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Experimental and Numerical Analysis of Behaviour of Old Brick Masonries

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Abstract The calculation of old existing masonry structures needs a homogeneous mechanical behaviour law under tensile and compressive load until collapse. The samples extracted from existing buildings are necessarily limited in dimension and number and it is not possible to perform tests directly on a representative volume, so the numerical modelling of masonry mechanical behaviour has to be predicted from the behaviour of its constitutive elements. The aim of the study presented here was to develop a method able to define the homogeneous representative law for brick masonry from those of its components, bricks and mortar, in tension and in compression, including linear and non-linear domains. The method is numeric, fitted on experimental results. Tests were carried out on mortar samples, brick samples, and multilayer samples. Their experimental behaviour is described and a damage model is used to describe the behaviour of the masonry. An explanation is given of how the homogeneous characteristics of the masonry were defined and the influence of some parameters is presented.

Keywords: Brick masonry, experimental analysis, mechanical properties, modelling, homogenization

Introduction

To assess the load capacity of old masonry structures like masonry arch bridges, it is necessary to use a behaviour law including the non-linear domain up to collapse. This law is difficult to define. First, the old materials used one hundred or more years ago are poorly known today, if at all. Secondly, the samples available are small and very few in number. So, the laboratory tests cannot be carried out directly on a representative volume of the masonry extracted from the structure. Most of the time, engineers have to define mechanical parameters of the masonry from a few cores made of only one material, mortar, or brick, or a mixed brick-mortar core. How to pass from the characteristics of the blocks and the joints to the homogeneous characteristics of the masonry, representative of the mechanical behaviour of the whole building, is a major question, to which we try to give an answer in this study. Some authors have published on the topic in the last 20 years. A few of them have used an analytical approach (Cecchi 2009) for periodic and non-periodic materials but most approaches are both experimental and numerical (Luciano 1998, Pietruszczak 2003, Chairmoon 2008, Barbosa 2009).

We applied the method of defining a model and validating it by an experimental approach. The model used here is a damage model, which allows the softening compressive behaviour and the quasi-brittle behaviour in tension to be included in a single formulation. The aim of the study is to determine a masonry behaviour law, including the cracking effect of the materials and the effect of the brick-mortar interface, to be used in a global analysis of a masonry structure with an FEM code. The steps are the following:

- Experimental individual characterization of the mortar and of the bricks,
- Tests of multilayer brick – mortar samples,
- Fitting of the mortar and of the brick individual behaviour laws with a damage model,
- Modelling of the multilayer sample, parametric study of some relevant parameters,
- Fitting on last results of a single damage parameter set for the homogenized masonry behaviour law.

The Damage Model

The damage model used is based on an orthotropic material. It is a variant of the initial model described in detail in [9]. This short presentation adopts the 6-dimension vectorial representation of the classical 3×3 symmetric tensors. An effective stress $\vec{\tilde{\sigma}}$ is computed according to the elastic strain $\vec{\varepsilon}^{\,e}$, using the sound material stiffness matrix $\boldsymbol{C}^0$ (Eq.1).

$$\vec{\tilde{\sigma}} = \boldsymbol{C}^0 . \vec{\varepsilon}^{\,e} \tag{1}$$

The effective stresses are split into tension, $\vec{\tilde{\sigma}}^t$, and compression, $\vec{\tilde{\sigma}}^c$, parts according to the sign of the main stresses. The positive part is used in Rankine Criteria (maximal stress criteria) to assess the tensile damage tensor $\boldsymbol{D}^t$ which affects the positive effective stresses. The negative part of the effective stresses is used to assess a Drucker Pragger equivalent stress defined by Eq.2.

$$\tilde{\sigma}^{DP} = \sqrt{\frac{J^{2d}}{6}} + \delta \frac{I^1}{3} \tag{2}$$

With J^{2d} the second invariant of the deviator of $\vec{\tilde{\sigma}}^c$, I^1 the trace of $\vec{\tilde{\sigma}}^c$ and δ the Drucker Pragger constant, which depends on the internal friction angle, φ, as follows in (Eq.3).

$$\delta = \frac{2\sqrt{3}\, sin\, \varphi}{3 - sin\, \varphi} \tag{3}$$

The Drucker Pragger equivalent stress is used to assess a compressive damage tensor $\boldsymbol{D}^c$. Both $\boldsymbol{D}^t$ and $\boldsymbol{D}^c$ affect the effective stresses orthotropically to give $\vec{\sigma}$ (Eq.4, with $\boldsymbol{I}$ the identity tensor), the stress to be used at integration points of the finite element code.

$$\vec{\sigma} = (\boldsymbol{I} - \boldsymbol{D}^c).((\boldsymbol{I} - \boldsymbol{D}^t).\vec{\tilde{\sigma}}^t + \vec{\tilde{\sigma}}^c) \tag{4}$$

The evolution laws used to link the criteria and the damage lead to a softening phase of the behaviour laws as illustrated in Fig. 1. To avoid a dependence of the finite element solution on the mesh size (due to the localization induced by softening), the damage also depends on the finite element size.

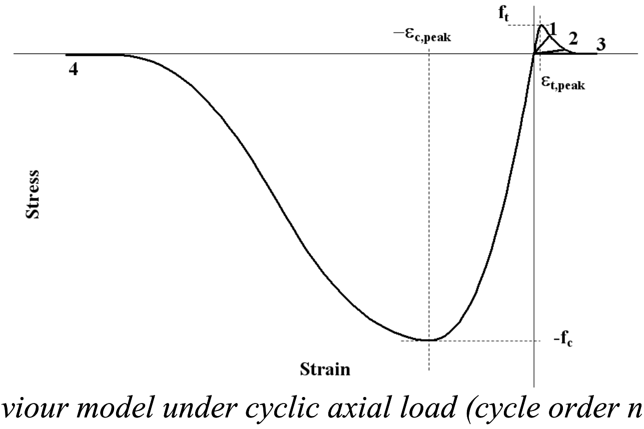

Figure 1: Behaviour model under cyclic axial load (cycle order numbered 1 to 4)

Experimental Tests in Laboratory

Brick samples In our region, the traditional architecture is based on brick masonry. The bricks are solid units without holes as used by the Roman civilization. They are large and thin. A few very small companies still make this kind of bricks for the restoration of monuments. In one of these companies, we bought new bricks manufactured like the old ones. Their dimensions were 37 cm * 24 cm * 5 cm (Fig. 2). They were mechanically moulded one by one.

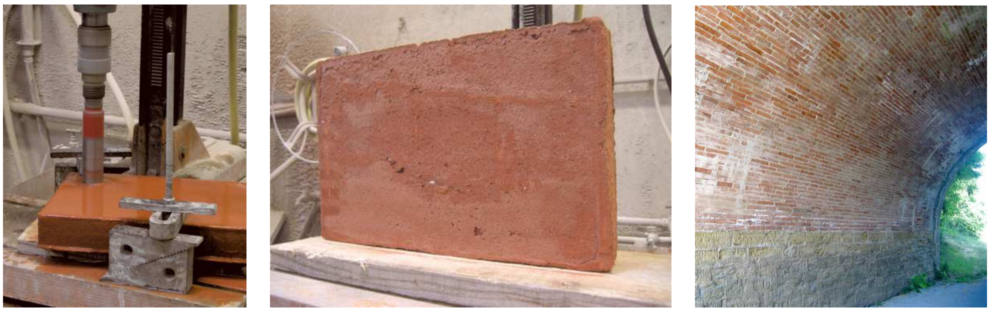

Figure 2: Bricks and vaults in Toulouse (France)

The mechanical tests carried out on bricks in our laboratory showed that the bricks were transverse isotropic and their mechanical characteristics in their own plane were higher (Table 1). The experimental stress-strain curves under compressive load are given in Fig. 4.

Lime Mortar Samples To make the mortar, a hydraulic lime was selected (SOCLI NHL 3.5) without any additive or cement, like the binder used in our region before 1940. The constitutive elements of this lime were $Ca(OH)_2$ (18%), calcite $CaCO_3$ (30%), silicate C_2S (40%) and quartz (10%). The lime was mixed with sand (lime : sand= 1:4 in mass) and water (water / lime = 0.6).
The mechanical characteristics obtained by laboratory tests on lime mortar samples are also given in Table 1. The experimental stress-strain curves under compressive load are presented in Fig. 4.

Table 1: Mechanical characteristics of bricks and lime mortar (with their coefficients of variation)

	Compressive strength fc [N/mm^2]	*Tensile strength ft* [N/mm^2]	*Young Modulus E* [N/mm^2]	*Poisson coefficient* ν
Brick ($\perp$ to its plane)	13.8 (17%)	-	5500 (26%)	0.08 (25%)
Brick (in- plane)	22.7 (16%)	6.03 (15%)	16700 (27%)	0.24 (32%)
mortar	3.7 (8%)	0.85 (3%)	5200 (17%)	0.17 (24%)

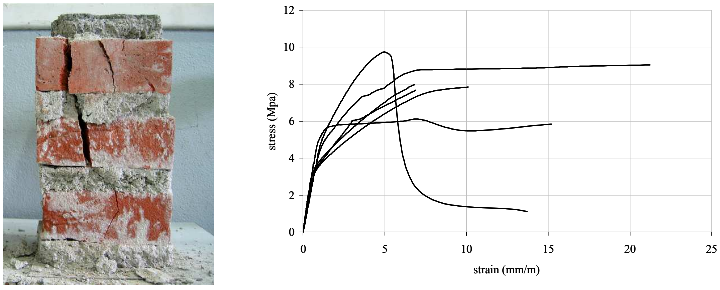

Figure 3: Brick - mortar multilayer samples - fracture scheme and stress-strain curves

Brick – Mortar Multilayer Samples The multilayer samples were made with 3 pieces of bricks as shown in Fig. 3. The thickness of the mortar joint was 2 cm. The compressive strength was 8.43 MPa with a large dispersion (12 samples tested, 19% of mean value). Above 3.5 MPa, the stress-strain curves were scattered. Vertical cracks crossed the bricks and the mortar without sliding at the mortar / brick interface. The stress-strain curves show two different types of post-peak behaviour: quasi-brittle behaviour or yielding with plastic behaviour.

The study of the displacements, tensile damage, D_t, compressive damage, D_c, and crack mouth opening displacement, C_{mod}, provided by the finite element analysis allowed better understanding of the behaviour of the multilayer samples under compressive load. Up to 3.5 MPa (value of the compressive strength of the mortar, less resistant than the bricks, here), the two materials were elastic but, due to its smaller elastic modulus, the mortar presented greater axial and transversal strains. As the load increased, first, the mortar yielded without failure thanks to the brick-mortar interface bond which had a containment effect from the brick onto the mortar. Above 6 MPa, the transversal strain of the mortar led to horizontal tension in the brick, which reached its tensile strength and cracked vertically.

Modelling of Brick and Mortar Behaviour

The damage model described above was used to model the mortar behaviour and brick behaviour, and then to calculate the multilayers. The fitted parameters are given in Table 2. In this first calculation, we made an assumption about the friction angle (Coulomb type): $\varphi = 30°$ for mortar and bricks. This assumption will be discussed below. The peak tensile strain adopted was $\varepsilon_{t,peak} = f_t / E$ where E is the Young modulus. For safety reasons, we adopted $f_{mt} = 0.1$ MPa.

Table 2: parameters of calculation

	fc [N/mm^2]	$\varepsilon_{c,peak}$ [mm/m]	G_c [N/mm]	E [N/mm^2]	ft [N/mm^2]	$\varepsilon_{t,peak}$ [mm/m]	G_f [N/mm]	*Poisson coefficient*
Bricks	13.8	4.	2.00	5500	6.0	1.09	0.20	0.15
Mortar	3.7	4.	1.50	5200	0.1	0.02	0.002	0.25

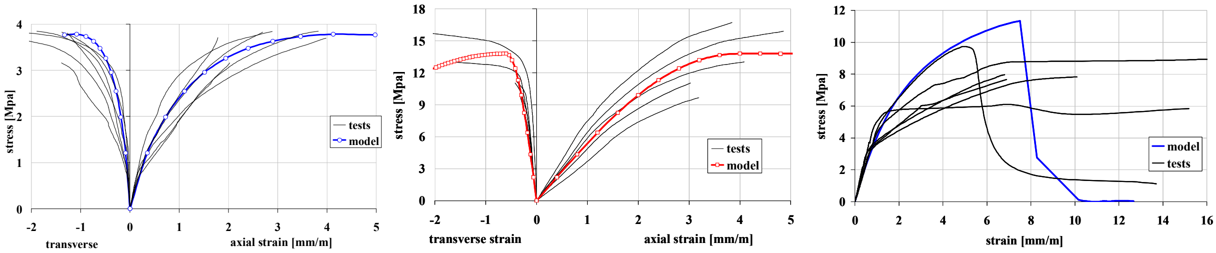

Figure 4: Comparison tests – numerical fitting for mortar (left), brick (centre) and multilayer (right)

The first calculation (Fig. 4) reproduces the quasi-brittle behaviour of the strongest sample. But the calculated load capacity of the multilayer was too high. Consequently, the mortar friction angle was decreased in order to approach the test results. In this aim, a parametric study of the influence of the friction angle and other parameters was carried out (Fig. 5). The influence of the friction angle (Fig. 5 (b)) on the resistance and on the behaviour of multilayers f_c is very sensitive: for friction angles above 25°, a slight increase in φ changes the post-peak behaviour. Finally, a friction angle of 20° was kept to fit the mean experimental value of the collapse load.

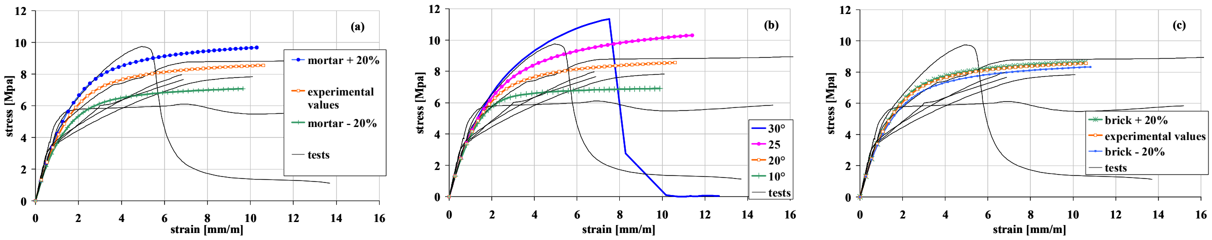

Figure 5: (a) Variation of mortar characteristics with ±20%; (b) Influence of friction angle of mortar; (c) Variation of brick characteristics with ±20%

To control the softening phase of the behaviour laws, the model needs a fracture energy. As this was not measured, its value was also adjusted by inverse analysis according to the results on multilayer tests. We obtained comparable orders of magnitude to the values that can be found in the literature (Lourenço 1996, Zhu 2006, Reyes 2008, Chairmoon 2008, Barbosa 2009).

A variation of ± 20% of the strength characteristics of the mortar (f_{mc}, f_{mt}, G_{ft}, G_{fc}) modifies the collapse load of the multilayer in the same proportions (Fig. 5 (a)). So, the characteristics of the mortar have to be chosen carefully. A variation of ± 20% in the characteristics of the bricks (f_{bc}, f_{bt}, G_{ft}, G_{fc}) modifies the collapse load of the multilayer by about only 4% (Fig. 5 (c)).

In order to validate the previous fitting procedure, little walls were tested in the laboratory and calculated with the selected parameters (Fig. 6). The numerical prediction of the collapse load was excellent but the plastic domain seemed too long. Decreasing the fracture energy in compression could improve the fitting.

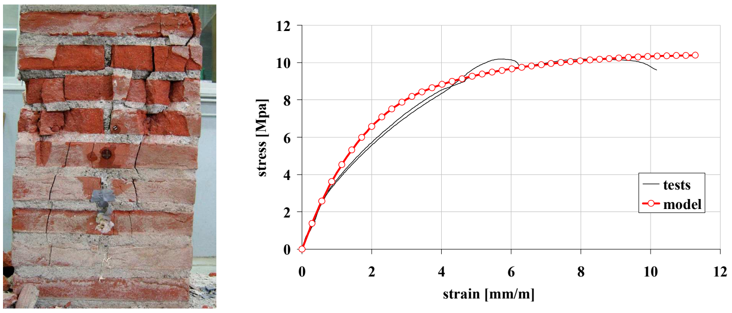

Figure 6: Small masonry walls

Macro-Modelling of Masonry

A representative volume (RV) of masonry was calculated with the fitted parameters given in Table 2 and a friction angle of 20°, in order to establish the homogeneous characteristics of masonry. The RV was virtually loaded in tension and compression. Then, the numerical curves of the composite response were fitted, as for an experimental test, with a single set of model parameters in order to obtain a numerical approximation of the RV behaviour (Fig. 7). The characteristics of the homogenized masonry, in tension, are very close to those of mortar. The characteristics finally obtained for the homogenized masonry are given in Table 3.

Table 3: parameters of the masonry homogeneous model

φ [°]	f_c [N/mm^2]	$\varepsilon_{c,peak}$ [mm/m]	E [N/mm^2]	G_{fc} [N/mm]	f_t [N/mm^2]	$\varepsilon_{t,peak}$ [mm/m]	G_{ft} [N/mm]	*Poisson coefficient*
20	11.0	5.	5400	0.70	0.1	0.0185	0.002	0.18

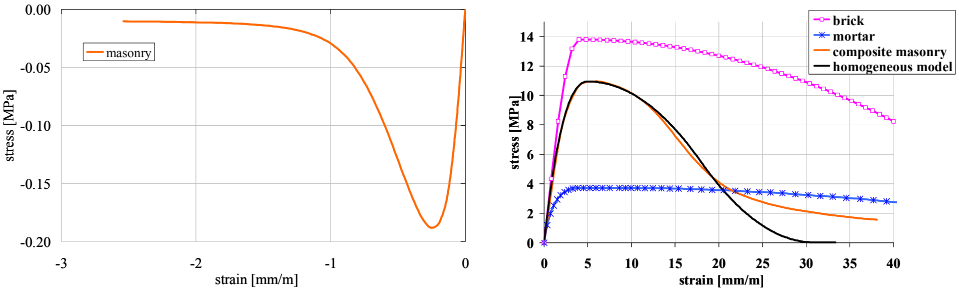

Figure 7: Homogeneous model of brick masonry, tension (left) and compression (right)

Conclusion

A damage model has been proposed to analyse the mechanical behaviour law of brick masonry. The parameters of the model are the compressive and tensile stresses, the peak stress, the Young modulus and the Poisson coefficient, a friction angle, φ, and two fracture energies G_f, one in compression and the other in tension. An experimental campaign was carried out in order to find the elastic parameters and strengths for individual materials (clay unit and mortar). The friction angle of mortar φ, and its fracture energy G_f, were deduced from a finite element inverse analysis based on composite specimens under compressive loads. Finally, the parameters obtained were used to numerically find the behaviour of a representative volume of masonry on which a homogenized behaviour law was fitted. The parametric study carried out in the framework of the inverse analysis dealing with the calibration of φ and G_f shows that the choice of mortar characteristics, and more especially of the friction angle, merits special attention.

This fitting methodology is currently being tested on another masonry type: a natural stone one. The homogenized behaviour law obtained can be used, not only for old masonry diagnosis, but also for the design of new structures. Currently, the methodology is being used to analyse the global behaviour of arch bridge masonry. Results will be published soon.

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