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Historical brick-masonry subjected to double flat-jack test: Acoustic emissions and scale effects on cracking density

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ABSTRACT

The results obtained varying the size of the masonry prism involved in the double flat-jack test are described. In these tests, not only the deformations have been acquired, but also the acoustic emissions (AE) events, in order to get information about local cracking in the specimens. In addition, a meso-scale numerical model of the test is presented, where every brick of the masonry is modeled in 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 AE events for different prism sizes. The model is also able to catch the decrease in the compressive strength with increasing size. Although a quantitative relation between the AE events and the amount of cracking is not easy to obtain, we have been able to prove that the two quantities are simply proportional to each other when increasing specimen sizes are considered, whereas both of them are not proportional to the same sizes, but rather obey a power-law.

1. Introduction

Non-destructive 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 or masonry structures is strictly correlated with the kind of structure to be analyzed and the data to be extracted [1,2]. For historical buildings, non-destructive evaluation (NDE) techniques are used for several purposes: (1) detecting hidden structural elements, such as floor structures, arches and piers; (2) determining masonry characteristics, mapping the heterogeneity 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, in particular, the single and double flat-jack tests [3,4]. The experimental campaign was recently performed on the medieval masonry of few towers in the Italian city of Alba [5]. In order to get more insight into the mechanical behavior, some aspects of the customary test [6] were varied, like the size of the sampled portion, to account for the influence of the size-scale. At the same time, the cracking processes taking place in some portions of the masonry structures were monitored using the acoustic emission (AE) technique. A similar approach has been already exploited in [7] attempting to link the amount of AE with the structural deflections.

The AE technique has proved particularly effective [8–10], 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 quasi-brittle 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 [11–13]. 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

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corresponding activity recorded on masonry elements of different sizes, tested to failure by means of double flat-jacks. On the other hand, in the following it is shown how the amount of cracking obtained from the numerical simulation and AE share the same scaling.

2. Non-destructive 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 [14]. 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 [6]. 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.

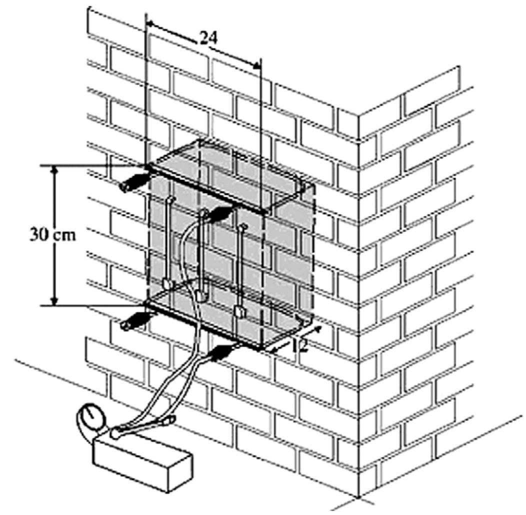

Fig. 1. Typical set-up for in situ flat-jack test. The dimensions given are those of the specimen referred to as Volume 1 (reprinted from [15]).

The reliability of the two tests was positively assessed in [16] by means of in plane numerical simulations.

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 [17,18].

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 50 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 capac-

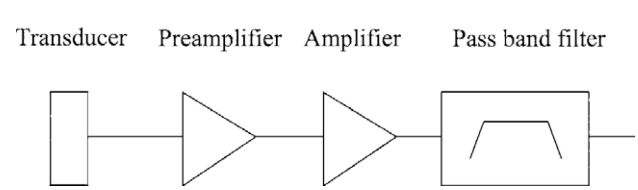

Fig. 2. Acoustic emission measurement system.

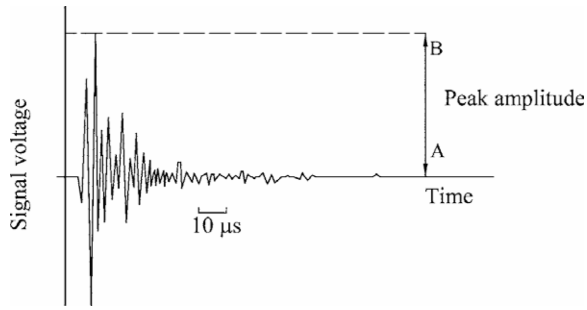

Fig. 3. AE signal identified by the transducer.

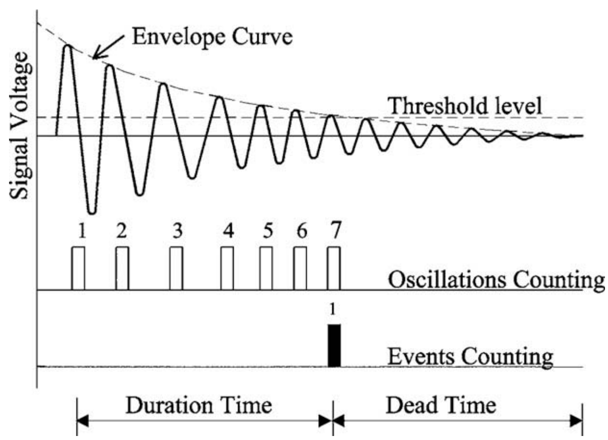

Fig. 4. Counting methods in AE technique.

ity 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 [19], the maximum amplitude of direct non amplified signals is about 100 μV, hence, neglecting the attenuation by reducing to a few centimeter 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 [20]. With this system, the intensity of a single event is, by definition, proportional to the number of oscillations N recorded in the time interval. Clearly, this hypothesis is fully justified only in the case of slow-crack growth [17,18,21].

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 [22] 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 [15,23]. 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 $24 \times 12\ \text{cm}^2$. 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.

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 Fig. 8. The vertical cuts allowed us for an easier interpretation of the results; nevertheless it is worth noting that this procedure could not be assumed as a common practice when dealing with cultural heritage, when destruction has to be minimized.

The tests were performed in keeping with the procedures specified in ASTM [6], other than for the vertical cuts produced in order to eliminate, in the cracked element, the influence of the adjacent masonry portions. As has been demonstrated in [16] by numerical simulations, the portion of masonry in between the two cuts behaves like a specimen subjected to pure compression. In the present case, the vertical cuts added to the standard procedure improve this assumption even in the case of more slender specimens. 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 possi-

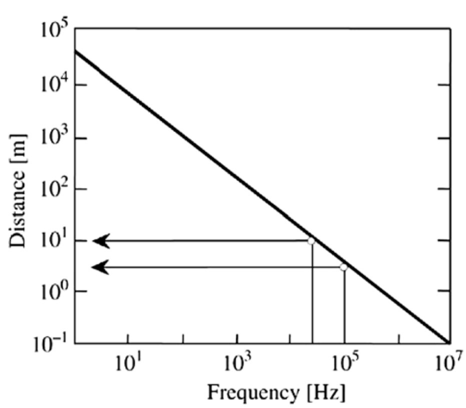

Fig. 5. Acoustic emission relationship between signal detection distance and signal frequency.

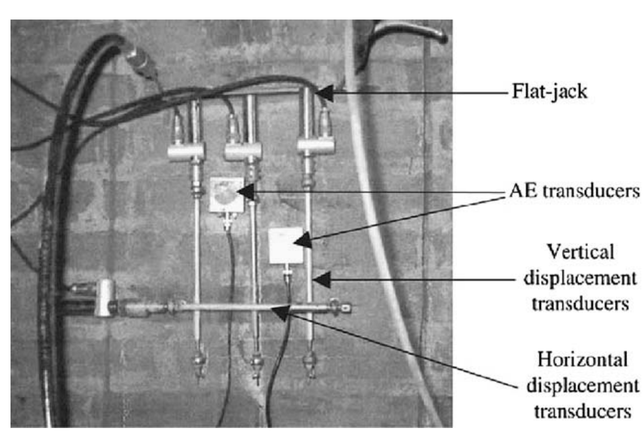

Fig. 6. Combined flat-jack test and AE monitoring.

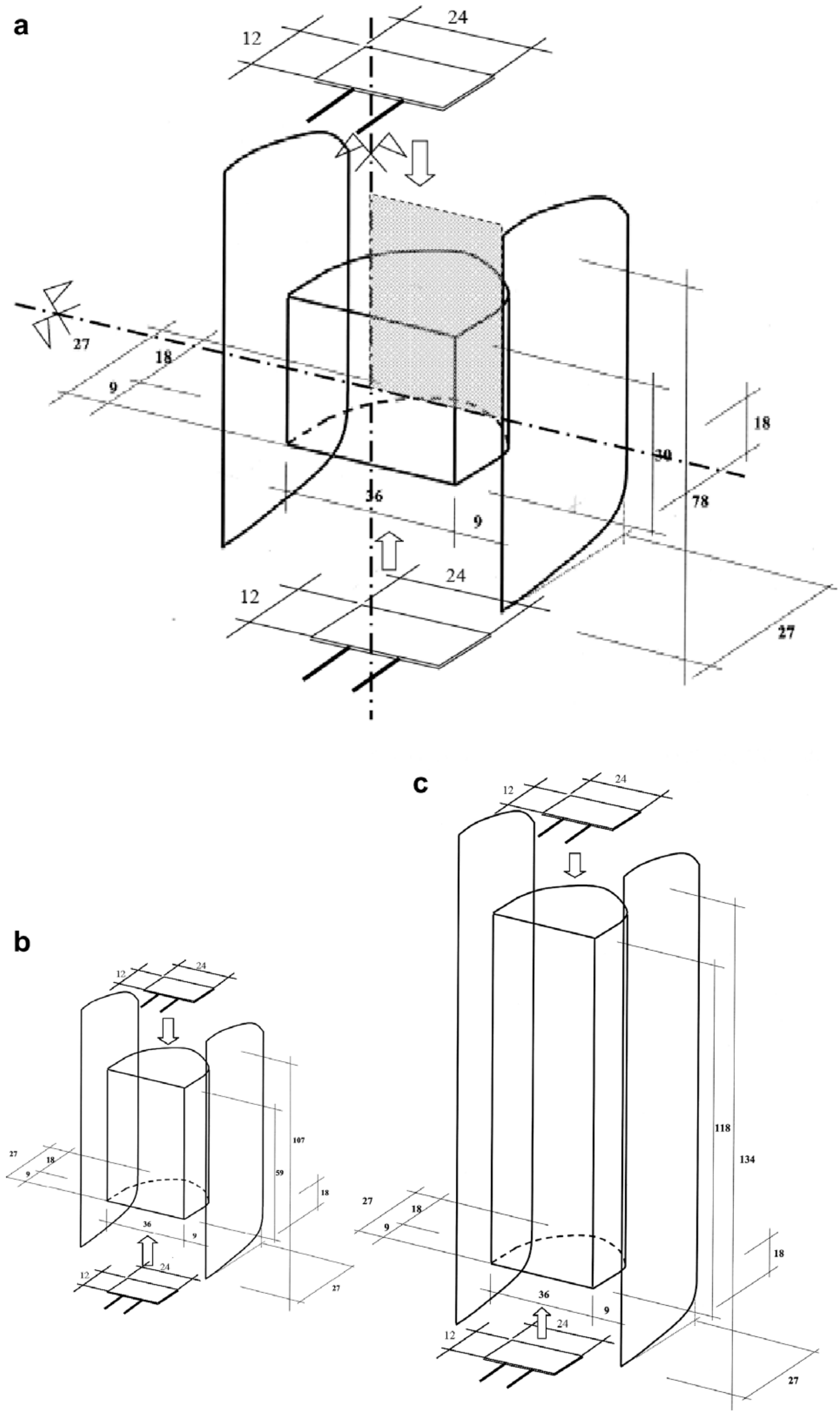

Fig. 7. Schemes of the double flat-jack tests performed on different wall sizes.

ble to reduce the friction effects on masonry behavior arising from the action of the flat-jacks.

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. The stress–strain diagrams obtained from experiments are shown in Fig. 9. 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.

Peak compressive strength was obtained from the load–displacement diagram, when the latter became highly nonlinear,

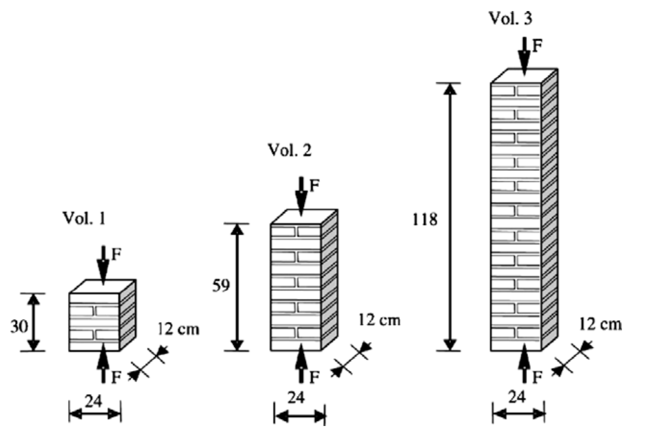

Fig. 8. Equivalent masonry prisms tested in compression by means of double flat-jacks.

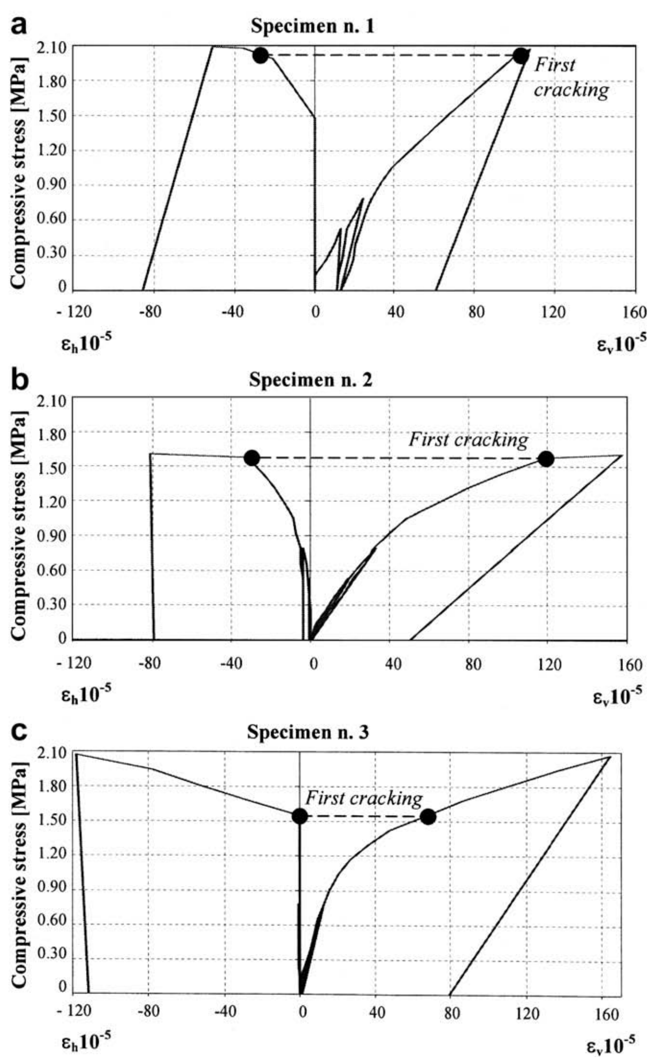

Fig. 9. Experimental results obtained from the double flat-jack tests.

denoting imminent failure. Compressive tests were performed on three different masonry portions.

Fig. 10 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

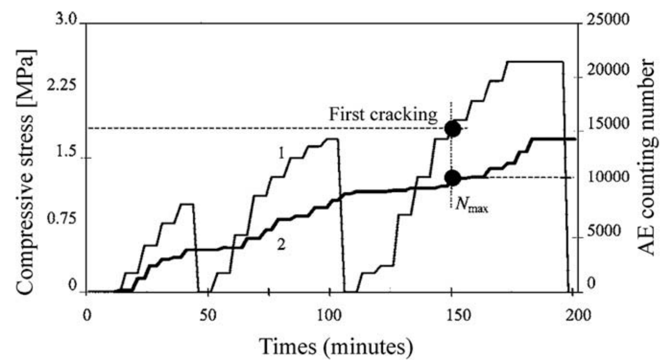

Fig. 10. Double flat-jack test on Volume 2: cumulative number of AE events (2) versus cyclic loading (1).

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

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

performed as a function of time and the diagram of the cumulative number of AE oscillations count. From the AE diagram it can be clearly seen that the material releases energy when the stress level reached previously is exceeded (Kaiser effect [24]). 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 $N_{max} \cong 12{,}000$. The experimental results obtained on the three masonry elements are summarized in Table 1.

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 adopted meso-scale modeling directly accounts for masonry anisotropy, being the texture of masonry explicitly represented. 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 analyzes were performed with the Finite Element Software DIANA 9.1 [25]. The mechanical properties of the materials are summarized in Table 2; the typical ratio between tensile and compressive strength [16] can be recognized.

Fig. 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. Fig. 11b shows details about the loading and boundary conditions.

In order to correctly simulate the nonlinear mechanical response of the test, it is crucial to follow the actual loading path as close as possible. The following procedure has been applied. First, a displacement is imposed to the top of the specimen.

The amount of such displacement can be calculated from another model of the masonry wall "uncut" that is 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 that 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.

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
Compressive strength	f_c	3×10^7 Pa	1×10^7 Pa

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

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 Fig. 13. It slightly changes varying the size, probably due to the different aspect ratio.

In a previous work [9], 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 for reinforced concrete structures [8]) 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 [11–13].

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

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

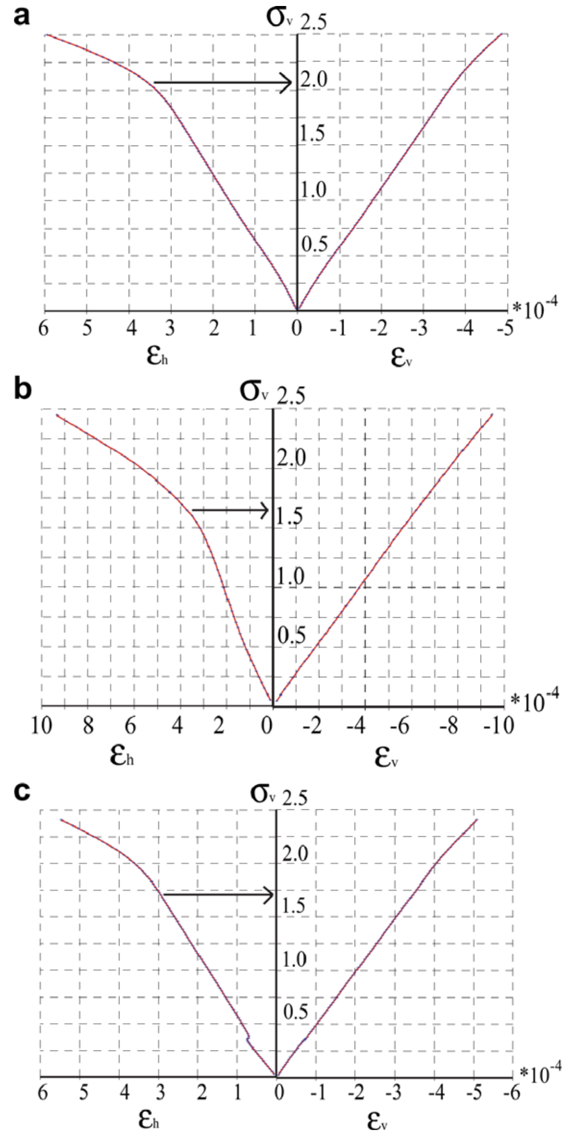

Fig. 12. Stress–strain diagrams: Volume 1 (a); Volume 2 (b) and Volume 3 (c). The arrow indicates when first cracking spreads within the specimen.

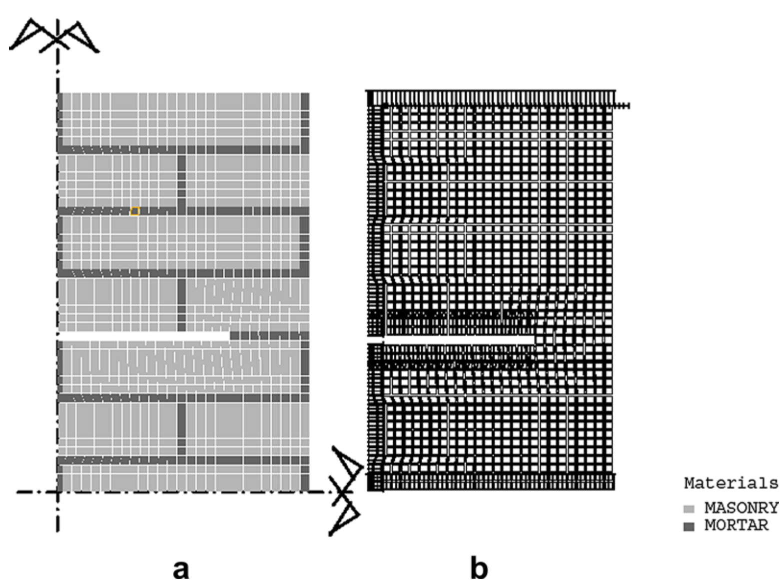

Fig. 11. Finite element mesh adopted for Volume 1 exploiting symmetry (cf. shaded area in Fig. 7a). Mesh and materials (a); loads and boundary conditions (b).

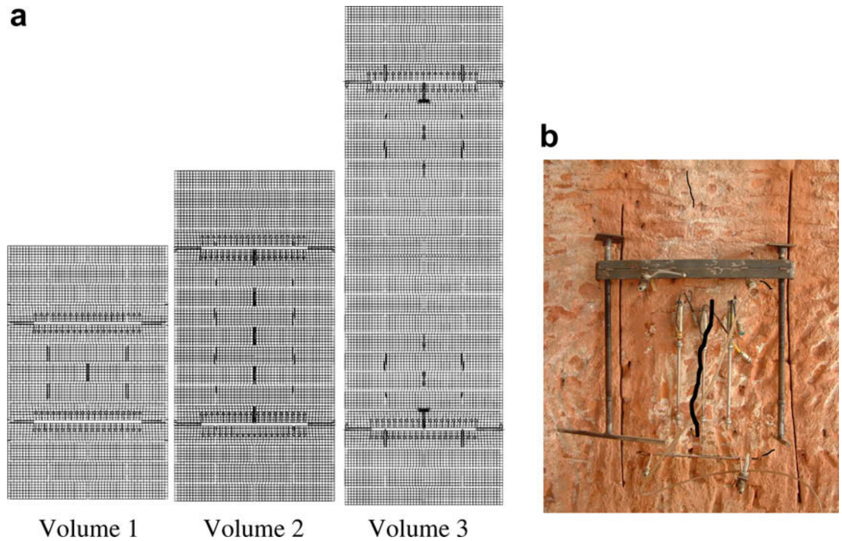

Fig. 13. Crack patterns due to flat-jack pressure in the specimens: numerical results (a) and experimental crack pattern emphasized with bold lines for the Volume 1 specimen (b).

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.

As a consequence, the domain on which the energy dissipation, and the acoustic emission, takes place is a fractal domain, with a dimension smaller than 3. For this reason, the scaling of the AE is anomalous, and the crack density decreases with increasing specimen size. This phenomenon is well recognized also in seismology [26], where seismic events are the counterparts of acoustic emissions.

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 the oscillations counts N, related to the AE 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 the AE oscillations count currently recorded by the monitoring apparatus.

Now, we can assume that the AE counting number 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 Fig. 14. For these reasons, it is possible to say that the numerical model is able to de-

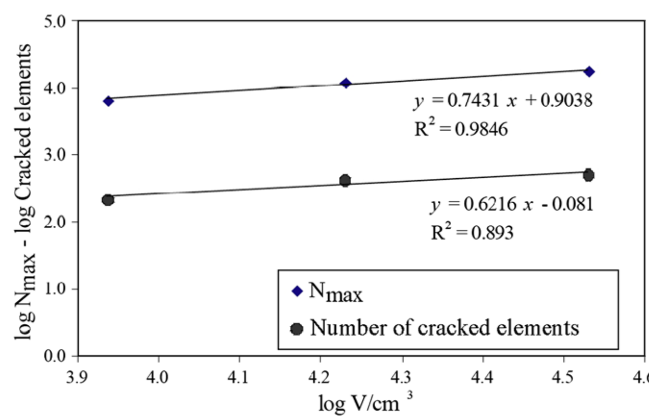

Fig. 14. Volume effect on N_{max} and on the number of cracked finite elements.

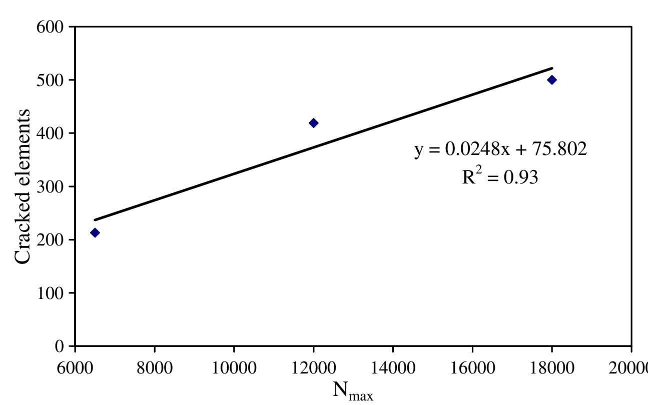

Fig. 15. Proportionality between N_{max} and the number of cracked finite elements.

scribe correctly the decrease of the compressive strength, as well as the decrease of crack density, with increasing specimen size.

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 Fig. 15, where the two quantities are plotted in a direct comparison. In fact, the calculated coefficient of linear regression is equal to 0.93.

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

6. Conclusions

A numerical simulation of an innovative double flat-jack test combined with acoustic emission monitoring 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. The model is also able to catch the decrease in the compressive strength with increasing size.

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. A good correlation is found between the amount of cracking simulated numerically and the experimental acoustic emissions counting for different prism sizes. The numerical model is able to describe correctly the decrease of the compressive strength, as well as the decrease of crack density, with increasing specimen size.

Although 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.

Acknowledgements

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