Numerical modeling of the tension-compression behavior of tie connections in brick masonry walls

Modelação numérica do comportamento de tração-compressão de ligadores em paredes de alvenaria

Javier Ortega[1] **| Nuno Mendes**[1] **| Graça Vasconcelos**[1]

[1] ISISE, Universidade do Minho, Portugal
Emails: javier.ortega@civil.uminho.pt; nunomendes@civil.uminho.pt; graca@civil.uminho.pt

abstract

Brick masonry veneer walls connected to infill walls inserted in a reinforced concrete (RC) frame is a very common constructive system in Portugal. The stability of the veneer wall is ensured by ties that make the connection with the masonry infill walls. These ties are the main structural element transferring the out-of-plane loads to the main structure during an earthquake. However, the characterization of the seismic behavior of these tie connections is an insufficiently explored topic. The present paper shows a numerical investigation that aims to simulate experimental results of tension and compression tests performed on masonry wallets connected by means of steel ties. The main objective of the present research is to obtain a better understanding of the complex structural behavior of this specific construction system to eventually develop simplified numerical tools to be used in engineering practice for the seismic design and retrofitting of brick masonry veneer walls.

Keywords: Brick masonry veneer walls, steel ties, experimental analysis, cyclic tension-compression tests, numerical analysis

resumo

As paredes de alvenaria não estruturais de fachada constituem um dos elementos construtivos mais tradicionais das envolventes de edifícios construídos em Portugal. A estabilidade destas paredes é garantida por ligadores que fazem a ligação com as paredes de alvenaria de enchimento. Estes ligadores são o principal elemento estrutural a transferir as cargas fora do plano para a estrutura principal durante um terremoto. No entanto, a caracterização do comportamento sísmico dos ligadores é ainda um tema insuficientemente explorado na literatura. O presente artigo mostra uma investigação numérica com o objetivo de simular ensaios de tração-compressão realizados em provetes de alvenaria ligados através de ligadores metálicos. O objetivo último da investigação será obter um melhor entendimento do complexo comportamento estrutural de esta tipologia construtiva e eventualmente propor ferramentas numéricas simplificadas que possam ser usadas por engenheiros na prática profissional para o desenho sísmico e reabilitação de paredes de alvenaria de fachada.

Palavras-chave: Paredes de alvenaria de fachada, ligadores metálicos, análise experimental, ensaios cíclicos de tração-compressão, análise numérica

1- INTRODUCTION

Brick masonry veneer walls consist of an exterior cladding separated from the structural interior backing by an air cavity, acting as a skin of the structure. Due to their aesthetics, durability and good thermal behavior, veneer walls are commonly observed in several countries in the world as a cladding on buildings. In Portugal, the backing structural system typically consists of reinforced concrete masonry infilled frames. This constructive solution can be also applied as a solution for renovation traditional façades and improve the energy efficiency of buildings.

Brick veneer walls are attached to the backing system through distinct types of ties. Some recent earthquakes brought to light some fragilities of this constructive system, resulting in damages due to combined in-plane and out-of-plane loads (Ceci et al 2010). One justification for the observed seismic vulnerability can be the absence of specific regulations for the design of brick masonry veneers. The present research relies on experimental and numerical analysis to understand the seismic behavior of tie connections. The main objective is to eventually develop guidelines for seismic design and detailing of brick masonry veneer walls and tie connections. In this work, a numerical modelling approach is presented, intended to simulate the experimental results of tension and compression tests performed on masonry wallets connected by means of steel ties.

2- EXPERIMENTAL SETUP AND RESULTS

The bond resistance of different types of ties was assessed through cyclic tension-compression tests performed on ties embedded in different brick masonry wallets. The specimens considered in the experimental campaign (Martins 2018) are brick masonry prisms representing common masonry infills and veneer walls with embedded ties at the bed joint. Three test specimens were built (Fig. 1): (a) brick masonry prisms representing masonry infills with embedded ties at the bed joints; (b) masonry prisms representing typical brick veneers with embedded ties at the bed joints; and (c) complete assemblages with brick masonry prisms representing brick veneers attached to brick masonry infills through ties. In case of the complete assemblages, an air cavity thickness of 100 mm was considered.

The experimental setup is shown in Fig.2. The masonry prisms were confined through steel plates connected by means of steel rods to prevent the movement of the specimen. Vertical confinement was also applied to the prisms to simulate building conditions. After that, tension-compression cyclic loads with cycles of increasing amplitude was applied. Each cycle was repeated to record strength and stiffness degradation. The load was imposed directly to the tie in case of single assemblages and to the brick veneer prism in case of complete assemblages. The tests were stopped after a displacement of at least 12 mm.

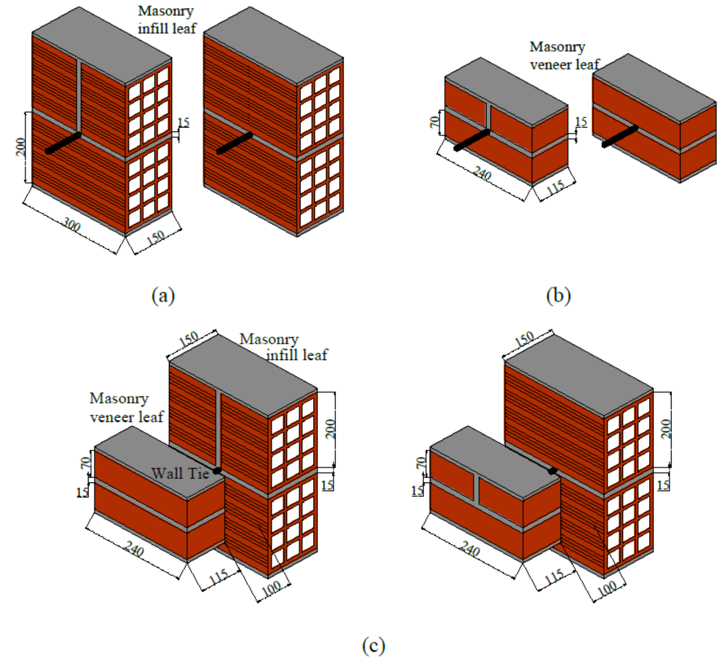


Fig. 1 | Test specimens: (a) brick masonry infill with embedded tie; (b) brick masonry veneer with embedded tie; (c) complete assemblage of brick masonry prims connected (Martins 2018)

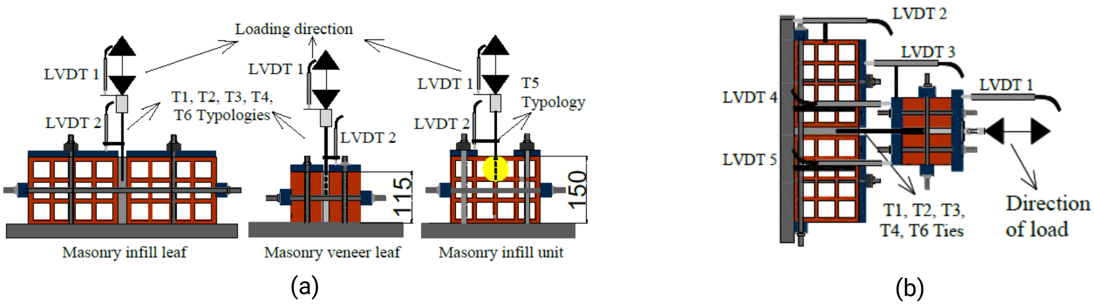
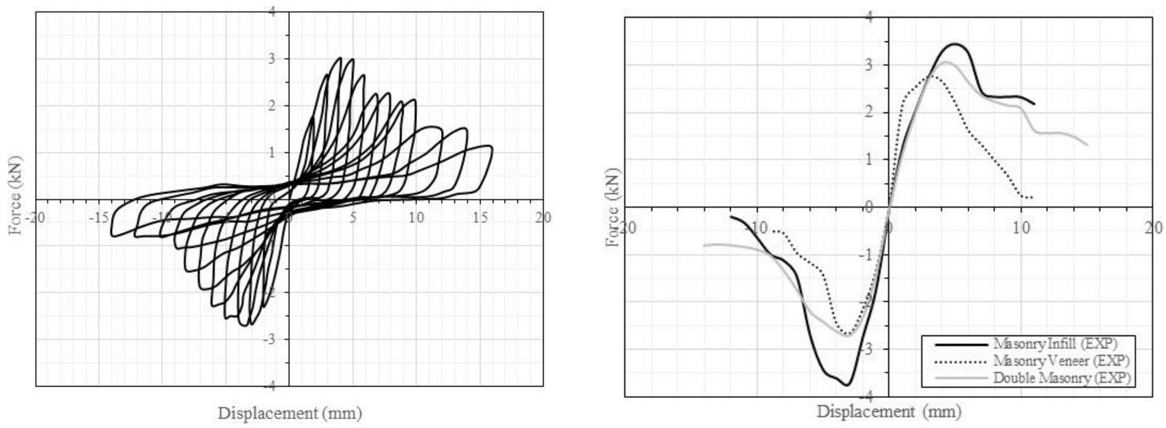


Fig. 2 | Representative scheme of the test setup for the different specimens: (a) single assemblages; and (b) complete assemblage (Martins 2018)

Several wall ties were considered during the experimental campaign (Martins 2018). In the present paper, only the results for one of the ties was considered. The tie is a stainless-steel commercial tie. It has a U-shaped cross section in the central part and the two extremes have a clamp shape with decreased cross-section (Fig. 3a). This tie was chosen because it showed a similar good behavior in tension and compression. The failure modes observed for this type of tie during the tests included sliding, combined sliding-cone failure of the mortar surrounding the tie, tie buckling and tie fracture (Fig.3 b).

Fig. 3 | (a) Geometry of the tie tested experimentally; and (b) example of tie connection failure mode observed for tie type

The average load-displacement diagram obtained in the tension-compression cyclic tests of the double assemblages is shown in Fig. 4a. Monotonic envelopes could be also defined for a better comparison of the behavior for different test configurations. Fig. 4b shows the envelope curves constructed using the first cycle for the single and complete assemblages. As previously stated, a combination of different failure modes was observed during the test. It was also noted that almost no damage was observed until maximum compression and tensile load was achieved. Typically, the maximum tensile load corresponds to tie pull-out from the mortar joint the maximum compressive load is associated to tie buckling.



(a) (b)

Fig. 4 | Tension-compression tests results: (a) Force-displacement diagram of complete assemblage specimen; (b) envelope curves from cyclic tests (Martins 2018)

3- NUMERICAL MODELING OF THE TIE CONNECTIONS

Numerical modeling results aimed to simulate the experimental force-displacement curves obtained to characterize the tension-compression behavior of the tie. Numerical models were thus built to replicate the different test specimens used in the experimental campaign. The present section discusses the modeling assumptions and results obtained.

3.1. Model geometry and material properties

The numerical model tried to replicate the test setup, boundary conditions and procedure. The masonry prisms are discretized into the two constituents (brick and mortar). The tie is embedded within the mortar and the connection is modelled using interface elements. In summary, the model has four main components: (a) the brick units; and (b) the mortar joint; (c) the tie; and (d) interface between tie and mortar (Fig. 5).

The overall geometry of the tie was slightly simplified with respect to the real one shown in Fig.3a. The cross-section of the tie is assumed to be constant and has the same dimensions of

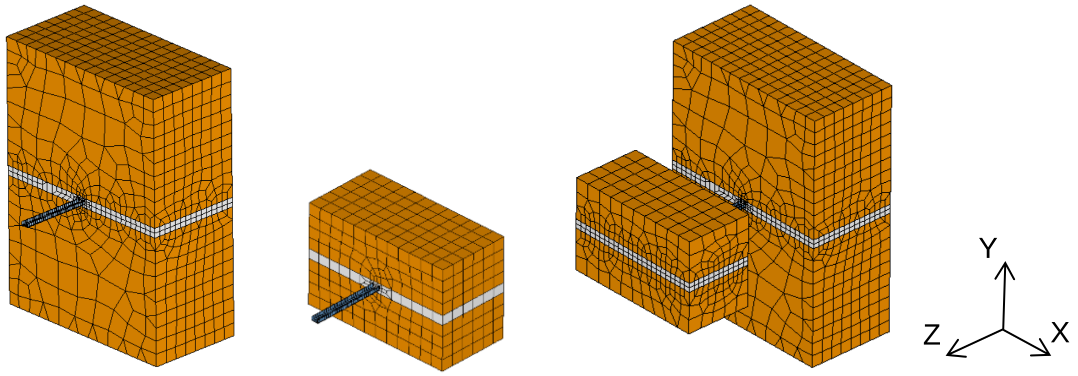


Fig. 5 | Three numerical models prepared to simulate the experimental tests

the cross-section of the central part of the real tie. The U-shape cross-section has a width of 12 mm, a height of 5.5 mm and a thickness of 0.5 mm. The clamp shaped extremes of the tie were neglected, assuming the same cross-section along the whole length of the tie, for simplification purposes. The embedment length of the tie within the masonry is the same of the experimental tests, being 60 mm in the infill brick masonry prism and 65 mm in the veneer masonry prism. The remaining dimensions respect the ones reported in the experimental campaign (Fig. 1).

Following also the test setup and procedure (Fig. 2), the boundary conditions and loads are also determined. First, the model is supported at the bottom. Only the translation in the direction parallel to the tie (Z) is restricted. A confinement load is applied in the two surfaces perpendicular to the Y direction. Following the test indications, a load of approximately 3% of the compressive strength of the masonry is considered. After the application of the load, the movement in Y direction is restricted in both sides. Also, the movement of the top part of the bricks in the Z direction is restricted, allowing only the mortar area to deform. Finally, the load is applied incrementally on one extreme of the tie. The main difference between the numerical and the experimental analysis is the fact that the load is applied monotonically in the numerical analysis, as an imposed displacement until a total of 10 mm using steps of 0.05 mm, while it is a cyclic load in the experimental analysis.

Regarding the material properties used for the analysis, most of them were extracted from the experimental characterization carried out for the bricks, mortar and tie. The properties are shown in Table 1. For the steel tie, a simple nonlinear model considering Von Mises and Tresca plasticity is assumed with yield stress of 350 MPa. The compressive strength of the mortar and bricks were characterized experimentally. Poisson's ratio is kept fixed as 0.15 (typical values may range between 0.1 and 0.2) and the density of the different materials are obtained from the experimental characterization and manufacturer's information. The rest of the material properties are computed based on the compressive strength.

Tensile strength (f_t) is estimated as 10% of the compressive strength. E is taken as $1000f_c$ as proposed by Eurocode 6 (EN-1996-1-1 2005). Recommendations by Angelillo et al. (2014) are followed for determining the values of fracture energy. A general value of 0.02 N/mm is assumed for the tension fracture energy (G_{fI}) and a ductility index of 1.6 mm is used to calculate G_{fc} ($G_{fc} = 1.6f_c$).

Table 1 | Material properties adopted for the numerical analysis

	E (GPa)	ν	ρ (kg/m³)	σ (MPa)			
Tie (steel)	200	0.3	7850	350			
	E (GPa)	ν	ρ (kg/m³)	f_c (MPa)	G_{fc} (N/mm)	f_t (MPa)	G_{fI} (N/mm)
Brick infill	2	0.15	800	4	6.4	0.4	0.02
Brick veneer	4	0.15	2100	24	38.4	2.4	0.02
Mortar infill	6.9	0.15	1850	6.9	1.725	0.69	0.02
Mortar veneer	5.2	0.15	1750	5.2	1.3	0.52	0.02
	K_n (N/mm³)	K_s (N/mm³)	c (MPa)	φ (rad)			
Interface infill	1	0.4	1.1	25º (0.44)			
Interface veneer	2.5	1	1.1	25º (0.44)			

With respect to the interface properties, a coulomb friction model is adopted for the nonlinear behaviour of the interface. The material properties necessary to define the model were calibrated numerically. The initial values were initially assumed from the experimental load-displacement curves and calibrated through a trial and error process. It is also noted that the initial value assumed for the compressive fracture energy (G_{fI}) had to be reduced 5 times in both infill and veneer masonry mortars to match the numerical results.

3.2. Results and discussion

Fig. 6 shows the numerical force-displacements curves obtained and compared with the experimental ones. The numerical curves in tension (Fig. 6a) matches reasonably well the experimental results both in terms of peak load and stiffness. Greater differences can be observed in the post-peak behaviour. Nevertheless, the numerical results capture the reduction of strength after reaching the peak. It is also noted that, in terms of damage and failure mode obtained, the numerical model also captures well the experimental results.

The failure mode seems to be a combination between the sliding of the tie and the cracking and failure of the masonry surrounding the tie. Cracking starts early, for lower values of imposed displacement (*d*), initiating at the areas surrounding the tie. Fig. 7 shows the damage evolution for the numerical model simulating the complete assemblage. Damage progressively increases

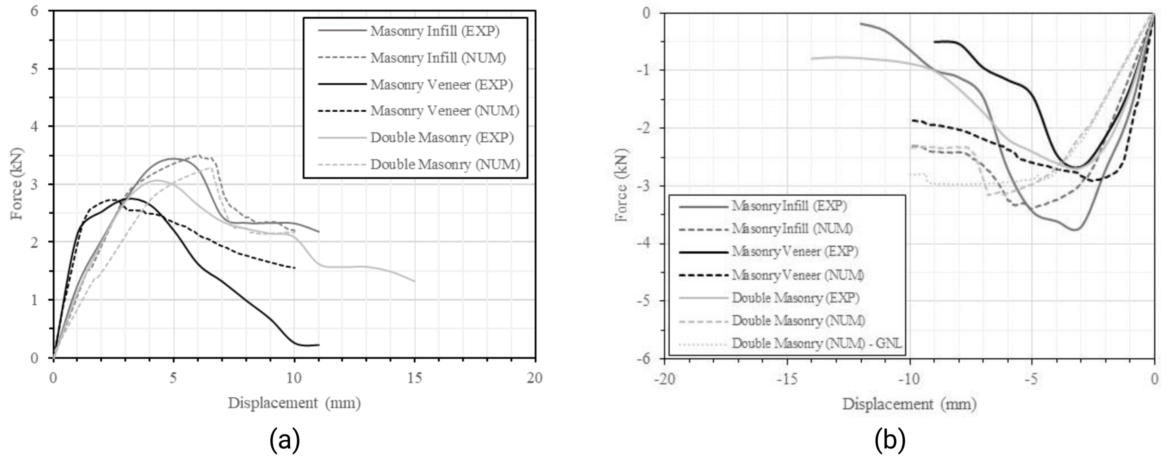


Fig. 6 | Numerical and experimental load-displacement curves obtained in: (a) tension; and (b) compression

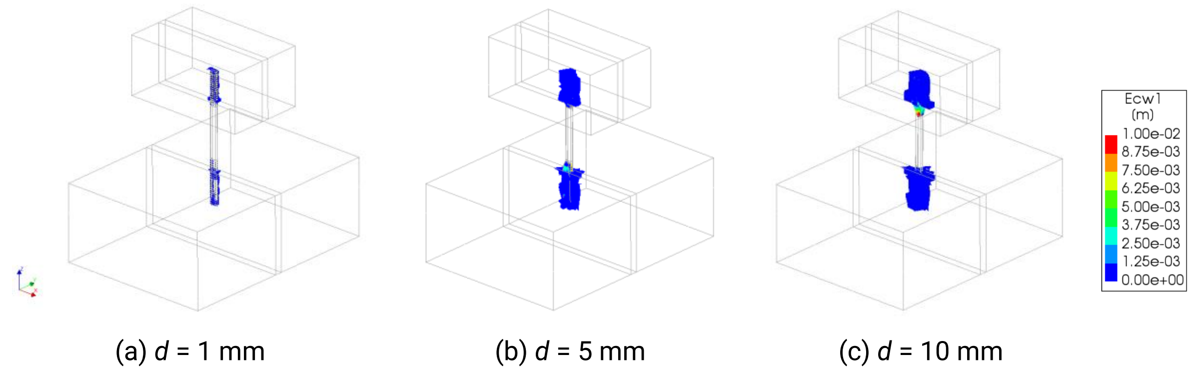


Fig. 7 | Damage evolution during the analysis of the complete assemblage in tension (crack width in m)

through the mortar area. At the end of the analysis, the area enclosed by the U-shaped cross-section of the tie fails, which seems to agree with the failure observed in the experimental results (Fig. 3b).

Results at the interface shows that sliding of the tie occurs simultaneously to the failure of the masonry surrounding the tie. Fig. 8 shows the evolution of relative displacements of the interface elements at peak load and end of the analysis. The displacements are higher in the exterior surfaces of the tie, illustrating the sliding of the tie. However, in the interior surface of the U-shaped tie, the relative displacements at the interface are reduced because

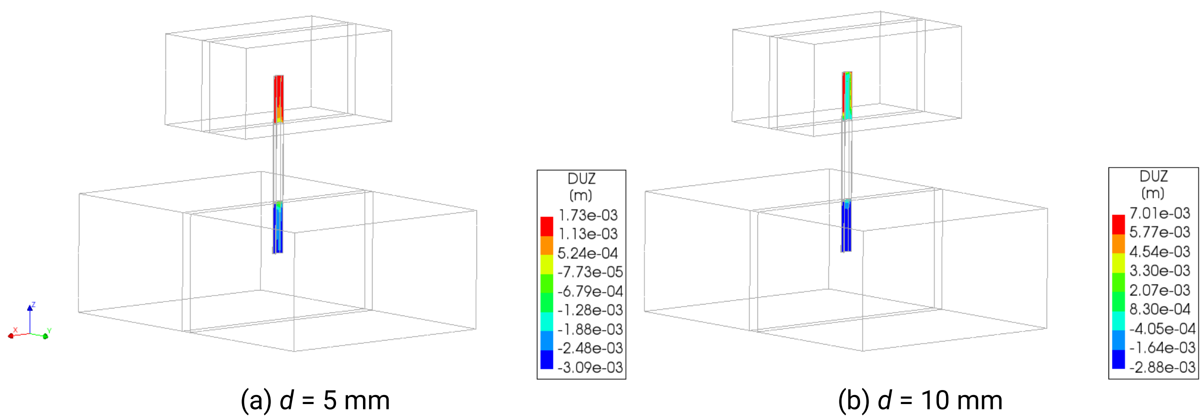


Fig. 8 | Evolution of interface relative displacement during the analysis of the complete assemblage in tension (displacement in m) the masonry is heavily cracked in that area. This shows that the failure mode is a combined sliding-cone failure of the mortar surrounding the tie, forming a shallow cone type of failure.

There are also high stresses at the tie at peak load (Fig. 9). For example, in the case of the numerical model simulating the complete assemblage, localized tensile stresses are close to the yield stress considered for the steel at the end of the analysis (σ = 350 MPa). Therefore, the model seems to be able to capture the different failure modes that were reported during the experimental campaign in tension: sliding, combined sliding-cone failure, and tie fracture.

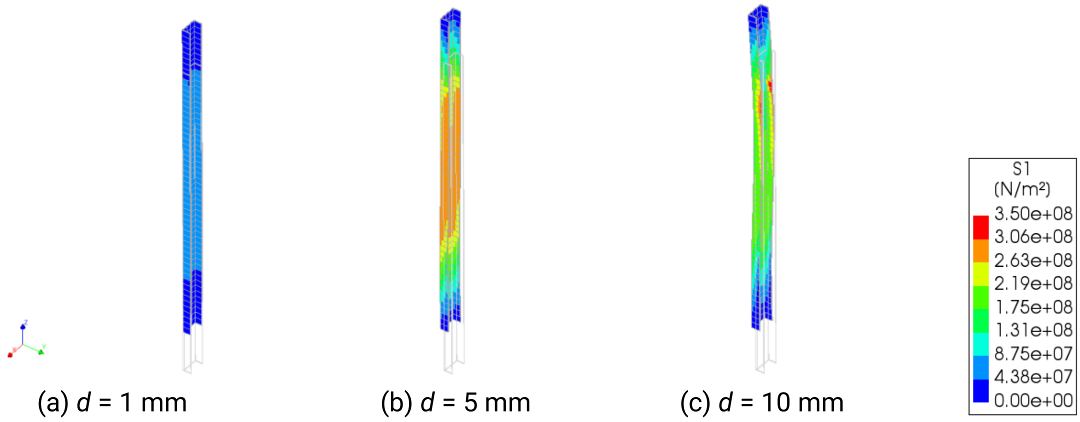


Fig. 9 | Evolution of maximum tensile stresses at the tie (stresses in N/m^2)

In compression, the numerical curves show greater variations with respect to the experimental ones (Fig. 6b). The stiffness of the experimental tests is lower than the numerical in the case of the brick masonry veneer and higher in the case of the brick masonry infill. This may indicate that the experimental tests show a slightly different behaviour in tension and compression, which is not well captured by the simplified numerical model. This is probably due to the model not being able to simulate the buckling of the tie that was observed in most cases experimentally. Even though the numerical model considers the geometrical nonlinearity, it does not consider possible common imperfections that can cause the buckling of the tie. The failure obtained in all cases is still a combination between the sliding of the tie and the cracking and failure of the masonry surrounding the tie (Fig. 10). Nevertheless, in terms of maximum load, results are similar with differences below 10%. Regarding the post-peak behaviour, the numerical results are not able to simulate the sudden decrease of strength after the peak load.

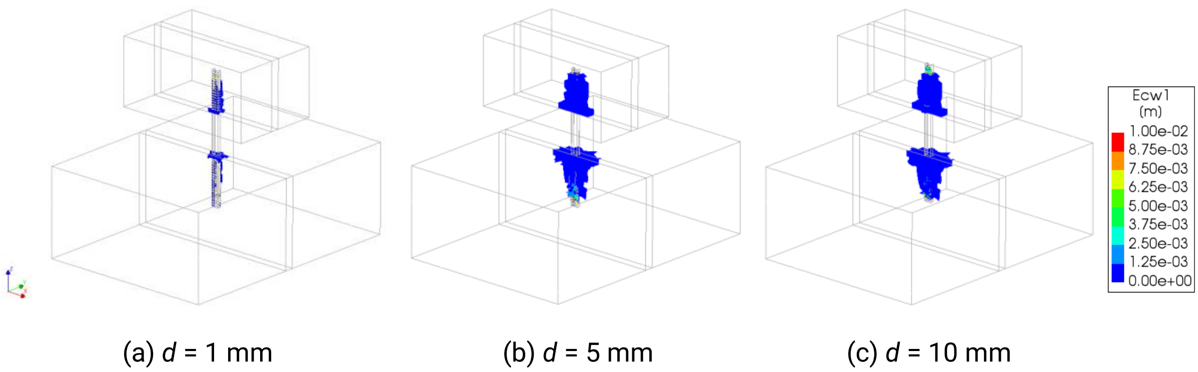


Fig. 10 | Damage evolution during the analysis of the complete assemblage in compression (crack width in m)

Finally, it should be noted that only the results of the complete assemblage were shown in detail in the present paper, but the results for the single assemblages are similar in terms of failure modes and evolution of damage. In conclusion, the numerical model is considered to be well calibrated and able to match well the experimental results both in terms of peak load and stiffness, validating the numerical approach.

4- CONCLUSIONS AND FUTURE WORK

The numerical approach aimed to simulate the structural behavior of a tie connection under tensile and compression, obtained from experimental cyclic tension-compression tests performed on ties embedded in different brick masonry wallets. Ties are the main structural connecting veneer walls to the main structural system, thus being responsible of transferring both in-plane and out-of-plane loads that can occur, for example under seismic loading. The main objective of the present paper was to obtain a better understanding of the structural behavior of ties under horizontal loading.

The numerical results match well the experimental ones in terms of peak load and stiffness. Additionally, the evolution of damage and failure modes are also well captured, particularly in tension, consisting of a combination between the sliding of the tie and cracking at the mortar surrounding the tie.

Once the reference model and numerical approach is validated, future work will focus on carrying out a parametric analysis to evaluate the influence of material and geometric properties of the tie and masonry, type of action and construction details. Eventually, this could help to develop simplified models and guidelines that can be used in professional practice for seismic design and detailing of brick masonry veneer walls and tie connections. This can be applied both for new construction and rehabilitation of existing buildings. It is noted that veneer walls can be a suitable solution for façade rehabilitation to improve the thermal and acoustic performance of the existing building stock.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the Portuguese Foundation for Science and Technology (FCT), through the financing of the research project SEVen - Development of Sustainable Ceramic Brick Masonry Veneer Walls for Building Envelops (PTDC/ECI-CON/30876/2017).

REFERENCES

Ceci, A.M., Contento, A., Fanale, L., Galeota, D., Gattuli, V., Lepidi, M., Potenza, F. 2010. Structural performance of the historic and moderns buildings of the University of L´Aquila during the seismic events of April 2009, Engineering Structures, 32, pp. 1899-1924.

Martins, A. 2018. Seismic Behaviour of Masonry Veneer Walls, Ph.D. Thesis, Universidade do Minho.

EN 1996-1-1: 2005. 2005. Eurocode 6. Design of masonry structures. Part 1-1: Common rules for reinforced and unreinforced masonry structures. European Committee for Standardization.

Angelillo, M., Lourenço, P.B., Milani, G. 2014. Masonry behaviour and modelling, in: M. Angelillo (Ed.), Mechanics of Masonry Structures. CISM International Centre for Mechanical Science, vol. 551, Springer, Vienna, pp. 1–26.