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NUMERICAL INVESTIGATION ON THE FLANGE EFFECT IN UNREINFORCED MASONRY WALL SYSTEM THROUGH NONLINEAR FINITE ELEMENT MODELLING

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Abstract

Equivalent frame modelling of unreinforced masonry buildings allows for nonlinear analysis with relatively low computational cost. The wall components, particularly piers and spandrels, are usually modelled as prismatic beam elements with rectangular cross section. Nonetheless, in case of effective connection between orthogonal walls, the so-called flange effect should be taken in due consideration, resulting into I-, T- and C-shaped cross sections of piers. Specifically, orthogonal walls partly contribute to the in-plane resistance of longitudinal walls, eventually producing some changes in nonlinear behaviour of masonry walls, failure modes, and seismic capacity features. This problem thus requires more advanced computational strategies to assess the flange effect.

In this paper, a numerical investigation aimed at assessing the flange effect is presented. A nonlinear finite element (FE) model was calibrated to reproduce the results of experimental tests on a flanged wall system. The FE model was then used to perform a parametric analysis, highlighting variations in the in-plane resistance of longitudinal walls as a result of collaboration with orthogonal walls.

Keywords: Masonry walls; seismic behaviour; flange effect; pushover analysis; finite element modelling.

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1 INTRODUCTION

The nonlinear analysis of unreinforced masonry (URM) buildings can be achieved through the modelling of equivalent frames, which offers relatively low computational costs. Typically, wall components such as pillars and spandrels are modelled as elements of prismatic beams with rectangular cross-sections. However, experiments conducted on entire buildings and the study of earthquake-induced damage have shown that, in case of effective connections between orthogonal walls, the flange effect cannot be neglected and should be taken into account [1,2]. This effect significantly contributes to the strength in the plane of longitudinal walls, influencing the nonlinear behaviour of masonry walls, their failure modes, and seismic capacity characteristics. Consequently, more advanced computational strategies are required to account for the flange effect even when using an equivalent frame modelling.

In [2], the effect of flanges on the lateral behaviour of URM walls was investigated. Experiments were carried out on clay brick walls with flanges of different lengths and locations, founding that the presence of flanges has significant impact on the in-plane behaviour of the wall. The results were compared with previous analytical research, which showed a high level of correlation. Drift limits based on the wall failure mode were also proposed. In [3], the in-plane force-displacement response of URM walls with flanges subjected to pseudo-static cyclic lateral loading was experimentally investigated. Wall flanges were found to increase the displacement capacity of the in-plane loaded wall, compared to a wall without flanges. The measured shear strength of the walls was compared to that predicted through an analytical model for diagonal tension strength, highlighting a good agreement. Additionally, a general force-displacement relationship consistent with the experimental data was suggested, which can be used for modelling URM walls and improving acceptance criteria. More recently, a method to simulate the behaviour of entire buildings by considering the connection between the piers was proposed [4]. Finite element analyses were performed on masonry walls with symmetrical cross-sections to investigate the axial load redistribution between the flanges and the web. Some practical recommendations for simulating an imperfect wall-to-wall connection in historic buildings were provided as well. Patel and Dubey [5] carried out a parametric study on the in-plane behaviour of masonry walls, examining various factors such as pre-compression, material properties, aspect ratios, and boundary conditions. The masonry walls were modelled using the simplified micro-modelling approach in the finite element analysis software ABAQUS/Standard, highlighting that flanged walls have a different strength and damage pattern compared to rectangular walls. Sajid et al. [6] conducted quasi-static cyclic tests on full-scale walls with and without flanges to compare their lateral stiffness, strength, and deformability. Results showed the influence of vertical stresses and flanges on the seismic response of URM walls.

In this paper, a numerical study is presented to assess the flange effect on seismic capacity of URM walls. A nonlinear finite element model (FEM) was calibrated to replicate the results of experimental tests on a flanged wall system. The FEM model was then used to detail the collaboration mechanism of the flange in order to set up an equivalent frame model that would allow for the interaction between longitudinal and orthogonal walls.

2 METHODOLOGY

The proposed work is based on an experimental study [1] in which the effects of wall intersections and flanges were investigated through a series of quasi-static cyclic tests on four full-scale wall specimens. The latter were representative of C-shaped load-bearing walls of typical low-rise URM buildings in Northern Europe. Two of those specimens were constructed with standard solid calcium-silicate bricks and fully mortared head-and-bed joints with thickness of 10 mm.

Specifically, numerical simulation of the experimental tests was carried out on a wall system with C shape, composed of three partitions with equal thickness, length, and height. The central wall was 4-m-long, while the two lateral walls had total length of 0.880 m. Figure 2 shows the wall system. The central wall is herein defined as “flange” whereas the two lateral walls are defined as “webs”. The wall system had an overall height of 2.511 m. The experimental tests were performed under a doubly-fixed support condition, with vertical load applied only on the flange. To set up the test, a high-strength mortar was laid only on top of the flange before placing a concrete plate. The joint between the plate and top of the wing walls was then filled to complete the test configuration. The masonry structure of the wall suggests that the flange and wings were perfectly connected to each other, which was taken into consideration during the tests.

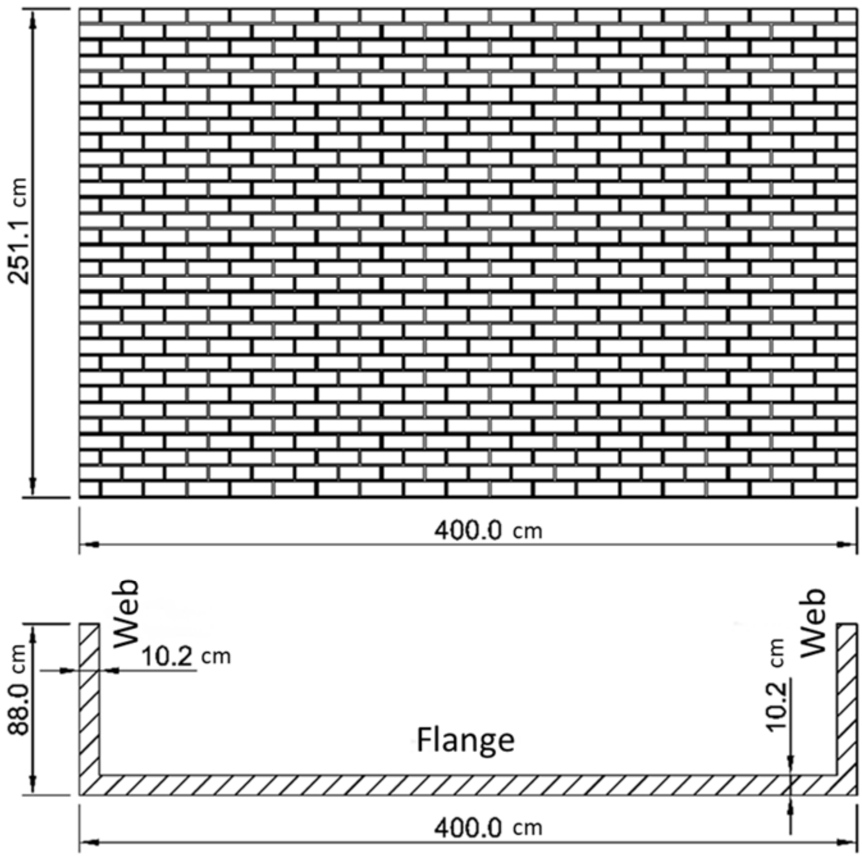

Figure 1. Case study wall system.

The wall system is made of solid calcium-silicate bricks with fully filled horizontal and vertical joints. To perform numerical modelling of the wall system, mechanical properties were defined through material characterization tests that were carried out during the experimental campaign [1]. Missing data was supplemented based on code indications. The resulting values of the mechanical parameters are reported in Table 1 that includes the following parameters: elastic modulus (E); tangential elastic modulus (G); unit weight (w); – uniaxial compressive strength (f_m); shear strength under zero confining stress (cohesion) (f_{v0}); limit value of shear strength ($f_{v,lim}$).

Table 1. Mechanical properties of masonry.

E [MPa]	***G*** [MPa]	***w*** [kN/m^3]	f_m [MPa]	f_{v0} [MPa]	$f_{v,lim}$ [MPa]
7250	2900	18.26	8.32	0.49	1.31

The first phase of the study was focused on the mechanical modelling of the masonry based on the data available in [1], in order to carry out the implementation of the constitutive behaviour. Through a literature search, the constitutive model proposed by Senthivel and Sinha [7] was identified, as it was specifically proposed for solid calcium-silicate brickwork. Figures 2a and 2b show the constitutive model assigned to the whole masonry in compression and tension, respectively, for FE macro-modelling in ABAQUS. The constitutive model assumed in the FE macro-modelling was also considered in an equivalent frame modelling (EFM) approach by developing and analysing a fibre structural model using proprietary software developed in MATLAB® [8,9].

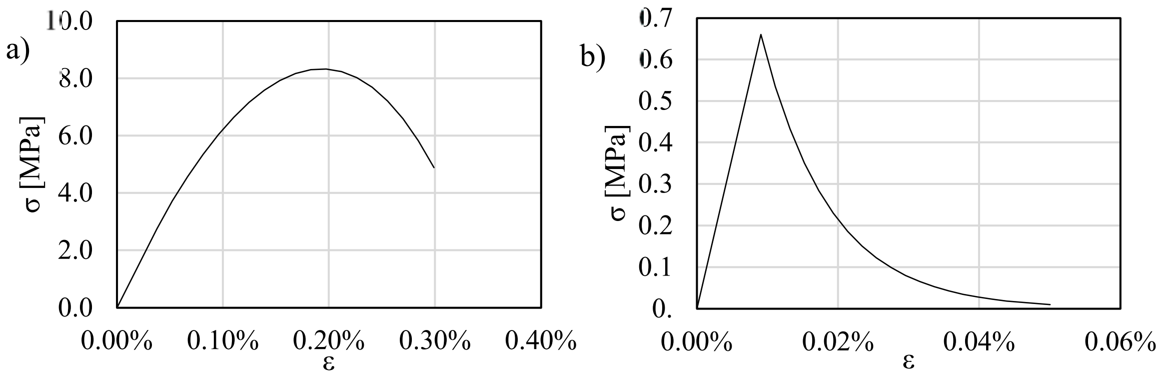

Figure 2. Constitutive model of masonry: (a) compression; (b) tension.

3 NONLINEAR FINITE ELEMENT ANALYSIS

To study the response of a flanged wall, a nonlinear finite element model was developed in the commercial software ABAQUS/Standard. The analysis involved modelling the masonry wall as a continuum using solid elements, proper boundary conditions on top and at the bottom of the wall, and in-plane lateral loading with displacement control.The wall was discretized using tetrahedral solid elements with four nodes (C3D4) and a characteristic length of approximately 100 mm.

The choice of element size was based on mesh sensitivity analysis, aimed at achieving balance between accuracy and computational cost. The masonry material was modelled using the concrete damaged plasticity (CDP) model, which is a popular and widely validated model for masonry materials. The CDP model takes into account the nonlinear behaviour of masonry under compression, tension, and shear, as well as the effects of cracking and damage.

Table 2 outlines the parameter use to describe material plasticity, as follows: dilation angle (Ψ); eccentricity (ε); the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (σ_{b0}/σ_{c0}); the ratio of the second stress invariant on the tensile meridian (K_c); viscosity (μ).

Table 1 - Concrete damaged plasticity parameters

Ψ	ε	σ_{b0}/σ_{c0}	K_c	μ
10°	0.1	1.16	0.667	1e-5

The wall was loaded by applying gravitational forces only on the flange, as done in the experimental test.

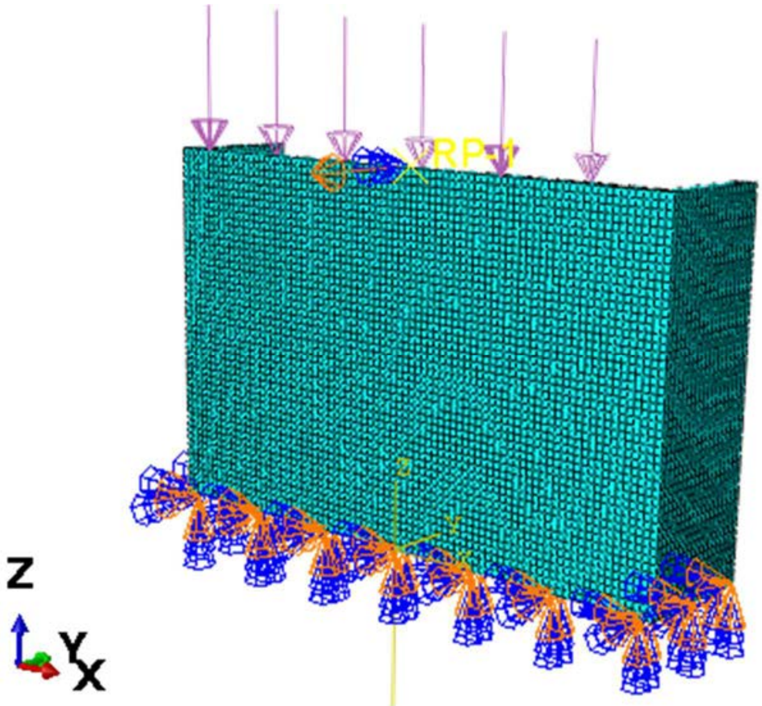

Figure 3. Finite element model with boundaries and loading conditions.

To investigate the behaviour of the masonry wall, a nonlinear incremental analysis with displacement control was performed in both directions along the y-axis. In the positive direction, the analysis was able to simulate the experimental results very accurately, capturing both the initial stiffness of the wall and its displacement capacity and maximum shear. The simulation results were compared to experimental data. Figure 3 presents the analysis model used in the study, which was developed to investigate the behaviour of the wall.

The model included the boundary and loading conditions, as well as the finite element mesh used to discretize the wall. The boundary conditions were selected to reflect the experimental conditions of the wall, including its supports and the loading configuration. Specifically, the bottom of the wall was assumed to be fixed, whereas the top was subjected to lateral displacement in the y-direction under zero rotations. The displacement was applied in a stepwise manner until the desired displacement was achieved.

The FE analysis allowed estimating the transfer of axial load from the flange to the webs under increasing horizontal displacement. Figure 4 shows the axial load acting on the base cross-section of the flange and the sum of the normal stresses acting on the base of the two webs. Analysis results highlight that the transfer of normal stress from the flange to the webs is a phenomenon that begins under small displacements.

Both in the FE analysis and in the experimental test, the wall showed a linear elastic response up to a drift of 0.05%. The first visible damage was associated with flexural tensile cracking at the upper and lower ends of the wall. Cracking was observed under drifts around 0.08% and was followed by flattening of the force-displacement response, which is indicative of rocking/flexural behaviour.

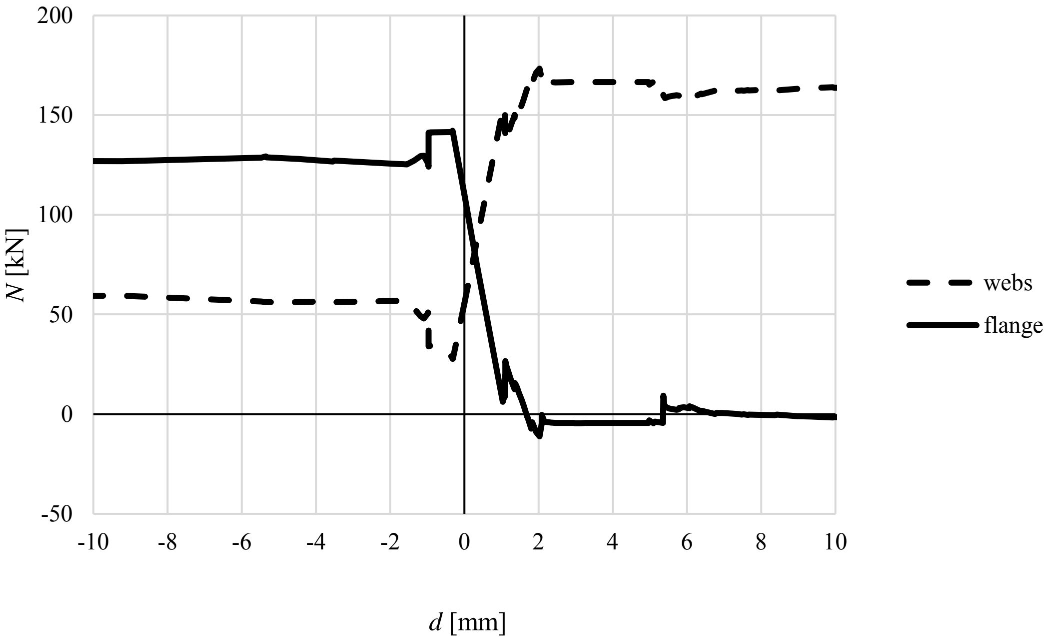

Figure 4. Axial load transfer from flange to webs.

Under large drift levels, hybrid damage mechanisms were observed, usually associated with rocking/flexural behaviour under negative thrust (compression flange) and shear-sliding response under positive thrust (tensile flange). Figure 5a shows the tensile damage representing the simulation of cracking, whereas Figure 5b shows the crack pattern at the end of the experimental test.

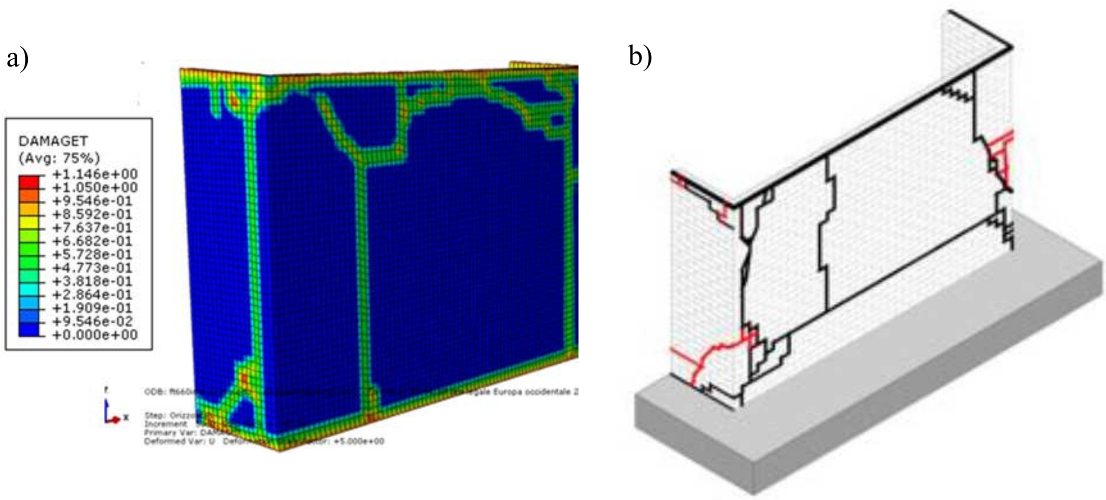

Figure 5. Damage map: (a) numerical; (b) experimental.

4 EQUIVALENT FRAME MODEL ANALYSIS

The wall was also analyzed using an Equivalent Frame Modeling (EFM) approach, employing the same mechanical parameters as those used in Finite Element Modeling (FEM). The EFM analyses were carried out using a proprietary MATLAB code, which allows for nonlinear static analysis of masonry structures using a fiber macro-element that was recently developed and experimentally validated by Parisi and Acconcia [7,8]. The macro-element takes into account flexural, shear, and rocking behavioural modes, considering both geometric and mechanical nonlinearities as well as the macroscopic constitutive behavior of masonry.

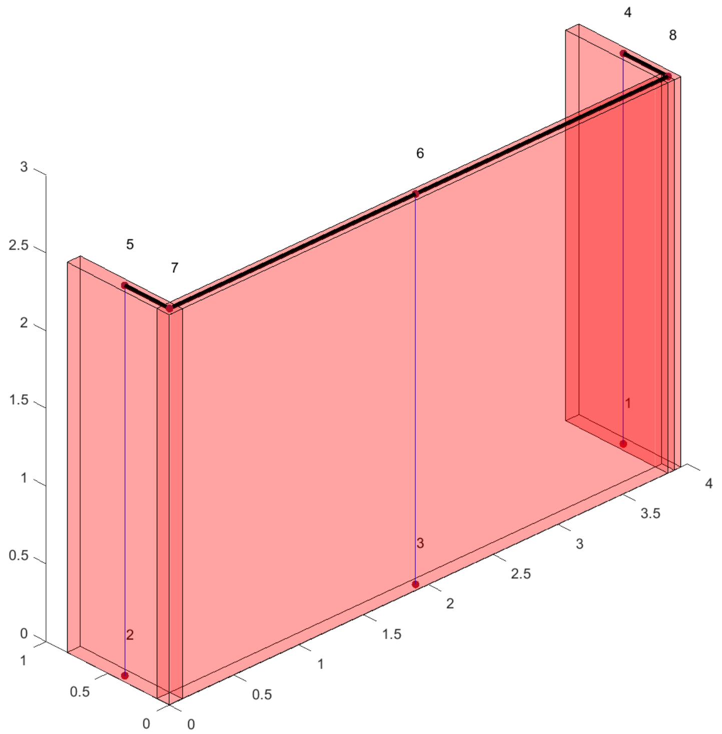

Figure 6. Equivalent frame model of the wall specimen (dimensions in m).

Starting from the equivalent frame modeling, constitutive models were used to obtain the EFM curves shown in Figure 5, together with those obtained through FEM and experimental testing in both directions of the applied horizontal displacement.

Analysis results highlight the limitations of the EFM approach, which does not allow to simulate the axial load transfer from the flange to the webs that gradually occurs as the horizontal displacement increases.

Therefore, the EFM analyses were performed considering two different load models: the former considered the axial load applied exclusively to the flange, as happened in the experimental test and as hypothesized in the FEM modelling; the latter model was based on the axial load already transferred to the webs. Figure 7 shows a comparison between the experimental capacity curves, those obtained through the FEM and those obtained through the EFM analysis.

It can be noted that the curve obtained considering the load already applied to the webs allows a better simulation of the behaviour that the wall exhibited during the experimental test, in terms of initial stiffness, displacement capacity and maximum shear. It can therefore be deduced that an element should be developed which allows the webs and the flanges to be constrained together so as to allow the transfer of axial load between the flange and the webs.

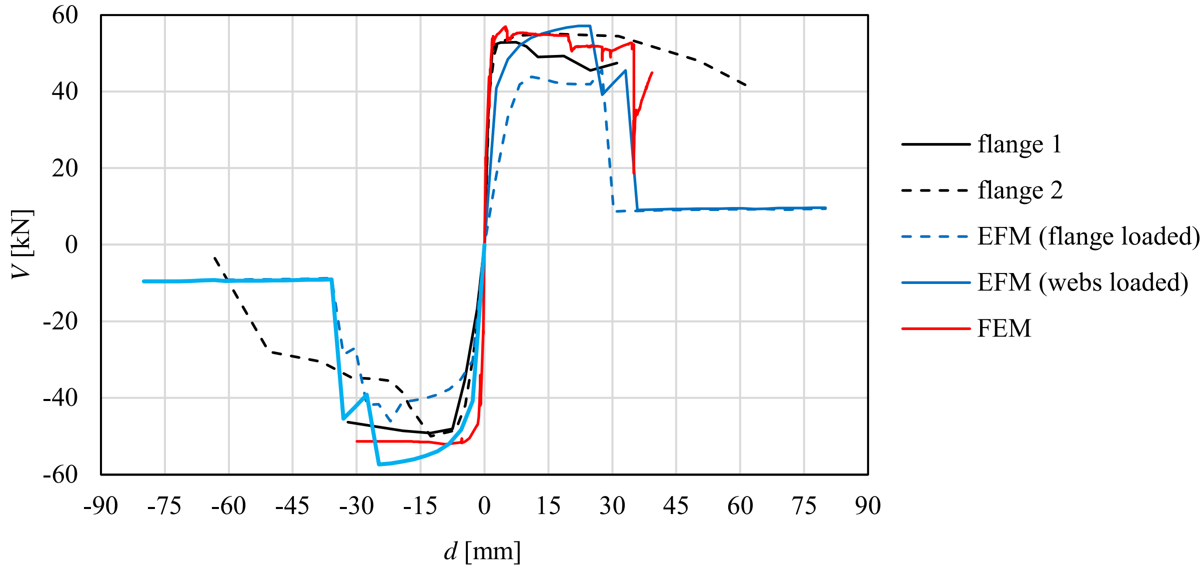

Figure 7. Comparison between capacity curves.

5 CONCLUSIONS

The paper has presented a numerical investigation on the effects of flange on the in-plane lateral behaviour of URM walls, in terms of crack patterns and capacity features such as lateral stiffness, maximum base shear and displacement.

A satisfactory agreement between a nonlinear finite element model based on the macro-modelling smeared crack approach and experimental data regarding a full-scale flanged wall. The redistribution of the axial load between the flange and the webs has been investigated, highlighting its significant influence on the simulation of the experimental behaviour.

The same wall specimen was studied through an equivalent frame modelling, simulating both the initial condition in which the axial load was applied only on the flange and the condition in which the load had already transferred to the webs. The numerical-experimental comparison outlines the limitation of equivalent frame modelling in capturing nonlinear redistribution of axial stresses between flange and webs under increasing horizontal displacement. Numerical and experimental studies are thus required to properly account for web-flange interaction in simplified equivalent frame models of URM walls.

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REFERENCES

[1] S. Kallioras, L. Grottoli, F. Graziotti, Quasi-static cyclic tests on U-shaped unreinforced masonry walls made of calcium-silicate bricks and blocks, *EUCENTRE Research Report EUC092/2020U*, EUCENTRE, Pavia, Italy, 2020. Available at www.eucentre.it/nam-project.

[2] A. Russell, J. Ingham, The influence of flanges on the in-plane performance of URM walls in New Zealand buildings. *NZSEE Annual Conference*, 2010.

[3] A.P. Russell, K.J. Elwood, J.M. Ingham, Lateral force-displacement response of unreinforced masonry walls with flanges, *Journal of Structural Engineering*, 140, 04013087, 2014.

[4] S. Cattari, S. Alfano, S. Lagomarsino, A Practice-Oriented Proposal to Consider the Flange Effect in Equivalent Frame Modeling of Masonry Buildings. *Buildings*, 13(2), 462, 2023.

[5] K. P. Patel, R. N. Dubey, Effect of flanges on the in-plane behavior of the masonry walls. *Engineering Structures*, 273, 115059, 2022.

[6] H. U. Sajid, M. Ashraf, Q. Ali, S.H. Sajid, Effects of vertical stresses and flanges on seismic behavior of unreinforced brick masonry. *Engineering Structures*, 155, 394-409, 2018

[7] R. Senthivel, S.N. Sinha, Behaviour of calcium silicate brick masonry under cyclic uniaxial compression. *Proceedings of the 6th international masonry conference*, London, UK, 412–422, 2022.

[8] F. Parisi, E. Acconcia, Formulation and experimental validation of distributed plasticity macroelement for unreinforced masonry walls. J. Kubica, A. Kwiecień, Ł. Bednarz, eds. *Brick and Block Masonry – From Historical to Sustainable Masonry, Proceedings of the 17th International Brick/Block Masonry Conference*, Kraków, Poland, July 5-8, 2020.

[9] F. Parisi, E. Acconcia, Fibre-based capacity model for URM piers subjected to combined in-plane and out-of-plane actions. *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece, June 18-21, 2018.