Numerical analysis of a masonry infill (divided into smaller wallettes) under in-plane cyclic loading

A. Drougkas, C.-E. Adami, E. Vintzileou & V. Palieraki
National Technical University of Athens, Faculty of Civil Engineering, 15773 Athens, Greece

ABSTRACT: Masonry infill in reinforced concrete frames has been recognised as being a strong factor influencing the seismic behaviour of buildings. Therefore, the development of innovative infill systems, coupled with the rigorous study of their behaviour, is of significant importance. Within the framework of the INSYSME project (http://www.insysme.eu/), a new infill system was designed and tested. The defining feature of the system, composed of clay units, is the division of the masonry wall into smaller, and thus more flexible, wallettes separated by vertical joints. The frames are subjected to in-plane cyclic shear loading to the point of irreversible damage of the masonry. Subsequently, the experiments are simulated using nonlinear finite element analysis in an effort to highlight the features of the response of the actual structure, to predict the maximum force and to reproduce the failure mode. The finite element modelling consists in individually simulating the behaviour of the frame, masonry and interfaces between the masonry and the infill and between the three wallettes. For this purpose push-over analyses were carried out. Masonry was considered as an equivalent composite material with nonlinear behaviour; the constitutive model is based on smeared crack approach and simulates the main failure modes of masonry under tension, compression and shear. Special care was taken for the description of wallette-to-wallette and wallette-to-RC frame interfaces. The mechanical properties of the masonry were identified from compression tests of single wallettes, while nonlinear parameters are selected from the literature. The numerical results of the analysis are verified with the experimental results obtained during in-plane cyclic tests. The comparison of the numerical and experimental data demonstrates that the numerical model estimates successfully the response of the RC infilled frame. Moreover, a parametric study is carried out, with the purpose to investigate the influence of selected material parameters on the predicted response.

1 INTRODUCTION

Reinforced concrete frame construction with masonry walls for enclosures and partitions accounts for a large percentage of new buildings and of existing structures from the previous several decades. While the masonry infill is often disregarded in the analysis and design of new structures, its significance in the assessment and redesign of existing buildings is recognised by modern design codes, such as Eurocode 8 (CEN 2005).

Masonry infill can increase the stiffness and bearing capacity of reinforced concrete frames to a significant degree. This is especially true in the case of seismic loading. Nevertheless, special care is not often taken in the construction of the infill, resulting in extensive damage to the building's masonry and increasing the cost of structural repair. Within the framework of INSYSME project, experimental investigation on full scale frames with masonry infills is carried out at the Laboratory of Reinforced Concrete (LRC), National Technical University of Athens (NTUA). Two innovative infill systems are developed and their in-plane and out-of-plane response is experimentally investigated. In parallel, the behaviour of the infilled frames is being modeled using the Finite Element Method (FEM), with the aim to predict their pathology and the experimentally recorded response.

In this paper the experimental campaign involving in-plane cyclic shear tests performed on a reinforced concrete frame with a masonry infill divided into smaller wallettes (INSYSTEM 1) is briefly presented. More details about the system are given in (Vintzileou et al. 2016). Moreover, a nonlinear finite element analysis is employed in the simulation of the experiments, which is enriched through a parametric investigation. The results of these analyses are presented and discussed in the following sections.

2 EXPERIMENTAL DATA

2.1 *Outline of experimental campaign*

A reinforced concrete frame was constructed in full scale at the Laboratory of Reinforced Concrete of the National Technical University of Athens. It was constructed on a stiff foundation slab, which also serves for the anchoring of the column reinforcement bars. The foundation slab was rigidly connected to the lab floor through the use of dowels. The frame and its reinforcement were designed according to the Eurocode provisions (CEN 2004a; CEN 2004b) with the added intent of limiting as much as possible the damage on itself so that the damage on the masonry may arise more clearly. The clear span of the beam is

3.10 m and its clear height is 2.35 m. The beam and the columns have a width of 0.40 m.

The infill masonry was constructed using a clay block available in the market. These units result in a wall with a thickness of 0.24 m. The wall was separated in smaller wallettes through vertical sliding joints infilled with cement mortar. The aspect ratio of the wallettes results in a delay of the onset of shear failure in the wall compared to a monolithic wall spanning the entire area delimited by the reinforced concrete frame. Figure 1 shows the specimen used for the experimental testing.

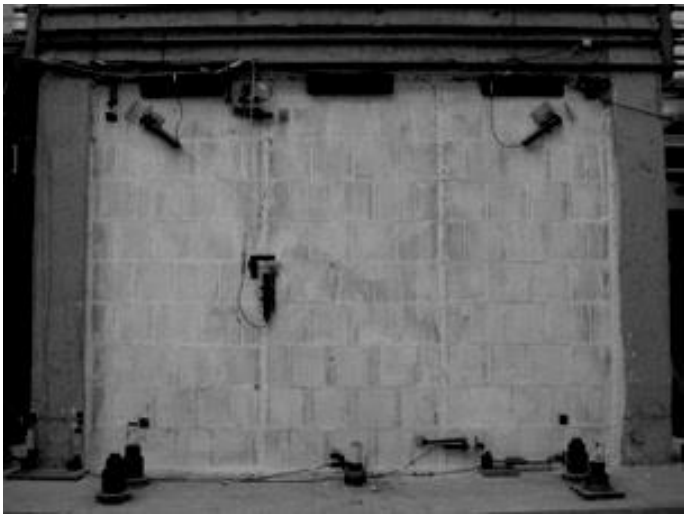

Figure 1: Specimen for in-plane shear testing (Vintzileou et al. 2016).

The infilled frame was subjected to quasi-static cyclic in-plane shear loads. For each chosen level of applied positive and negative displacement three cycles were performed. The test was displacement controlled and the displacements were applied at the top beam of the frame. No additional vertical loading was applied at the frame or the infill masonry. The cycles were continued until the drop in the reaction force was deemed sufficient and when non-repairable damage was registered in the wall.

2.2 *Results*

The hysteresis loops obtained from the experiment are presented in Figure 2. The peak force registered was 702.5 kN (mean value of the force measured in the two loading directions), obtained for an applied displacement of 40mm corresponding to a interstorey drift value, δ, equal to 1.75%. The peak applied deformation was 57.5 mm (drift approx. equal to 2.45%).

The damage pattern registered at the end of the test, after a maximum deformation of 57.5 mm had been applied, is illustrated in Figure 3. Separation of the masonry walls from the surrounding frame and of the wallettes from each other was registered for low levels of applied displacement. Diagonal cracking was not propagated through the entire wall but evidence of diagonal cracking was noted in each individual wallette, particularly in the two outer wallettes. Significant damage was also noted at the top of the masonry wall, along the contact with the overlaying concrete beam. Cracking of the units initiated at an applied displacement of 20 mm, below which the wall is deemed repairable.

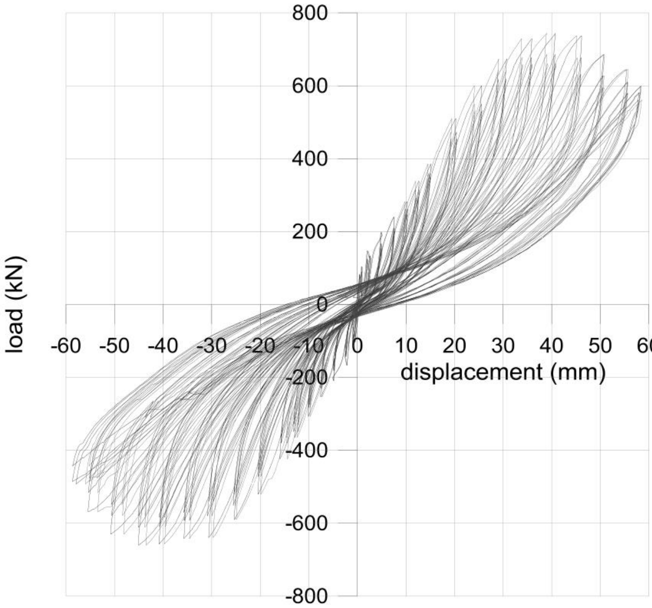

Figure 2: Experimentally derived hysteresis loops (Vintzileou et al. 2016).

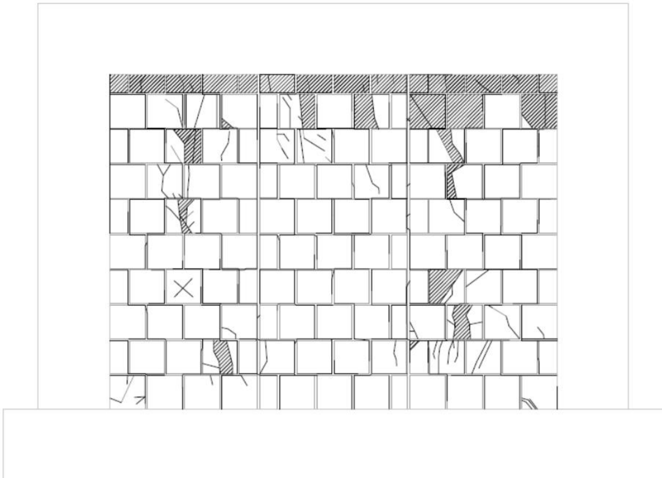

Figure 3: Crack pattern the specimen consisting of three walls at δ=2.45%.

3 NUMERICAL MODELING

3.1 *Modelling strategy*

The experiments were simulated using nonlinear finite element analysis. The model creation and the calculations were performed using the DIANA finite element package (TNO 2012).

The models utilized in the simulation of the experiments included the separate representation of the concrete frame, masonry and interface between the two. The models did not include the foundation beam or slab as it was deemed unnecessary due to their very high stiffness and the fact that they were not directly loaded.

The reinforced concrete frame and the masonry infill were modelled using 8-node quadrilateral plane stress elements. The interaction of the wall and the frame was modelled using 6-node interface elements. Embedded reinforcement elements were used to simulate the reinforcement of the RC elements. Plane stress modelling is adequate in this case due to the dimensions of the frame and the nature of the loading. Furthermore, it is an option that can provide the needed numerical results with a relatively low computational cost. The mesh is illustrated in Figure 4. The average element edge length was roughly 75 mm.

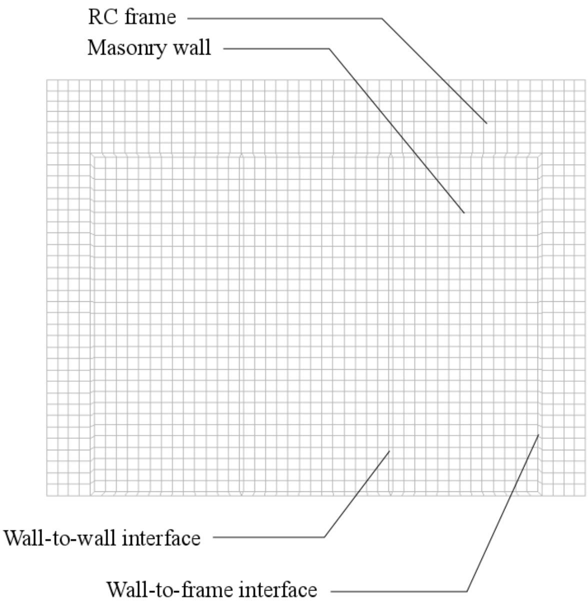

Figure 4: Finite element mesh used in analyses.

The displacements at the base of the model were constrained. Following the application of the self-weight in the vertical direction, the beam was displaced horizontally in its plane direction. Instead of a cyclic load, the in-plane load was applied in a monotonic fashion. While monotonic loading only allows for the numerical results to be compared with the experimental force-displacement envelope, cyclic loading increases the constitutive complexity to a prohibitive degree and beyond the scope of this investigation.

The material properties used in the analyses are presented in Table 1. The compressive strength of the concrete and the masonry were determined through experimental testing. The Young's modulus and tensile strength of the concrete were determined according to the values prescribed by Eurocode 2 (CEN 2004a) and slightly adjusted after a parametric calibration. The Young's modulus and tensile strength of masonry was prescribed a value consistent with its compressive strength according to the relevant literature. The interface strength properties and elastic stiffness were determined according to the properties and thickness of the mortar joint used for filling the gap between the masonry and the reinforced concrete frame. The values for the shear and tensile strength in the table correspond to the interfaces between the infill and the frame. The interfaces between the three wallettes in INSYSTEM 1 were made fragile in tension and shear, in order to account for the lower level workmanship and mortar compaction possible to be achieved in these elongated vertical joints. They are, however, still capable of transmitting compressive forces.

Table 1: Material properties for concrete, reinforcement, masonry and interfaces.

	E (N/mm^2)	v (-)	f_c (N/mm^2)	f_t (N/mm^2)	G^I (N/mm)
Concrete	20000	0.20	23	2.3	0.0705
Masonry	1000	0.20	3	0.3	0.0178
Steel	200000	-	500	500	-
	k_n (N/mm^3)	k_s (N/mm^3)	c (N/mm^2)	$tan(\varphi)$ (-)	f_t (N/mm^2)
Interface	56	20	0.2	0.75	0.2

3.2 *Constitutive laws*

The continuum elements were prescribed a total strain crack model (Selby & Vecchio 1993) using an exponential softening law in tension, based on fracture energy, and parabolic hardening in compression (Feenstra & Borst 1996). Ideally plastic behaviour was assumed in compression for all components. The biaxial behaviour is accounted for using the Hsieh-Ting-Chen failure criterion (Hsieh et al. 1982). The combination of these laws can simulate the behaviour of the continuum parts of the model up to and following failure in compression, tension and shear.

The interfaces are modelled using the Mohr-Coulomb failure criterion in shear combined with a Rankine cut-off in tension. Thus the interfaces may fail in either shear or tension.

The reinforcement steel is considered to behave in a linear elastic-perfectly plastic manner in both tension and compression. Perfect bonding is assumed with the surrounding concrete.

3.3 *Properties for parametric study*

The properties shown in Table 1 were reached after experimental tests, slight calibration and a few rational assumptions. In order to overcome the uncertainties inherent in the determination of the properties of masonry, a sensitivity analysis was carried out. This analysis focused on one hand on the material properties of the masonry and on the other on the arrangement of the infill wallettes.

The material parameters here investigated include the compressive and tensile strength of the masonry. The values chosen were a low value of half the initial value and a high value equal to twice the initial parameter.

The nonlinearity of the interfaces was also investigated. A comparison was attempted between the initial model and a model in which the interfaces between the wallettes themselves and with the surrounding frame are kept linear elastic.

Two effects of the geometrical arrangement of the wallettes were also studied: one with the infill divided into two wallettes and one divided into four. The overall dimensions of the frame, the thickness of the joints and the thickness of the masonry were kept constant.

Each material and geometrical parameter was altered individually and no combinations of altered parameters were attempted. Regardless, a large set of analyses results was produced which serves to highlight the influence of numerous parameters and characteristics of the infill on the global behaviour of the frames.

4 ANALYSIS RESULTS

In this section the main results (Force vs displacement envelopes and crack pattern) of the analyses are presented and compared to those derived from the experimental campaign. Then, the results of the parametric study are shown and discussed upon.

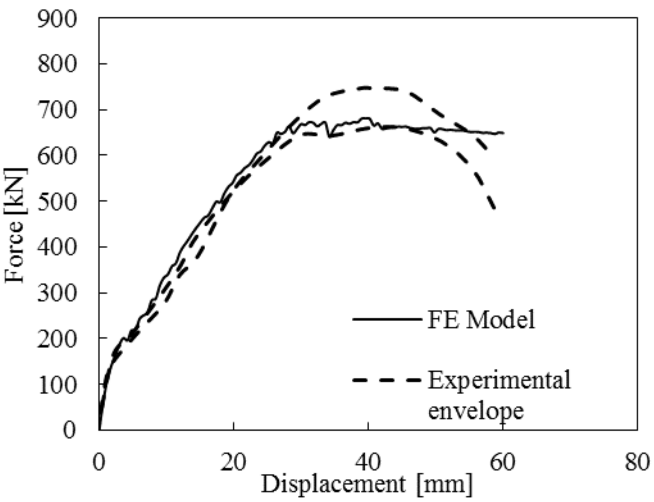

Figure 5: Force-displacement experimental envelope vs. numerical results for initial analysis.

4.1 *Initial results*

The force-displacement curve obtained from the initial analysis and its comparison with the experimental envelope for actuator extension and contraction is shown in Figure 5. The comparison between the numerical and experimental curves shows that a very good agreement has been obtained in terms of both structural stiffness and peak force.

The failure mode obtained from the numerical analysis is shown in Figure 6. A large diagonal crack is formed in the first wallette in the direction of the applied load. The other two wallettes show more limited, but still quite pronounced, cracking. Separation of the masonry from the frame is also noted at the interface with the beam and at the base of the first column in the direction of the load. Some separation is also registered between the wallettes near their base and at their top.

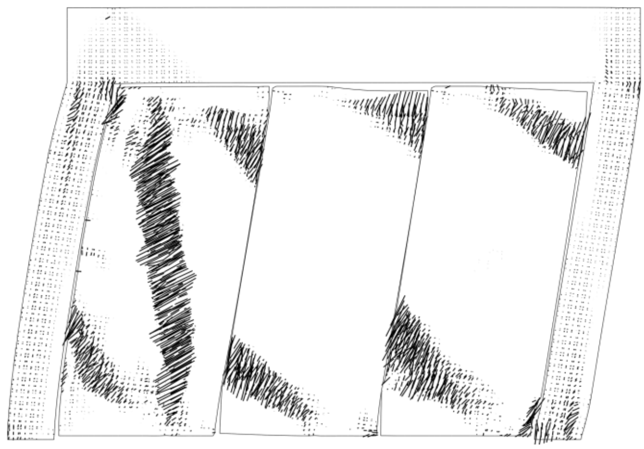

Figure 6: Cracking pattern and deformed shape obtained from numerical analysis at peak displacement.

Diffuse cracking is noted at both columns, particularly at the beam-column nodes and at the base. The cracking at the beam is limited, apart from near the nodes.

The cracking pattern is in good agreement with the experimental findings shown in Figure 3, according to which the damage was more extensive on the external wallettes rather than in the central one. Cracking damage is also registered at the top of all three wallettes. Finally, separation of the wallettes from the frame is noted at the early stages of loading and results in a decrease in the global structural stiffness of the model.

4.2 *Parametric analysis results*

Having obtained good results from the initial analysis, the parametric investigation can serve to underline the importance of a few selected parameters on the results.

The influence of the compressive strength of the masonry on the response of the infilled frame is shown in Figure 7. While the difference in the peak force is not proportional to the difference in the material parameter, the results are rather sensitive to changes in the compressive strength of the infill. As regards to the value of the initial stiffness of the infilled frame, one may observe that this is not sensitive to the compressive strength of the masonry, at least for the values of compressive strengths examined here.

in the infill to two results in an increase in the peak force and in the structural stiffness. However, the shift in failure mode due to the changing aspect ratio of each wallette results in a small decrease in the post-peak ductility as well. A small increase in the peak force was also registered when the aspect ratio is increased by increasing the number of wallettes to four. In this case the height-to-length aspect ratio of the wallettes is more favourable for achieving a higher degree of ductility, as is indeed the case in the numerical results.

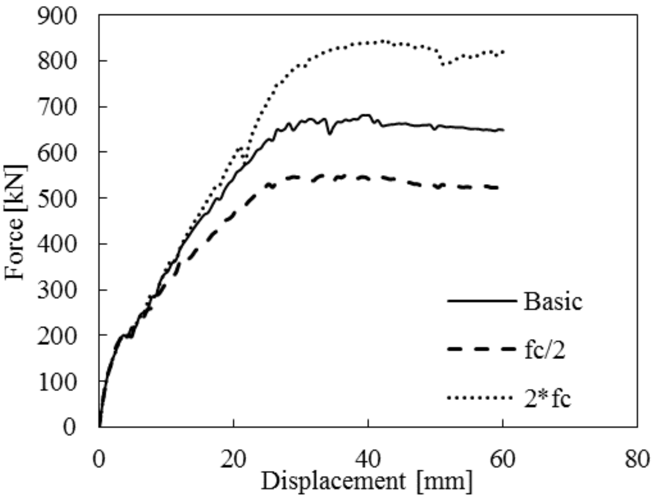

Figure 7: Influence of compressive strength of masonry.

The effect of the tensile strength of the masonry on the behaviour of the infilled frame is illustrated in Figure 8. While the influence on the peak force is rather small, further underlining the importance of the compressive strut, a reduction in the tensile strength results in a drop in the post-peak behaviour.

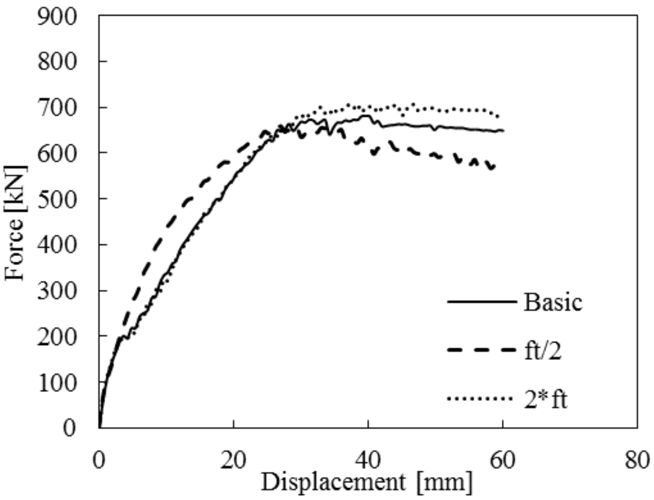

Figure 8: Influence of tensile strength of masonry.

The effect of the nonlinearity of the interfaces is indicated in Figure 9. The nonlinearity of the interfaces appears to have a critical effect in the global stiffness of the structure. Separation and sliding between the frame and the infill, and between the wallettes themselves, occurs for very low levels of applied shear force, as was noted in the experimental campaign. When this relative movement is limited through the assumption of linear elasticity of the interfaces the global structural stiffness is increased by a considerable amount. Nevertheless, the peak shear force is not significantly altered, but is attained at a much lower drift level.

Illustrated in Figure 10 is the effect of the number of wallettes to which the infill is divided on the behaviour of the structure. Reducing the height-to length ratio of the wallettes by reducing their number

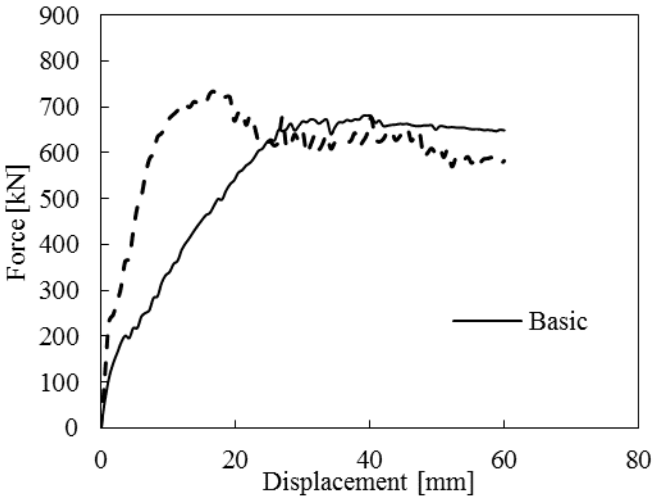

Figure 9: Influence of interface nonlinearity.

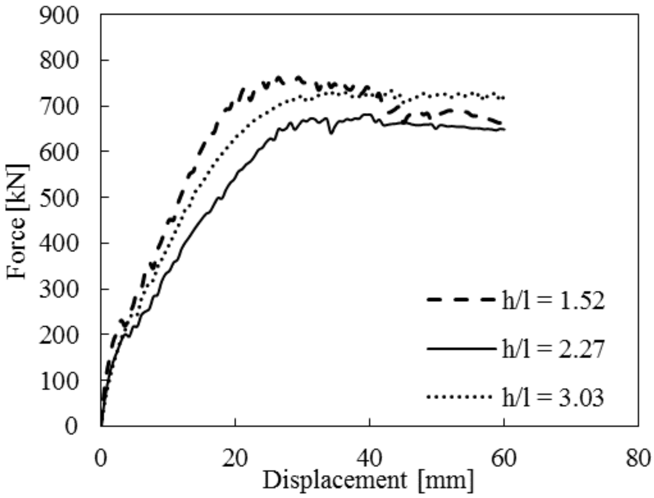

Figure 10: Influence of wallette height-to-length aspect ratio.

5 CONCLUSIONS

A nonlinear FE model of a reinforced concrete frame infilled with a system of masonry wallettes separated by vertical joints was used for the simulation of in-plane shear experimental tests. Good agreement was found between the experimental and numerical results in terms of peak shear force, global structural stiffness and failure mode.

The parametric investigation highlighted the sensitivity of the numerical results to a number of material parameters. It further demonstrated the importance of interface nonlinearity in achieving a proper representation of the stiffness of the infilled frame.

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7 REFERENCES

CEN, 2004a. *EN 1992-1-1 - Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*,

CEN, 2004b. *EN 1998-1:2004 — Eurocode 8: Design of structures for earthquake resistance — Part 1: General rules, seismic actions and rules for buildings*,

CEN, 2005. *EN 1998-3:2005 — Eurocode 8: Design of structures for earthquake resistance — Part 3: Assessment and retrofitting of buildings*,

Feenstra, P.H. & Borst, R. De, 1996. A composite plasticity model for concrete. *International Journal of Solids and Structures*, 33(5), pp.707–730. Available at: http://www.sciencedirect.com/science/article/pii/002076839500060N [Accessed February 7, 2014].

Hsieh, S.S., Ting, E.C. & Chen, W.F., 1982. A plastic-fracture model for concrete. *International Journal of Solids and Structures*, 18(3), pp.181–197. Available at: http://www.sciencedirect.com/science/article/pii/0020768382900014.

Selby, R.G. & Vecchio, F.J., 1993. *Three-dimensional Constitutive Relations for Reinforced Concrete*, University of Toronto, Department of Civil Engineering.

TNO, 2012. *DIANA User's Manual*, Delft: TNO DIANA BV.

Vintzileou, E.N., Adami, C.-E. & Palieraki, V., 2016. In-plane and out of plane response of a masonry infill divided into smaller wallettes. In *Proc. 16th International Brick and Block Masonry Conference, Padova, Italy*.