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Nonlinear analyses of adobe masonry walls reinforced with fiberglass mesh

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ABSTRACT: Previous experimental tests and numerical analyses have shown that the ratio between the mechanical properties (such as strength, stiffness and fracture mechanic properties) of both mortar and brick, as well as the use of additives, influence both design approaches (in terms of basic assumptions and analytical models) and the global response of the walls (in terms of strength and ductility). An accurate analysis is presented in the case of adobe (earth blocks) constructions reinforced with fiberglass mesh. Main issues and variability in the behavior of seismic resisting walls are highlighted. Main aim of the overall research activity is to improve the knowledge about the structural behavior of adobe structural members reinforced with fiberglass mesh inside horizontal mortar joints.

1 INTRODUCTION

Adobe earth constructions were widespread in the ancient world and earth is doubtless one of the most used materials in ancient times. The main reasons of adobe buildings spread are the cheapness and handiness of both the adobe bricks production and constructions as well as the good properties of adobe in terms of heat and sound insulation. With the introduction of reinforced concrete the number of adobe buildings has become progressively lesser. Nevertheless, as reported by Houben & Guillaud (1994), it is estimated that approximately 30% of the world's population still lives in buildings constructed with earth. Despite its past and present spread, adobe constructions are prone to damage under seismic actions, and most of these buildings are located in areas of high seismic risk. Therefore the preservation of adobe structures and, in particular their reinforcement, is nowadays an important structural issue. Seismic resistance of adobe masonry structures primarily depends on the seismic response of individual walls. Previous experimental tests by Turanli & Saritas (2011) showed the effect of fiberglass reinforcement on adobe masonry walls. Typical walls failure mode under earthquake actions is the (diagonal) cracking mode that occurs when the principal tensile stresses developed in the wall under a combination of vertical and horizontal loads exceed the tensile strength of the adobe material. In fact, seismic characterization of the masonry structural element is generally carried out through diagonal compression tests. This test, as shown by Lignola et al. (2009) allows evaluating the effects of variables such as type of masonry unit, mortar, workmanship, etc. and, as suggested by the ASTM (1981), allows to assess the diagonal tensile or shear strength of masonry assemblages by loading them in compression along one diagonal, thus causing a diagonal tension failure with the specimen splitting apart parallel to the direction of load.

2 SUMMARY OF EXPERIMENTAL OUTCOMES

2.1 Test setup and mechanical characterization

Experimental diagonal compressive tests by Turanli & Saritas (2011) on adobe walls reinforced with plaster reinforcement mesh have been used as a benchmark for the numerical analyses. The geometry of adobe masonry panels experimentally tested is reproduced in figure 1. In particular the tested panels were built with the global size (80x80x10.5 cm^3) and bricks size (10.5x10.5x21.5 cm^3) as shown in figure 1, but with different adobe soil composition and curing for both the bricks and the mortar. The panels were built by the placement of a plaster reinforcement fiberglass mesh (with equal spacing 5 cmx5 cm) inside the horizontal mortar joint of the adobe blocks. These kinds of mesh are very cheap and popularly used for reinforced plaster coatings applied on the exterior and interior faces of walls in the construction industry.

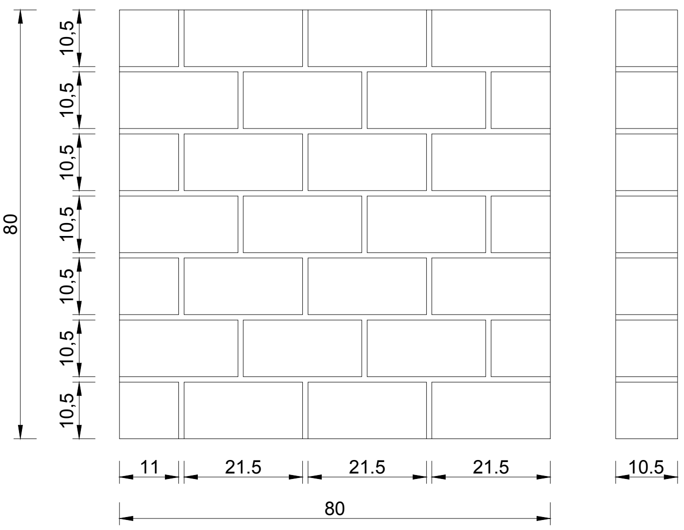

Figure 1. Adobe masonry panel geometry.

Mechanical characterization of the material is given by Turanli & Saritas (2011) and, the missing data have been evaluated. Tensile and compressive strengths of both the brick and the mortar, for different curing times, were computed by interpolation with reference to the values proposed by Turanli (1985). Such tests provide data from 0 days to 28 days curing, for plain soil. Trends with curing time show that strength is almost doubled for both mortar and bricks.

3 NONLINEAR NUMERICAL ANALYSES

3.1 Finite element method

The influence of fiberglass plaster mesh reinforcement coupled with a strong mortar or high cured constituent materials on the global structural behavior has been studied by means of a Finite Element Method (FEM) model. The FEM model has been validated through the comparison of the experimental data and numerical FEM outcomes. In particular the models without mesh were validated in a previous work by Giamundo et al. (2012). Parametric analyses were conducted by means of two dimensional micro-modeling under plane-stress assumption. The analyses were performed varying the mechanical parameters for both the bricks and the mortar. Adopted values for the tensile and compressive strength, according to curing time are reported in table 1. Typical values for the fiberglass mesh mechanical parameters have been used. In particular, according to the experimental tests, a fiberglass mesh having weight 100 g/m^2, density 2.5 g/cm^2 and strength 1000 N/50 mm has been considered. Lacking of experimental counterpart, numerical simulations were performed applying a better mortar, namely “mortar B” instead of plain fresh mortar, and considering for both mortar and bricks the same properties due to long curing, namely longer than 28 days. The FEM model used (see figure 2) is constituted by more than 13,000 eight-node quadrilateral isoparametric plane stress elements based on quadratic interpolation and Gauss integration. All the analyses have been performed by means of the TNO DIANA v9.4.4 code.

Table 1. Material mechanical properties

Properties	Plain soil	Plain soil	Plain soil	Mortar B
Curing days	0	28	>28	0
Tensile Strength [MPa]	0.0392	0.0784	0.098	0.0980
Compressive Strength [MPa]	3.32	6.64	8.30	8.30

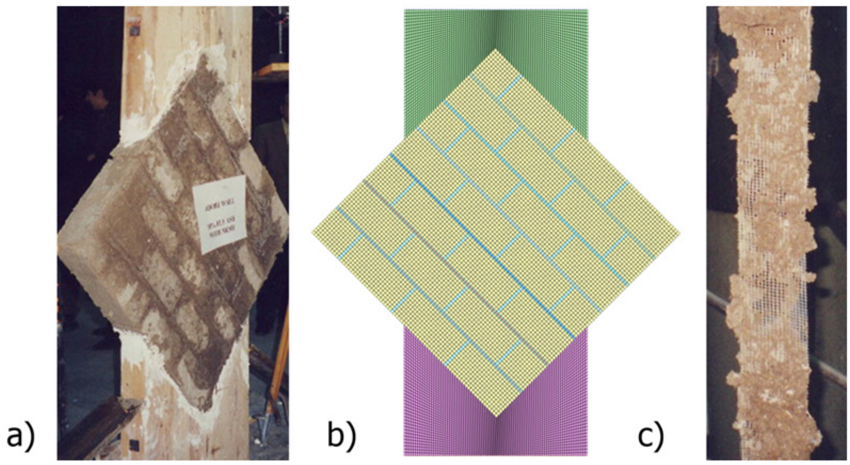

Figure 2. Test setup: a) experimental, b) finite element model (with mesh) c) Removed fiberglass mesh from horizontal mortar joint.

In the FEM model bricks and mortar are modeled individually, without interface elements between them, according to total strain model coupled with the rotating crack stress-strain relationship approach. In particular in the total strain approach the constitutive model describes the stress as a function of the strain and in the rotating crack approach stress-strain relationships are evaluated in the principal directions of the strain vector as reported in Manie & Kinstra (2010). Interface elements have been neglected, according to previous studies by Lignola et al. (2009) and (2011), mainly due to the lack of experimental properties. Few data were available for constituent materials, especially for the nonlinear post peak phase, so that ideal plasticity was assumed in compression, while in tension two limit cases were considered, namely ideal plasticity and brittle failure. All the analyses were performed under displacement control measuring in-plane deformations and evolution of reacting stresses. The diagonal compressive axial load has been applied, as a displacement load, through two wooden supports. The supports have been modeled (by means of eight-node quadrilateral isoparametric plane stress element as well) at the two opposite corners of the panel (see figure 2b) according to experimental test setup by Turanli & Saritas (2011). As a boundary condition the bases were fixed.

3.2 *Numerical program*

The results of FEM analyses were validated through comparison between the experimental and numerical outcomes. In particular three cases were considered, each one including both an ideal tensile plastic behavior and a brittle tensile failure, namely:

- plain tested: the wall is made of plain adobe bricks 28 dd. curing and fresh plain mortar (i.e. 0 dd. curing), Young modulus for both materials is 20 MPa (Giamundo et al. 2012);
- long term: this wall is made of plain adobe bricks and plain mortar after long curing time (i.e. curing time higher than about 28 dd.); Young moduli were the same as the first case, for comparison purpose with previous results (Giamundo et al. 2012);
- mortar B: this wall is considered for comparison purpose only with plain tested wall; the wall is made of plain adobe bricks 28 dd. curing and a better mortar compared to plain soil; Young moduli were the same as the first case.

4 OUTCOMES OF NUMERICAL ANALYSES

The behavior of adobe wall panels reinforced with fiberglass mesh was analyzed (varying tension softening models) in terms of load-displacement curve, shear stress-average diagonal strain curve, shear stress-average shear strain curve, Poisson ratio-displacement and Shear modulus-displacement curves. According to ASTM E519-81 (1981) standard method, the shear stress, τ, has been computed as $\tau = 0.707\ V/A_n$, were V = diagonal load and A_n = net section area of the uncracked section of the panel (in the considered case $A_n = 0.092\ m^2$). The average vertical and horizontal strains, ε_v and ε_h have been computed as the average displacement along the compressive and tensile diagonals, respectively, over the same gauge length (400 mm). The shear strain, γ, according to ASTM E519-81 (1981), is $\gamma = \varepsilon_v + \varepsilon_h$. The Shear modulus, G, and the Poisson ratio, ν, were computed according to the well-known solid mechanics relationship, as $\nu = -\varepsilon_h/\varepsilon_v$ and $G = \tau/\gamma$ respectively, where E is the Young Modulus. Failure modes, in all the considered cases, were also checked by means of the crack patterns. Experimental failure mode mainly involved cracking and detachment of lateral corners of the panel, outside the compressed strut between the two wooden loading supports. In the considered cases the numerical outcomes mainly showed the same cracking pattern, but the spreading of cracks (smeared crack strain field in numerical simulations), depends mainly on post peak tensile behavior of soil. In next figures solid signs represent experimental data, while continuous and dashed lines represent brittle and ideal post peak tensile behavior, respectively in FEM. A small cross remarks the failure point for brittle material.

4.1 *FEM model: validation*

The model of the panel without mesh has been validated and deeply discussed in a previous study by Giamundo et al. (2012), while the model of the panel with mesh is herein validated. The plain tested panel is almost a homogeneous panel, in the sense that mortar and bricks are made of the same material. However, different curing times differentiate the two materials: mortar is almost fresh, while bricks are cured for 28 dd., so that their strength, both in tension and compression was higher. Crack pattern almost involved vertical lines connecting the wooden supports. Global response in terms of Force/Displacement highlights an almost linear behavior, as shown in figure 3, and brittle material better catches experimental failure, both in terms of crack pattern and of failure load. In the case of brittle material the shear modulus, G, as well as the Poisson ratio, ν, exhibits, up to the failure, the same trend of the case of ideal material. Of course, the ideal material yields to a longer loading branch. The strength of the plain panel with mesh is about 25% higher, compared to plain soil without mesh and the ultimate displacement is about 50% higher.

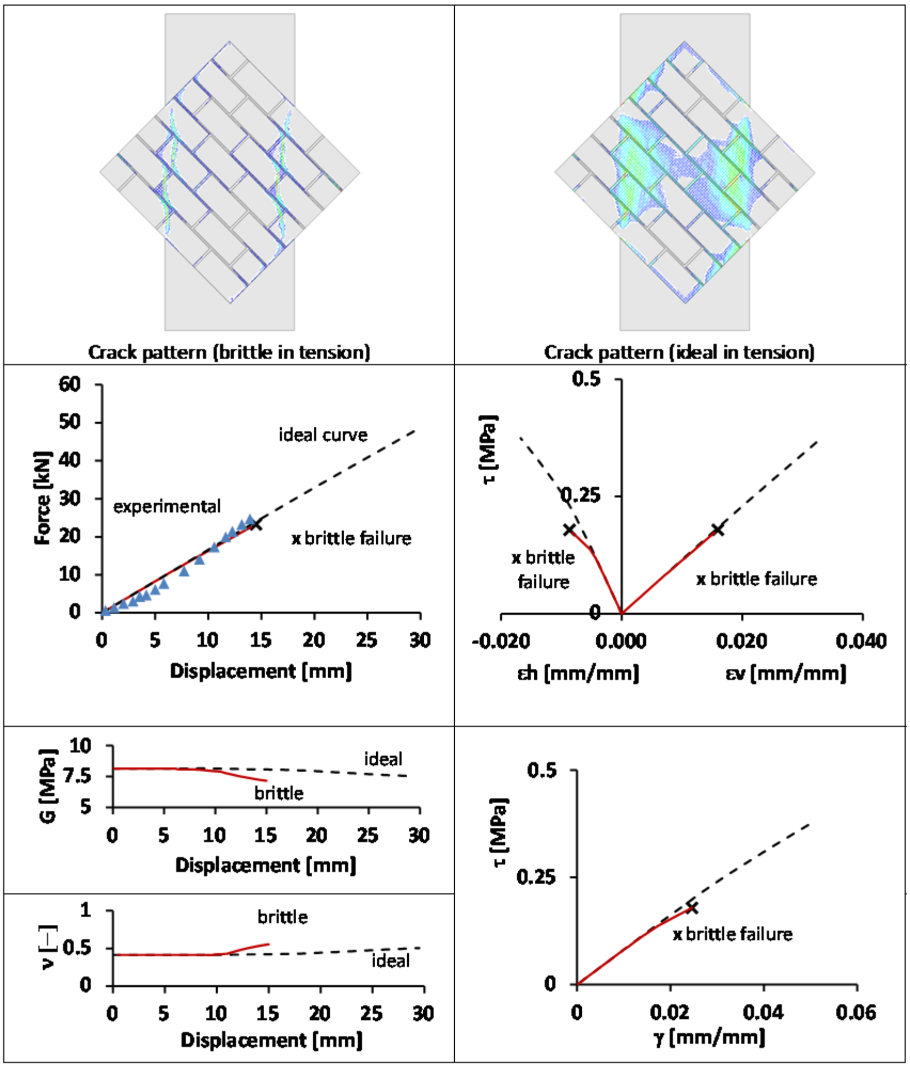

Figure 3. Experimental-theoretical comparison (plain adobe soil with mesh)

4.2 *FEM model: long term curing*

The long term curing panel was not experimentally tested and it is part of the numerical experimentation aimed to assess the influence of strength of materials on global behavior of the masonry panel reinforced also with mesh. According to Turanli (1985), the mortar and bricks, have identical mechanical properties. In particular the strength of the two materials is the same; corresponding to the strength after more than 28 dd. curing. The long term strength is about

25% higher, compared to plain soil bricks cured for 28 dd. and 2.5 times higher than plain soil mortar without curing. The crack pattern is similar compared to plain panel (see figure 4) but a wider crack pattern was found due to the higher mechanical properties. The global response in terms of Force/Displacement is almost linear up to failure point in the case of ideal material, while in the case of brittle material the graph has a second less stiff branch after a displacement of 17 mm. The stiffness reduction is related to a global cracking damage also accompanied by deterioration of the shear modulus, G, and Poisson ratio, ν. The difference, compared to plain panel with mesh is the strength of materials, and the global effect is an increase of shear strength comparable to the increase of basic material strength (about doubled). Compared to the plain panel without mesh an increase of strength of about 2.3 times is noticed while the ultimate displacement is almost doubled.

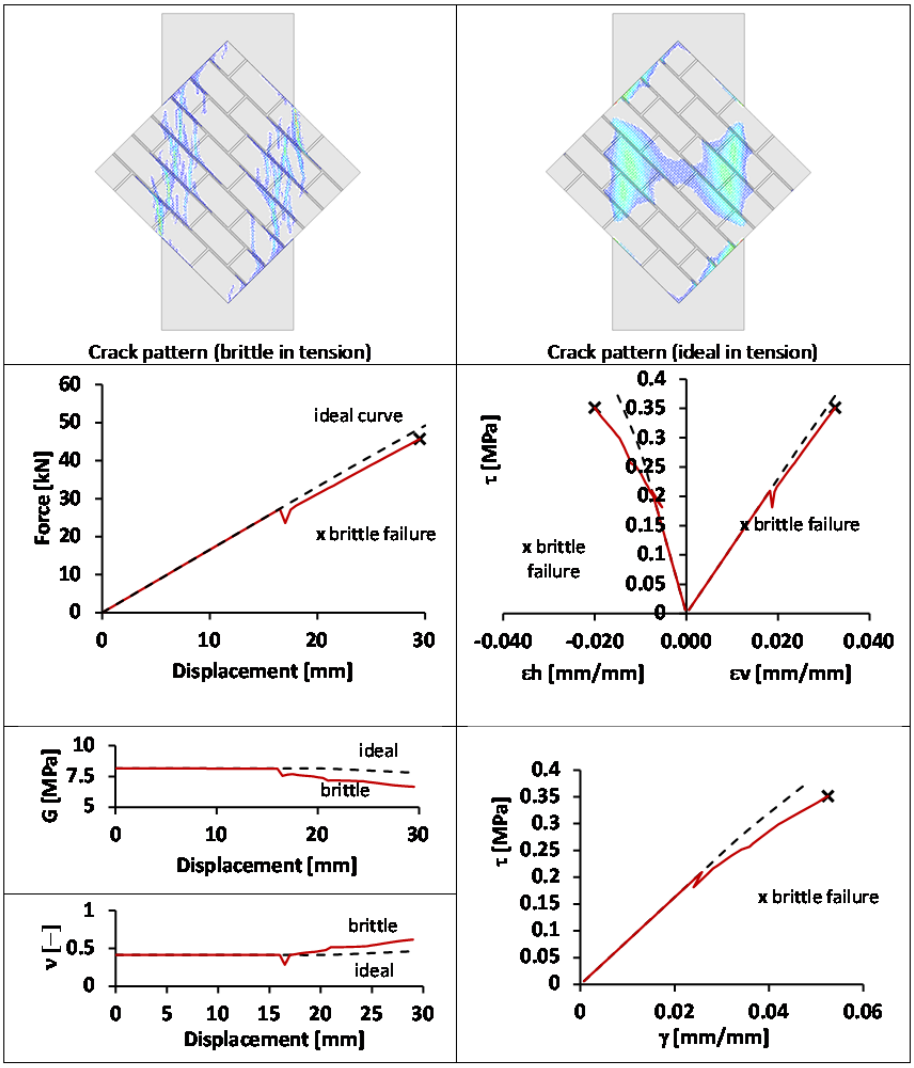

Figure 4. Numerical experimentation: Long term curing

4.3 FEM model: mortar B

As the case of long term curing the panel with a better mortar was not tested in reality, but it is part of the numerical experimentation on the validated model aimed to assess the influence of strength of materials on global behavior of the masonry panel reinforced with mesh. Compared to the first plain panel (having identical Young Moduli only), the strength of the mortar is about 2.5 times higher, compared to plain soil mortar (0 dd. curing); bricks are the same as in first plain panel. The global response in terms of Force/Displacement and crack pattern is almost similar (see figure 5) to the previous case of long term curing panel with mesh. This is mainly due to the presence of the mesh that makes less evident the benefits of the strength of basic materials on the global behavior. As well as in the previous case, compared to plain panel with mesh, the strength is doubled. Compared to the plain panel without mesh, the increase of strength is about 2.3 times and the ultimate displacement is doubled again.

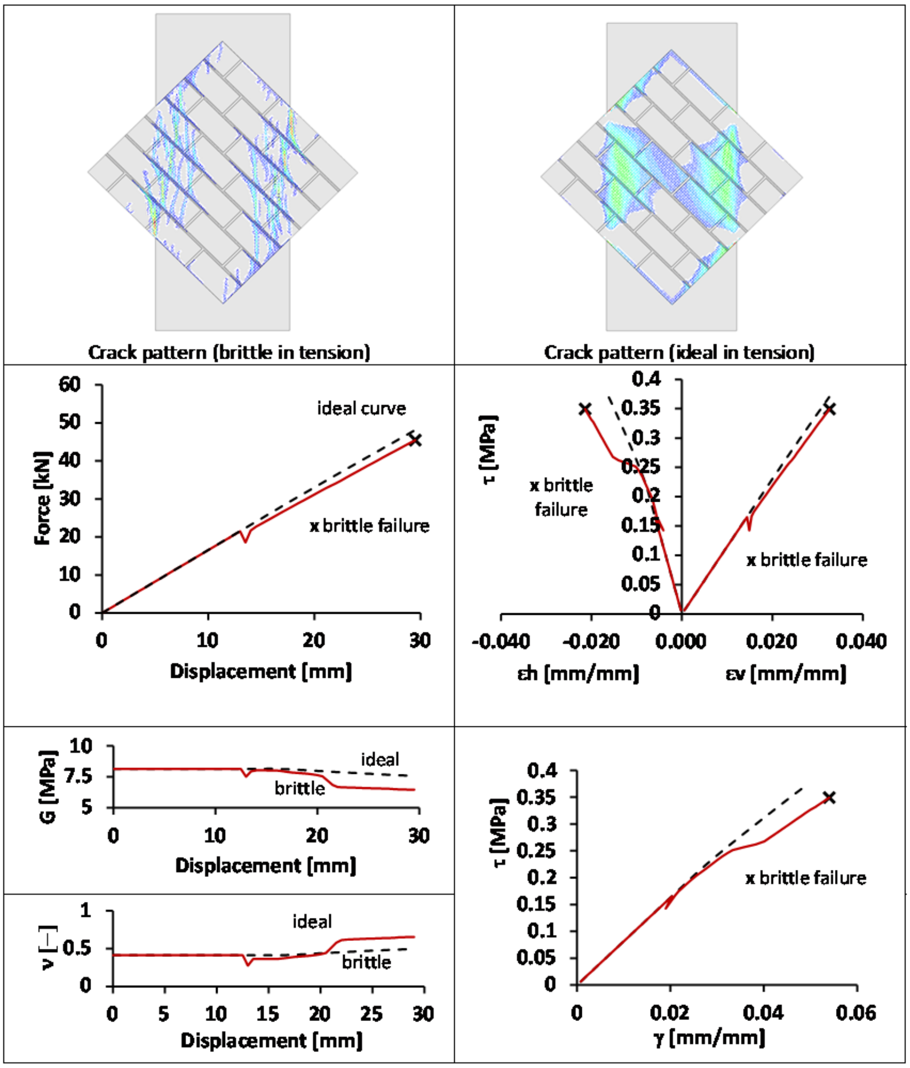

Figure 5. Numerical experimentation: Mortar B

5 CONCLUSIONS

Earth is still a widespread construction material all around the World. Many adobe historical constructions and structures are now in the need of conservation. Despite their diffusion, only few experimental tests about their reinforcement are available, hence numerical experimentation is seen as a feasible way to deepen knowledge on seismic behavior of such constructions. After validating the numerical model, FEM simulations can be used as a tool to increase the knowledge on the effect of constituent materials and cheap fiberglass mesh reinforcement on global performances. In fact, both the intrinsic variability of soil material, and the variability due to aging and composition jeopardize seriously the seismic performance of adobe constructions. Scope of the present study is to highlight the influence of the fiberglass mesh reinforcement coupled with the effect of mortar and brick composition and aging on the shear performance of in-plane walls, after validating the model based on experimental tests. A previous study by the authors has shown the behavior of the same considered panels without fiberglass mesh reinforcement. In table 2, ratios are evaluated with respect to plain soil test without mesh reinforcement. The increase of mortar strength (e.g. equal for both long term curing and better mortar simulations), yet having the same stiffness of basic materials, independently on the increase of brick strength, increases almost proportionally the global shear strength. However the benefic effect of the fiberglass mesh reinforcement reduces the benefits related to the better mechanical properties of the considered materials. The mesh is able to increase the shear strength of the panel, not altering its global stiffness.

Table 2. Main Results (the ratios are related to the plain without mesh)

FEM MODEL	Material level (input Data)				Global level (results)		
	Brick strength ratio	Mortar strength ratio	Brick stiffness ratio	Mortar stiffness ratio	G (MPa)	τ (MPa)	τ Ratio
Plain (without mesh)	1	1	1	1	8.07	0.15	1
Plain (mesh)	1	1	1	1	8.14	0.19	1.26
Long term curing (mesh)	2.5	2.5	1	1	8.14	0.35	2.31
Mortar B (mesh)	1	2.5	1	1	8.14	0.34	2.31

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