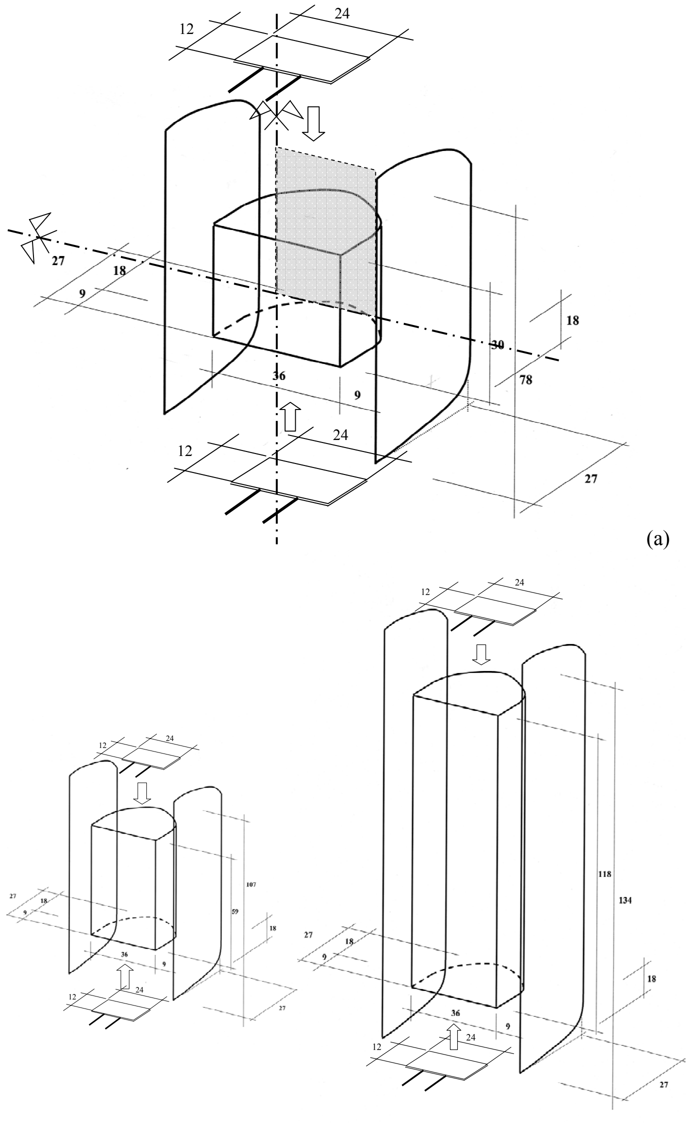


Figure 6. Combined flat-jack test and AE monitoring.

The minimum slenderness ratio of the specimens was h/t = 2.5, where h is the height of the prism comprised between the two flat-jacks and t = 120 mm the deepness of each flat-jack. This made it possible to reduce the friction effects on masonry behavior arising from the action of the flat-jacks.



(a)

(b) (c)

Figure 7. Schemes of the double flat-jack tests performed on different wall sizes.

During the tests, the stress-strain relationship of the masonry was determined by gradually increasing the pressure applied by the flat-jacks in the course of three loading-unloading cycles. Peak compressive strength was obtained from the load–displacement diagram, when the latter became highly nonlinear, denoting imminent failure. Compressive tests were performed on three different masonry portions. The prismatic masonry volumes tested in compression were delimited crosswise by vertical cuts (Fig. 7). Consequently, the in-situ test is equivalent to a compression test performed on specimens with different sizes, as shown in Figure 8. The tests were performed in keeping with the procedures specified in ASTM (1991b), other than for the vertical cuts produced in order to eliminate, in the cracked element, the influence of the adjacent masonry portions.

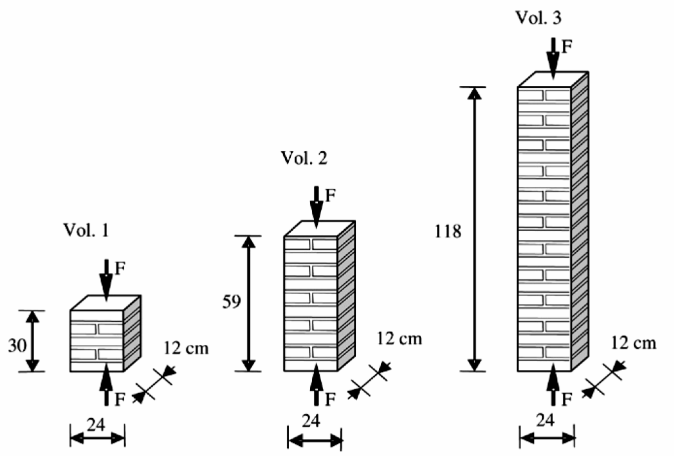


Figure 8. Equivalent masonry prisms tested in compression by means of double flat-jacks.

Figure 9 shows the results obtained from these tests for the intermediate element (Volume 2). Similar results were obtained for the other two elements. The figure also shows the three loading cycles performed as a function of time and the diagram of the cumulative number of AE counts. From the AE diagram it can be clearly seen that the material releases energy when the stress level reached previously is exceeded (Kaiser effect, Kaiser 1950). Moreover, from the diagram, we find that the cumulative number of AE counts at failure stress (i.e. immediately before the critical condition is reached) is $N_{\max} \cong 12000$. The experimental results obtained on the three masonry elements are summarized in Table 1.

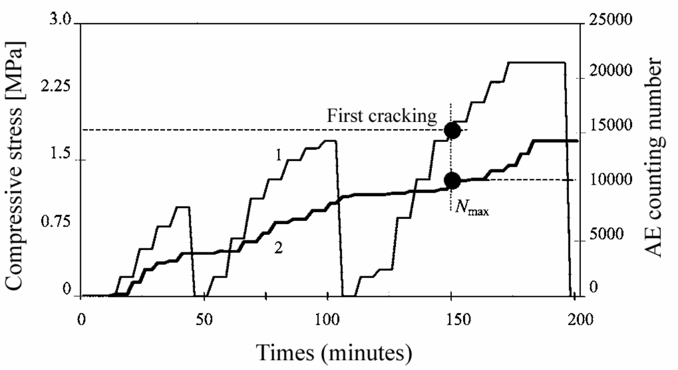


Figure 9. Double flat-jack test on Volume 2: cumulative number of AE events (2) versus cyclic loading (1).

Table 1
Experimental values obtained from flat-jack tests and AE measurements

Specimen	Volume (cm^3)	Peak stress (MPa)	$N_{\max}$ at σ_u
Vol. 1	8640	2.07	~6500
Vol. 2	16 992	1.61	~12 000
Vol. 3	33 984	1.59	~18 000

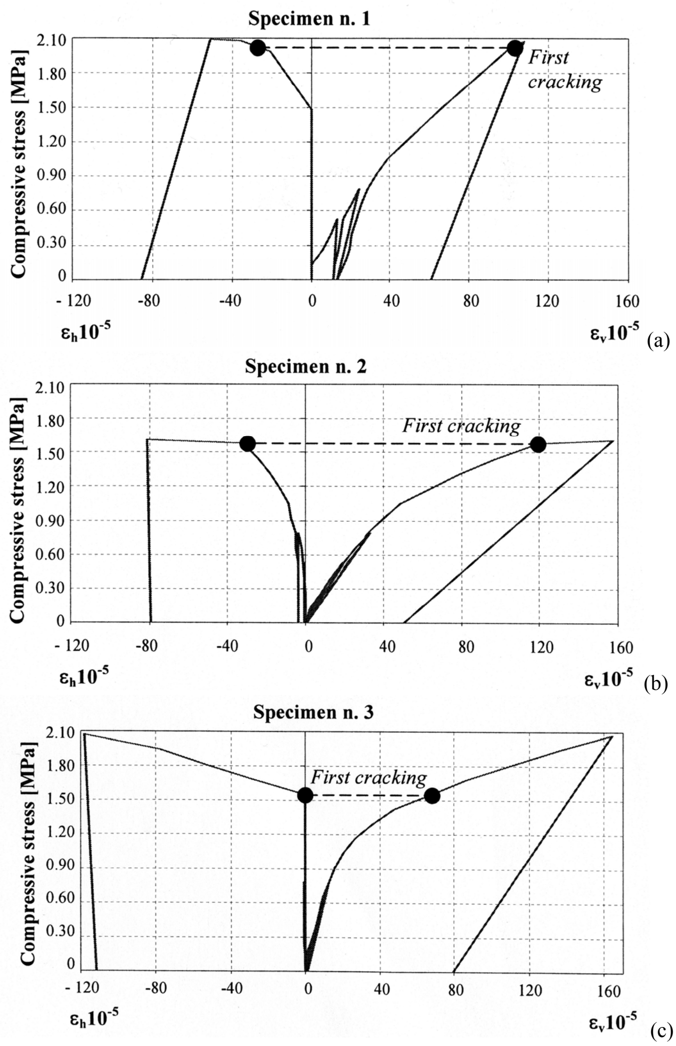


Figure10. Experimental results obtained from the double flat jack tests.

The stress-strain diagrams obtained from experiments are shown in Figure 10. The first cracking load, which reasonably corresponds to the compressive strength of the masonry, is deduced not only from a visual inspection during the test, but also monitoring when the horizontal strain suddenly increases.

5 NUMERICAL SIMULATION

The numerical model of the double flat-jack test was built exploiting the symmetry of the problem. Quadratic elements were used to represent both the brick units and the mortar joints. The failure of both components was assumed as ideal plasticity in compression and linear softening in tension. A fixed smeared crack model based on total deformation was used. All the analyses were performed with the Finite Element Software DIANA 9.1 (de Witte & Schreppers, 2005). The mechanical properties of the materials are summarized in Table 2.

Table 2
Mechanical properties adopted in the analysis

		Unit	Joint
Young's modulus	E	$6.0\ 10^{9}$ Pa	$1.0\ 10^{9}$ Pa
Poisson ratio	ν	0.15	0.15
Tensile strength	f_t	$3.0\ 10^{6}$ N	$3.0\ 10^{5}$ N
Fracture energy	G_f	50 N/m	10 N/m
Shear ret. Factor	β	0.01	0.01
Compress. strength	f_c	$3\ 10^{7}$ Pa	$1\ 10^{7}$ Pa

Figure 11a shows the mesh used to model the smallest specimen. Taking advantage of the problem symmetry, only one quarter of the geometry has been discretized. Figure 11b shows details about the loading and boundary conditions. The following procedure has been applied. First, a displacement is imposed to the top of the specimen.

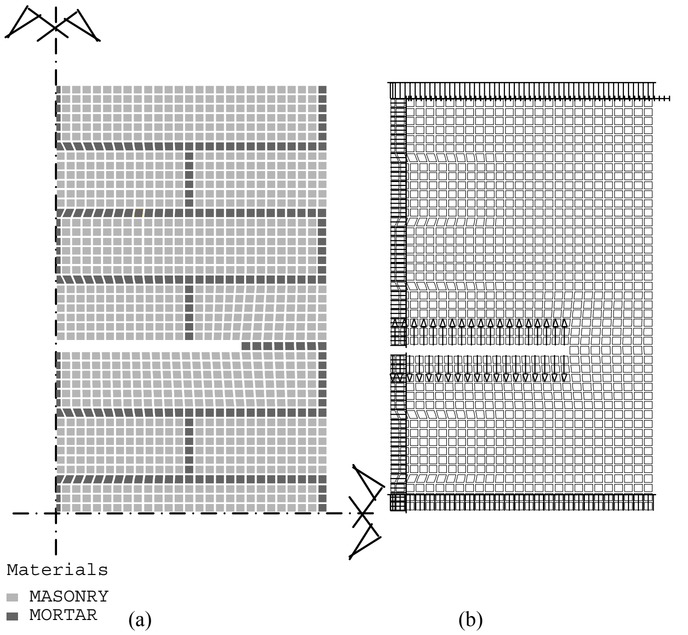


Figure 11. Finite element mesh adopted for Volume 1 exploiting symmetry (crf. Shaded area in Figure 7a). Mesh and materials (a); loads and boundary conditions (b).

The amount of such displacement can be calculated from another model of the masonry wall ("uncut"), without the cut where the flat-jack is placed afterward. This corresponds to the in situ configuration before the test. The imposed displacement is determined such then the vertical stress equals the in-situ value.

Afterwards, the pressure load in both sides of the cut is applied incrementally. When the pressure reaches the in-situ value of the vertical stress, the deformation of the model approaches the configuration obtained from the "uncut" model, exactly like in the experimental procedure.

If the load is increased further, the material comprised in between the two flat-jacks starts to damage. This behavior is caught correctly by the numerical model. Figure 12 shows the stress-strain diagrams obtained for the three different sizes. The arrows indicates the moment at which the horizontal strain suddenly increases, that corresponds to the first vertical cracking.

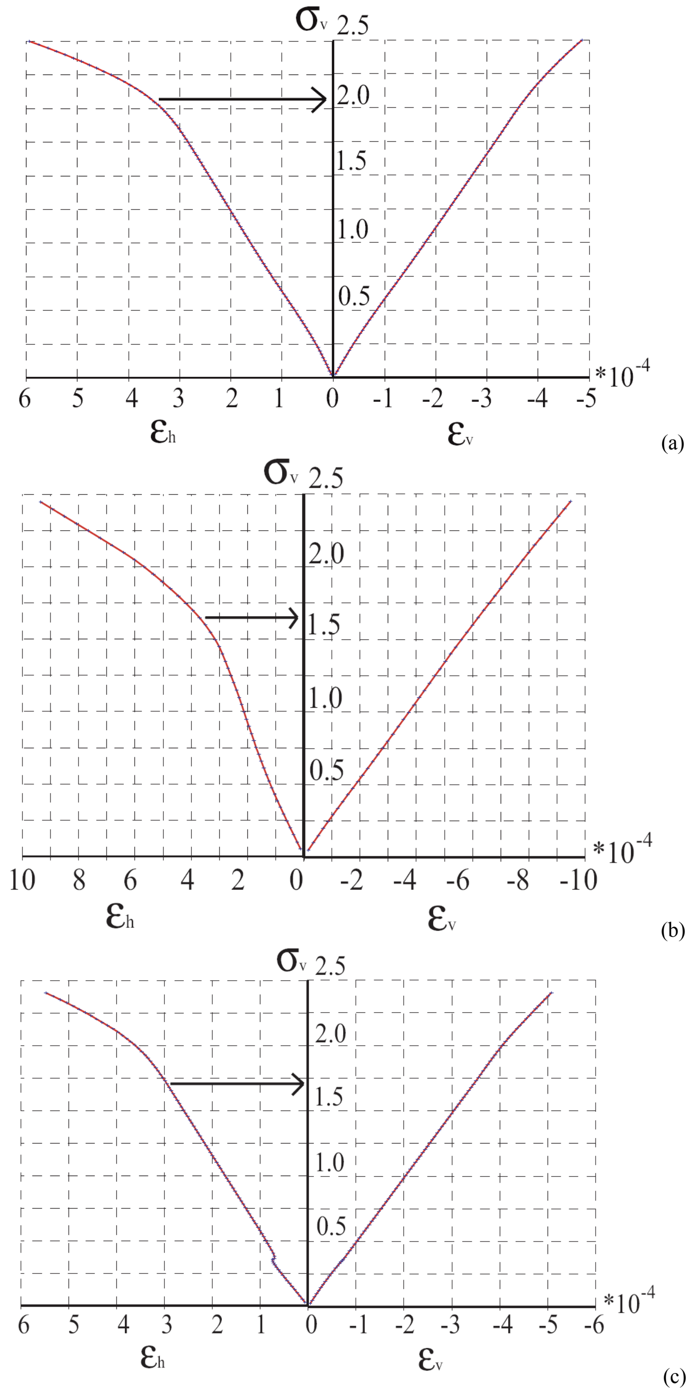


Figure 12. Stress-strain diagrams: Volume 1 (a); Volume 2 (b) and Volume 3 (c). The arrow indicates when first cracking spreads into the specimen.

The compressive strength decreases with increasing the specimen size in a rather good agreement with the experimental tests. On the other hand, the stress-strain path in compression looks a bit stiffer than the experimental one, especially after the cracking occurs.

The crack pattern for the three sizes is shown in Figure 13. It slightly changes varying the size, probably due to the different aspect ratio.

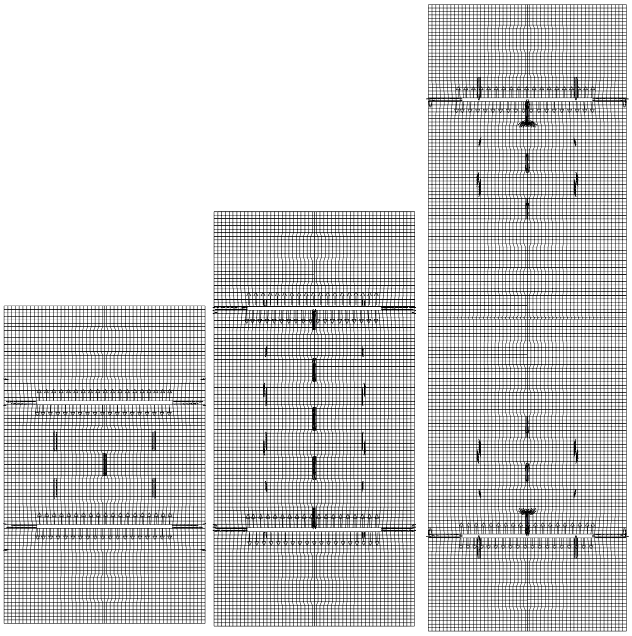


Figure 13. Crack patterns due to flat-jack pressure in the three specimens.

In a previous work (Carpinteri & Lacidogna 2006), a statistical and fractal analysis of data from laboratory experiments was performed, considering the multiscale aspect of cracking phenomena. The fractal criterion takes into account the multiscale character of energy dissipation and the strong size effects associated with it. This makes it possible to introduce a useful energy-related parameter for the determination of structural damage (as used by Carpinteri et al. 2003, 2004, for reinforced concrete structures) by comparing the AE monitoring results with the values obtained on masonry elements of different sizes tested up to failure by means of double jacks.

Fragmentation theories have shown that, during microcrack propagation, energy dissipation occurs in a fractal domain comprised between a surface and the specimen volume V (Carpinteri & Pugno 2002a, b, 2003).

This implies that a fractal energy density (having anomalous physical dimensions):

$$\Gamma = \frac{W_{\max}}{V^{D/3}}, \tag{4}$$

can be considered as the size-independent parameter. In the fractal criterion of Eq. (4), $W_{\max}$ = total dissipated energy; Γ = fractal energy density; and D = fractal exponent, comprised between 2 and 3. On the other hand, during microcrack propagation, acoustic emission events can be clearly detected. Since the energy dissipated, W, is proportional to the number of AE events, N, the critical density of acoustic emission events, Γ_{AE}, can be considered as a size-independent parameter:

$$\Gamma_{AE} = \frac{N_{\max}}{V^{D/3}}. \tag{5}$$

where Γ_{AE} = fractal acoustic emission energy density; and $N_{\max}$ is evaluated at the peak stress, σ_u. Eq. (5) predicts a volume effect on the maximum number of AE events for a specimen tested to failure.

The extent of structural damage can be worked out from the AE data recorded on a reference specimen (subscript r) obtained from the structure and tested to failure. Naturally, the fundamental assumption is that the damage level observed in the reference specimen is proportional to the level reached in the entire structure before monitoring is started.

From Eq. (5) we get:

$$N_{\max} = N_{\max,r}\left(\frac{V}{V_r}\right)^{D/3}, \tag{6}$$

from which we can obtain the structure critical number of AE events $N_{\max}$. An energy parameter describing the damage level of the structure can be defined as the following ratio:

$$\eta = \frac{W}{W_{\max}} = \frac{N}{N_{\max}}, \tag{7}$$

N being the number of AE events currently recorded by the monitoring apparatus.

Now, we can assume that the number of AE is also proportional to the number of Gauss points subjected to cracking in the finite element model. Therefore, the number of AE and the number of cracks in the finite element model should show the same exponent with respect to the considered volume. In fact, this is what we can substantially observe from Figure 14.

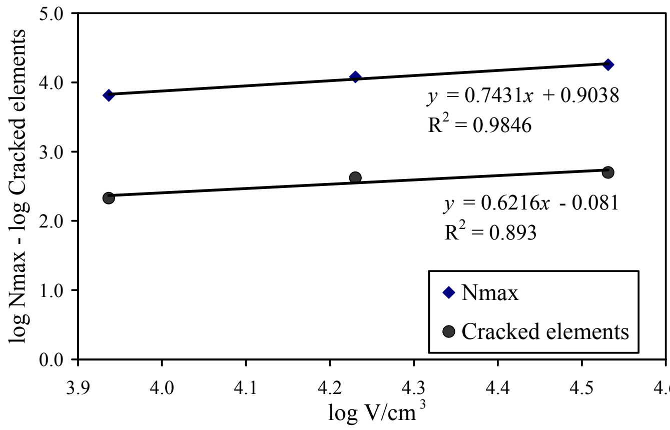


Figure 14 Volume effect on $N_{\max}$ and on the number of cracked finite elements.

The linear relation between the number of cracked elements (or Gauss points) in the finite element model, and the AE is put into evidence also in Figure 15, where the two quantities are plotted in a direct comparison.

Finally, let us observe that the slope of this linear relation depends on the discretization of the finite element model. Nevertheless, refining the mesh (e.g. dividing by two the linear size of each element) does not change sensibly the exponent in Figure 14.

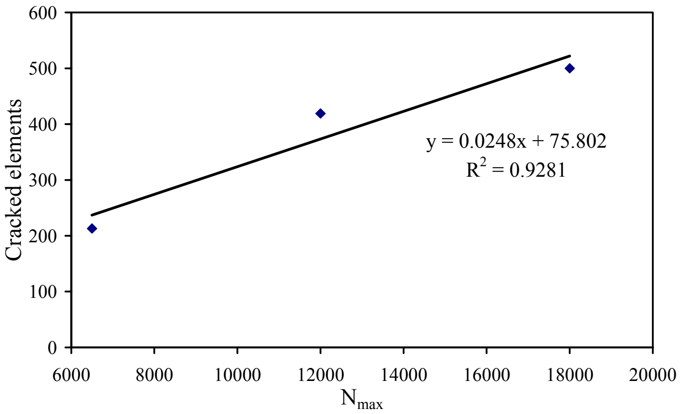


Figure 15. Linear dependency between N_{max} and the number of cracked finite elements.

6 CONCLUSIONS

A numerical simulation of an innovative double flat-jack test combined with AE has been proposed. The numerical results agree rather well with the experimental evidences, both in terms of the estimated compressive strength and of the crack pattern. In addition, the number of Acoustic Emissions is put into relation with the number of Gauss points in the finite element model where cracking takes place. AE can be considered like micro seismic events, so that at each crack advancement corresponds an energy emission.

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