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SIMULATION OF IN-PLANE SHEAR TESTS ON MASONRY WALLS USING MICRO-MODELING TECHNIQUES

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Abstract. *A series of experimental tests involving in-plane shear loading of masonry walls is numerically simulated using finite element detailed micro models. The experimental tests were performed on masonry walls composed of solid clay bricks and cement/lime mortar. The mechanical properties of the two constituent materials and the brick-mortar interface had been previously characterized. The walls were subjected to shear under varying levels of uniform vertical pre-stress.*

The finite element models are created by modeling the bricks, mortar and the brick-mortar interface separately. In this manner the failure due to shear, tension or compression can be modelled in each component individually. Nonlinear constitutive laws to model cracking under tension and yielding under compression are used for the continuum elements modelling the units and the mortar. For the tension and shear failure of the interfaces a friction-tension cut off model is employed.

Good agreement is found between the experimental and three-dimensional numerical results. The maximum load is well approximated for the entire range of vertical pre-stress level, resulting in a realistic numerically derived interaction diagram between vertical compression and maximum shear. Furthermore, an obvious shift is noted in the failure mode produced by the models which mirrors the modes observed in the experiments: failure of the interfaces for low vertical loads and failure of the mortar and the bricks for high vertical loads.

1 INTRODUCTION

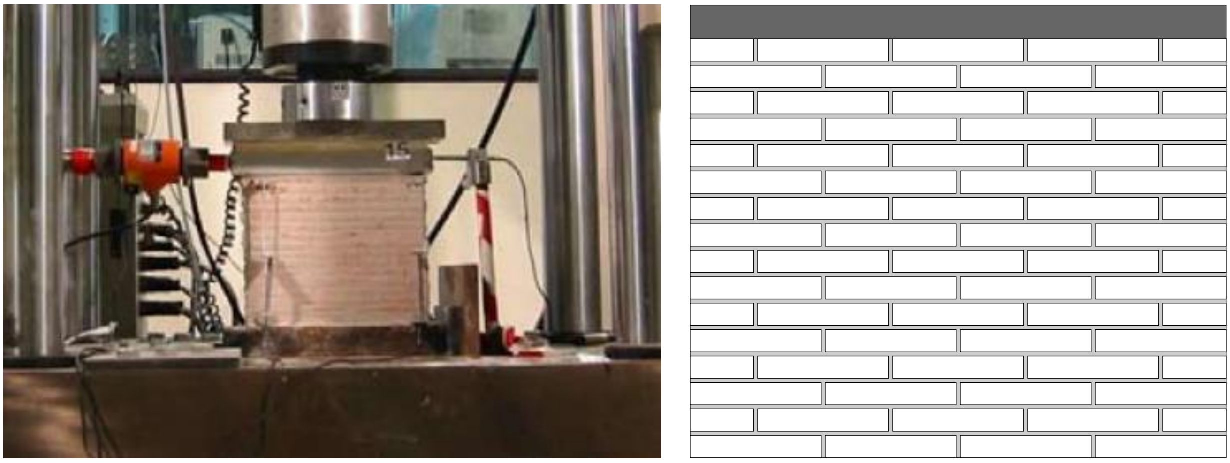
The main resisting mechanism of unreinforced masonry buildings to horizontal action, such as the one induced by earthquake events, is the in-plane shear function of their walls. For this reason, several empirical and analytical models have been developed for the estimation of the in-plane capacity of masonry walls [1,2]. The subject is also treated in modern design codes, although in a simplified fashion [3]. A combined experimental and numerical approach is therefore necessary for the detailed study of the response of walls subjected to horizontal loads.

The present research presents the experimental results obtained from the study of masonry walls subjected to horizontal loads under varying levels of vertical pre-stress [4]. The walls were composed of solid clay bricks and cement mortar. The experiments have been numerically reproduced using detailed micro-modeling techniques using various element types.

The effect of the element type on the obtained results was one of the subjects of investigation. Different modeling approaches based on different element types have been employed for this purpose.

2 CASE STUDY

The series of tests was performed on 15 quarter-scale walls under a wide range of vertical stress. The walls were constructed in a single leaf running bond arrangement using solid clay units and cement mortar. The length-height-width brick dimensions were 72.5 × 12.5 × 35 mm^3 and the bed and head joints were 2.5*mm* thick. The panels were 16 courses high and 4 bricks long. The walls were capped using a concrete beam, unto which both the vertical and horizontal loads were applied. Finally, the horizontal displacement was measured on the concrete beam. Figure 1 shows the wall geometry and the experimental setup.



(a) (b)

Figure 1: (a) Experimental setup and (b) wall geometry.

Both materials employed in the campaign were extensively characterized for the determination of their mechanical properties. In addition, the properties of the unit/mortar interface were determined through the testing of couplets and triplets. The bricks and the mortar were subjected to three-point bending and compression tests [5,6]. The tensile strength was derived from the flexural strength according to the Spanish Structural Concrete Code [7]. Small masonry assemblages were also subjected to compression tests for the determination of the compressive strength and Young’s modulus [8]. The material properties are summarized in Table

1, where f_c, f_t and E refer to the compressive strength, flexural strength and Young Modulus respectively, and c_0 and φ are the cohesion and the friction angle at the unit-mortar interface.

Table 1: Material properties

	f_c [MPa]	f_t [MPa]	E [MPa]
Units	35.0	15.2	4080
Mortar	8.34	1.36	3500
Wallette - Vertical	17.54		
	f_t [MPa]	c_0 [MPa]	φ [-]
Interface	0.55	0.42	39^0

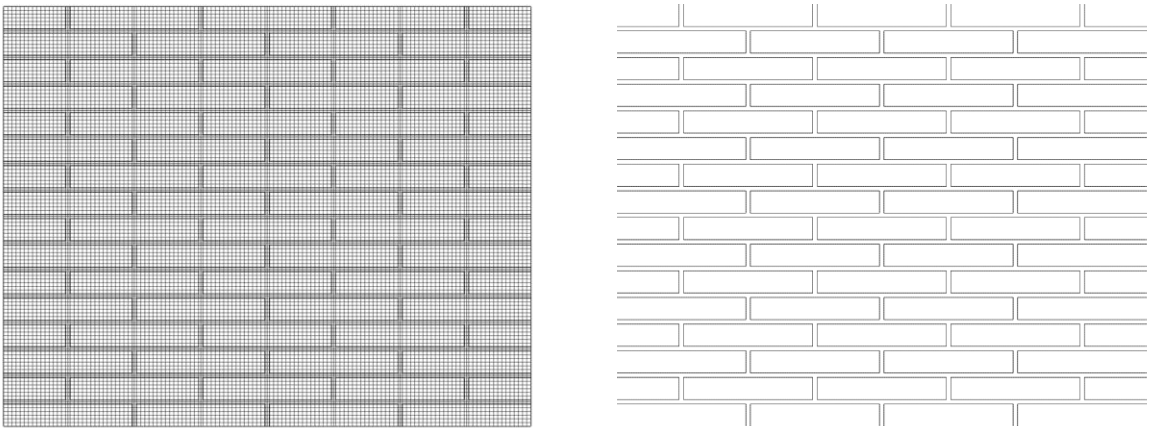
The walls were subjected to a vertical load followed by the application of the horizontal force while maintaining the vertical load constant. The top beam was left free to rotate, resulting in a simple cantilever configuration. A wide range of vertical stress levels was applied. The results in terms of maximum shear stress obtained are presented in Table 2.

Table 2: Wall experimental results: vertical pre-stress σ vs. maximum shear τ_{max}.

σ [MPa]	τ_{max} [MPa]
0.895	0.538
1.190	0.646
1.486	0.850
1.933	1.028
2.381	1.180
2.681	1.363
2.981	1.461
3.333	1.454
3.867	1.635
4.286	1.722
4.762	1.737
5.357	2.249
5.952	1.969
9.048	1.737

3 MODELS

The walls have been simulated using detailed micro-modeling techniques, meaning that the model includes separate representations of the units, the mortar and the unit/mortar interface. Using the same basic mesh, three models were used in the calculations: plane stress, plane strain and three-dimensional models. The basic mesh is shown in Figure 2. 16884 continuum and 4482 interface elements were used in the two plane models and six times as many in the three dimensional case.



(a) (b)

Figure 2: Finite element mesh: (a) continuum and (b) interface elements.

The constitutive law used for the units and mortar was a smeared crack model in tension [9] using exponential tension softening and employing a parabolic compressive hardening/softening curve [10], all expressed in total strain context [11]. Pressure dependent behavior of the mortar was also taken into account [12]. This model is capable of simulating the behavior of the material in tension and compression under lateral stress and has proven capable of predicting the compressive strength of masonry [13]. It has also been shown to produce results for the compressive strength of masonry strongly dependent on the type of element used in the analysis: plane stress, plane strain or three dimensional elements, the third giving the most accurate results.

The interfaces were assigned a combined cracking/shearing model [14] capable of simulating shear sliding and tensile opening of the interface. Compressive damage was taken into account in the continuum elements only and not in the interfaces. The DIANA general purpose finite element code was used for the calculations [15].

4 NUMERICAL RESULTS

The accuracy of the numerical models varies according to the element type used, as can be seen in Figure 3. Apart from a very limited range of low vertical stress levels, the plane stress (PS) model produced the least accurate results due to being unable to correctly simulate the confinement of the mortar in the joints for high levels of vertical compressive stress. Therefore, the maximum shear predicited using plane stress was very low. The thee-dimensional and plane strain (PE) models were far more accurate throughout the range of vertical prestress level and, in fact, produced similar results in terms of maximum horizontal force, with the plane strain model giving the highest values for the maximum shear for the highest levels of vertical pre-stress.

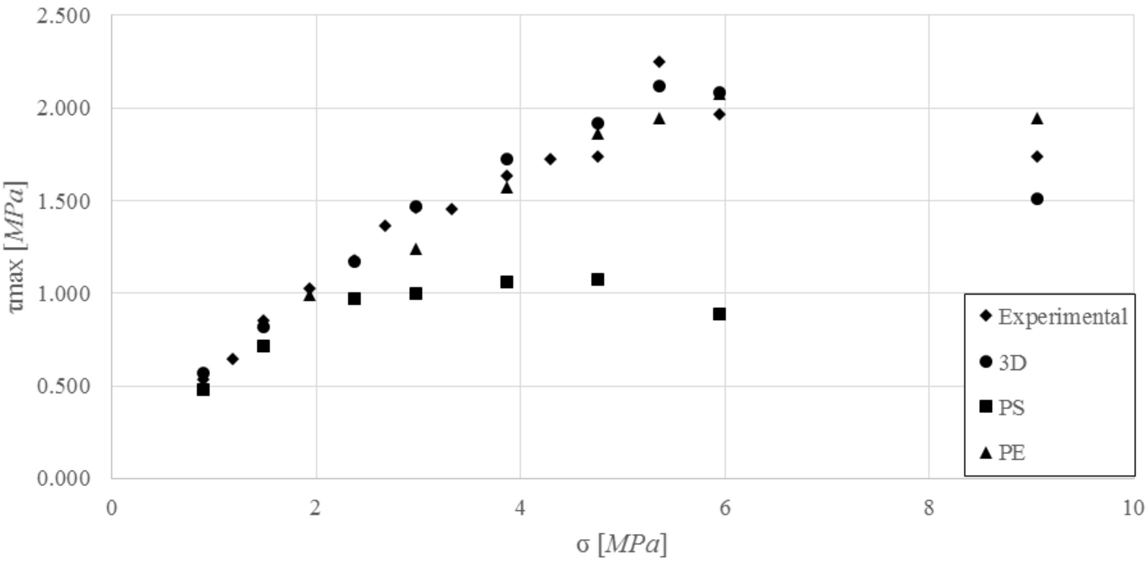


Figure 3: Interaction diagram comparison between experimental, 3D, plane stress and plane strain values.

Figure 4 shows the stress-displacement diagrams obtained from the 3D model. The shift in failure mode and the decrease of ductility for higher levels of vertical stress is clearly shown. Characteristic failure modes for various levels of vertical pre-stress are shown in Figure 5 as they were obtained from the three-dimensional model. The shift from interface tensile failure to shear sliding and finally diagonal cracking and crushing of the compressed toe is illustrated. Whereas the PE model produced similar failure mechanisms, the PS models were characterized by a much more brittle behavior in the compressed toe due to the reduced amount of lateral confinement of the mortar in the joints and hence a much smaller increase in local compressive ductility. This is especially evident for higher levels of vertical pre-stress, where the largest divergence in terms of capacity were also registered.

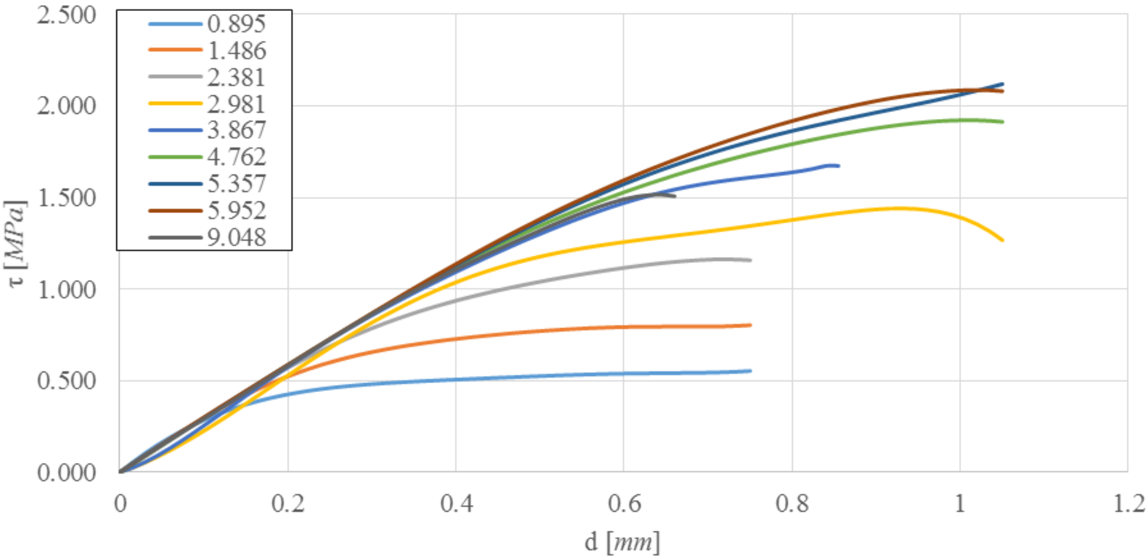
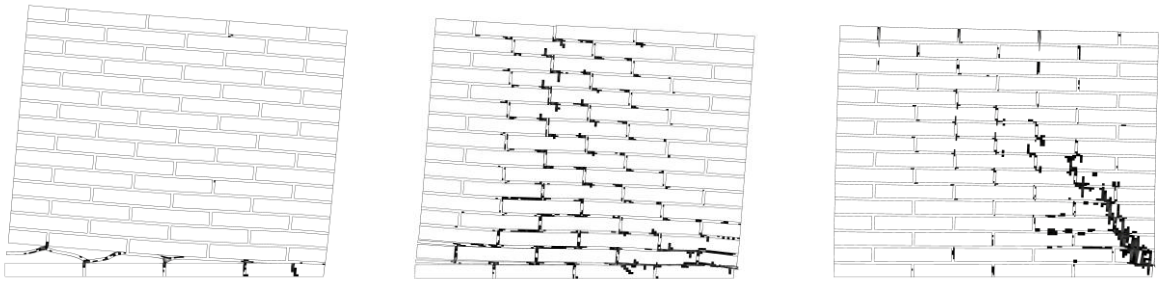


Figure 4: Shear stress-displacement diagrams for 3D model for various levels of vertical pre-stress.



(a) (b) (c)

Figure 5: Failure mode examples. Deformation and tensile damage patterns for varying levels of vertical pre-stress: (a) σ = 0.893 MPa, (b) σ = 2.981 MPa and (c) σ = 9.048 MPa.

The large difference in predicted shear strength between the three modeling approaches for medium and high levels of vertical pre-stress, especially between the PS case and the other cases, indicate a strong dependence of the behavior of the wall under shear on the behavior of the mortar in the joints under lateral confinement. This effect has been previously noted in numerical studies on masonry under compression. This effect is less pronounced in this particular case, owing to the more direct involvement of shear and tension failure modes as well as the compressive mode. Hence the similar results obtained from plane strain and three-dimensional models. Nevertheless, the trend of plane stress to greatly underestimate the ultimate load and of plane strain to overestimate it is encountered here as well.

Overall, it has been shown that out-off-plane stress in the mortar joints, resulting in lateral confinement under in-plane compressive loads, is critical not only for the numerical determination of the compressive strength of masonry but for the realistic simulation of shear walls as well.

5 CONCLUSIONS

A series of experimental tests of unreinforced masonry walls under in-plane shear has been modeled using finite element detailed micro-models. Three different approaches have been used, namely plane stress, plane strain and three dimensional elements. The shear capacity obtained in the numerical predictions has been found strongly dependent on the type of element, the plane stress assumption being unable to produce accurate results, whereas the plane strain and three-dimensional models have produced far more successful reproductions of the experimental results.

According to the analyses carried out, the influence of the compressive behavior of the mortar in the joints is most successfully modeled with the three-dimensional model. The differences between the three approaches are more evident for the highest levels of vertical pre-stress.

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REFERENCES

[1] Turnšek V, Cacovic F. Some experimental results on the strength of brick masonry walls. Proc. 2nd Intern. Brick Mason. Conf., 1971, p. 149–56.

[2] Mann W, Muller H. Failure of Shear-Stressed Masonry. An Enlarged Theory, Tests and Application to Shear Walls. Proc. Br. Ceram. Soc., 1982, p. 223–35.

[3] CEN. EN 1996-1-1: Rules for reinforced and unreinforced masonry. 2005.

[4] Charry Ablanque JA. Estudio Experimental del Comportamiento de Paredes de Obra de Fábrica de Ladrillo ante la Acción de Cargas Laterales. Department of Strength of Materials and Structural Engineering, Technical University of Catalonia, Barcelona Spain: PhD dissertation; 2010.

[5] CEN. BS-EN 1015-11 - Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar. 2007.

[6] CEN. UNE-EN 772-1 - Métodos de ensayo de piezzas para fábrica de albañilería - Parte 2: Determinción de la resistencia a compresión. 2011.

[7] Ministerio de Fomento de España. Real Decreto 2661/1998 - Instrucción de Hormigón Estructural. 1998.

[8] CEN. BS-EN 1052-1 - Methods of test for masonry - Part 1: Determination of compressive strength. 1999.

[9] Vecchio FJ, Collins MP. The modified compression-field theory for reinforced concrete elements subjected to shear. Am Concr Inst J 1986;83:219–31.

[10] Feenstra P, Borst R De. A composite plasticity model for concrete. Int J Solids Struct 1996;33:707–30.

[11] Selby RG, Vecchio FJ. A constitutive model for analysis of reinforced concrete solids. Can J Civ Eng 1997;24:460–70.

[12] Hsieh SS, Ting EC, Chen WF. A plastic-fracture model for concrete. Int J Solids Struct 1982;18:181–97.

[13] Drougkas A, Roca P, Molins C. Micro-Modeling of Stack Bond Masonry in Compression Using a Plasticity Law. XII Int. Conf. Comput. Plast., 2013.

[14] Lourenço PB, Rots JG. Multisurface interface model for analysis of masonry structures. J Eng Mech 1997;123:660.

[15] TNO. DIANA User’s Manual. Delft: TNO DIANA BV; 2012.