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FINITE ELEMENT MICRO-MODELLING AS A PROXY FOR EXPERIMENTAL TESTS ON MASONRY-INFILLED RC FRAMES

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Abstract

The use of macro-models, namely strut models, is known to be an efficient tool to represent the structural behaviour of infill walls under earthquakes. However, to obtain realistic results, the mechanical properties of these simplified models need to be calibrated and validated using experimental data. Due to the variability of the masonry infills types, configurations, construction technologies and materials across countries, as well as to the significant cost of experimental tests, the available experimental data do not cover all the possibilities and requirements. Therefore, alternative approaches need to be established to obtain adequate data to calibrate the referred simplified models. The proposed paper introduces a detailed finite element modelling approach that can be used as an alternative to experimental tests to represent the behaviour of masonry-infilled reinforced concrete (RC) frames, thus providing sufficient results to calibrate and validate the referred macro models. The paper addresses the relevant issues in the development of numerical models involving nonlinear finite elements using the commercial software ANSYS and provides details about the proposed strategy to enable its replication by other researchers. In order to validate the proposed numerical approach, several experimental specimens of masonry-infilled RC frames are analysed. These experimental specimens have different infill configurations (e.g. panels with solid infill and partially infilled panels) and were subjected to cyclic loading tests. The comparison between numerical and experimental results shows that the proposed numerical modelling approach is able to capture the overall nonlinear behaviour of the physical specimens with adequate accuracy. The developed micro-model is able to predict the strength and failure mechanisms of the physical specimens and the obtained data is then used to calibrate the structural parameters of a single strut model. The results show that the proposed micro-modelling approach can be used as a proxy for experimental data to calibrate simplified models used in performance analysis frameworks requiring a higher number of analyses.

Keywords: Finite element; masonry infill; RC frame; cyclic loading; strut model; ANSYS.

1. Introduction

Over decades, reinforced concrete (RC) frames with masonry infills have been used around the world, even in earthquake-prone regions. Commonly, only the RC frames were involved in the structural analysis of such structures, disregarding the contribution of the masonry for the structural behaviour. However, past earthquakes (e.g. Kocaeli, Turkey, 1999, Chania, 2008, San Antonio, 2010, Tabanlı (Van), Turkey, 2011 and Nepal, 2015) have caused huge losses in lives and properties due to the interaction between the infill panel and the RC frame, as shown in Fig. 1. These field evidences show that infill walls have a structural contribution during lateral loading that should not be neglected.

In order to assess the contribution of infill walls to the structural behaviour, several experimental campaigns have been conducted over time. Polyakov [1] carried out one of the earliest experimental tests. The main observation of his experimental study was that the infill wall works as a lateral bracing for the surrounding frame. Based on this observation, Stafford-Smith and Mainstone [2, 3] proposed that the compressive loading path in the masonry panel (due to horizontal loading) could be oriented mainly along its diagonal. Therefore, a way to represent the structural behaviour of the infill panel is to replace it by an equivalent strut. Since then, several studies were carried out to calibrate the structural parameters of this equivalent strut. Generally, these studies can be categorized into two main groups: a) stiffness-based studies that tried to define the geometric cross section of the proposed strut which would then be associated with an equivalent material representing the masonry material [4-6]; b) strength-based studies which tried to define a backbone curve for the force-displacement curve of the equivalent strut element [7-9].

a) Infill shear and major frame damages, Chania 2008 [10]

b) Infill shear and minor frame damages, Nepal 2015

c) In-plane shear failure in infill and shear failure at the ends of RC column, San Antonio 2010 [11]

d) Captive column failure, Managua 1972 [12]

e) A collapsed soft storey apartment building in the Marina District, San Francisco 1989 (Loma Prieta Earthquake) [13]

f) Damage to an apartment building with a soft first storey in Bordj-Kiffan city, Algeria 2003 [14]

Fig. 1 – Damages to masonry infilled RC frames after several earthquakes

Several researchers have developed analytical formulas to define the structural properties of the proposed strut model. As referred before, these developments can be categorized into two main groups: a) stiffness-based studies and b) strength-based studies. Some of the existing formulas were tested against data from nine different experimental campaigns. Table 1 shows a comparison of the ratios between the ultimate lateral strength predicted for the strut model (based on several formulas) and the corresponding ultimate strength based on experimental data. The comparison is made using both stiffness- and strength-based approaches selected from the literature. The results of a third approach (termed experimentally-based approach) where the RC bare frame behaviour curve is subtracted from the global masonry-infilled RC frame curve and then linearized/adapted to the strut model are also represented. As can be seen, the strength-based approach provides a better prediction of the ultimate strength when compared to stiffness-based method. However, the strength-based approach predictions still have a large error. On other hand, the experimentally-based approach provides reliable predictions with errors that don't exceed 10%. Therefore, in order to get realistic results, the parameters of the proposed strut model should be calibrated using experimental data. Due to the significant cost of experimental tests, the use of results obtained from nonlinear finite element micro-models as a proxy for experimental data to calibrate the strut parameters is considered as an effective alternative approach.

Table 1 – Comparison of the infill maximum strength obtained from different approaches with those obtained from experimental tests

	Ratio of computed to measured maximum strength of the strut models						
	Stiffness-based approach			Strength-based approach			Experimentally based approach
Specimen ID	Holmes [4]	Mainstone [5]	Hendry [6]	Dolšek, et al. [7]	Panagiotakos, et al. [9]	Bertoldi, et al. [8]	
S-III/2 [15]	0.43	0.16	0.35	0.85	0.93	0.84	0.95
S-S [16, 17]	1.18	0.45	1.06	1.02	1.16	1.04	0.91
S-Ft1 [18]	1.23	0.44	0.84	1.46	1.73	1.43	0.90
S-M2 [19]	2.17	0.60	0.92	2.6	2.8	2.16	1.00
S-DFS [20]	7.32	2.11	3.84	2.01	1.94	1.89	0.98
S-F1 [21]	8.42	3.00	5.73	3.33	3.9	3.33	0.975
S-6 [22]	1.84	0.55	0.89	0.81	0.91	0.8	1.06
S-7 [22]	2.47	0.72	1.14	0.39	0.44	0.38	0.93
S- 5 [22]	5.04	1.42	2.13	0.85	0.94	0.83	0.98
S-11 [22]	2.43	0.71	0.90	0.99	1.22	0.93	0.92
S- 12 [22]	4.77	1.39	1.77	0.8	0.99	0.75	0.92
S-4 [22]	3.96	1.13	1.70	1.56	1.74	1.53	1.01
S- SBF [23]	5.15	1.64	2.49	3.37	3.89	3.4	0.90
S- IS [16, 17]	14.15	4.63	7.67	1.95	2.21	1.99	0.99
S-unit1 [24]	57.58	14.82	15.33	6.73	7.15	6.39	0.96
Min. ratio	0.43	0.16	0.35	0.39	0.44	0.38	0.90
Max. ratio	57.58	14.82	15.33	6.73	7.15	6.39	1.06
Average ratio	**7.88**	**2.25**	**3.12**	**1.91**	**2.13**	**1.85**	**0.96**
Coef. Var. ratio	**1.80**	**1.63**	**1.27**	**0.85**	**0.82**	**0.84**	**0.05**

In this context, the proposed paper presents an efficient numerical approach to calibrate the structural parameters of single strut models based on the results of detailed nonlinear finite element micro models. The relevant issues and details for the development of these nonlinear finite element models using the commercial software ANSYS to analyse the behaviour of masonry-infilled RC frames under lateral loading are first addressed. In order to validate the proposed numerical approach, experimental tests carried out in several specimens of masonry-infilled RC frames are analysed. These specimens have different infill configurations (e.g. panels with solid infill and partially infilled panels) and were tested under cyclic lateral loading. The comparison between the numerical and experimental results shows that the proposed numerical modelling approach can capture the overall nonlinear behaviour of the physical specimens with adequate accuracy, predicting their strength and failure mechanisms. Finally, the data obtained from the micro-models is then used to calibrate the structural parameters of a single strut model.

2. Finite element micro-modelling

The components of the infilled RC frame are discretized into different types of finite elements depending on the expected behaviour of each component. The SOLID65 3D element was used to represent the brittle components (masonry and concrete) while the reinforcing steel was included in the real constants properties of this element which represent the longitudinal and transversal reinforcement using a smeared modelling approach. In the smeared modelling approach, the cross sections of the beam, columns, and their connections are meshed such that the longitudinal steel rebars are merged with a limited number of elements at appropriate reinforcement locations, rather than with the whole cross-section. The elements in the core of the sections (i.e. where there is no longitudinal reinforcement) are assigned with a real constant in which all volume ratios are equal to zero, which represents plain concrete. The same strategy is used for the transverse reinforcement along the members which accounted for the spacing between the stirrups.

The considered micro-modelling approach is based on the simplified method proposed by Lourenço, *et al.* [25] in which the masonry infill components are discretized into brick elements and interface elements. In the current study, contact elements (zero thickness elements) were used to model the mortar joints, which are mainly responsible for the frictional behaviour and the shear and tensile traction that may occur through the masonry courses or between the infill and the RC frame. The size of the brick elements was defined in order to represent its true size and half of the adjacent mortar joint, since joints were defined by zero-thickness elements. Accordingly, the thickness of the mortar is halved and each half is attached continuously to one side of the adjacent masonry unit. Figure 2 shows an illustration of the model components.

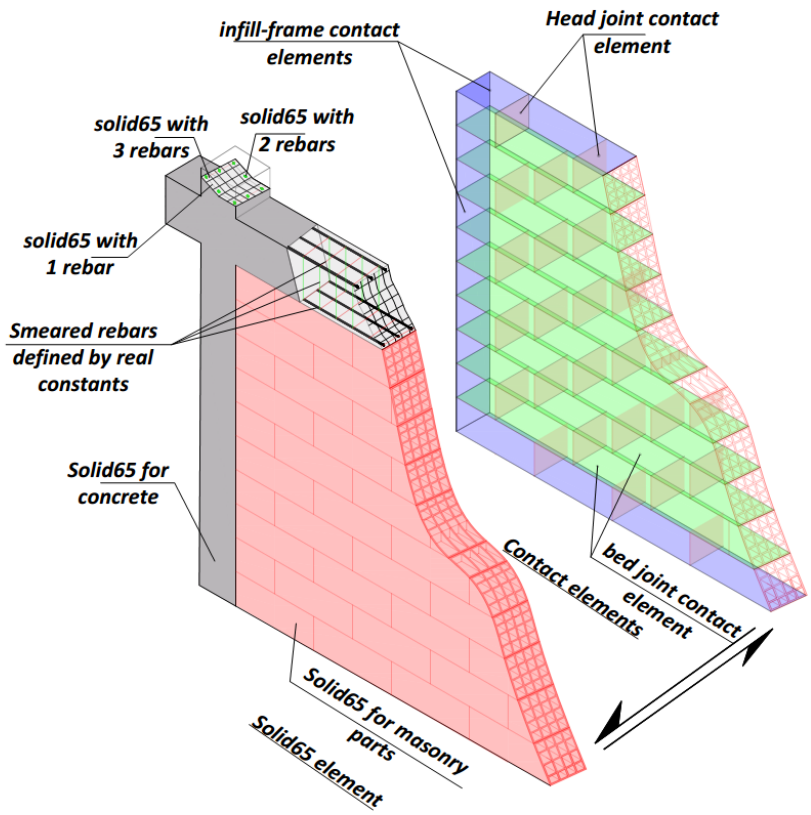


Fig. 2 – Discretization of the considered micro finite element model components for masonry-infilled RC frames

2.1 Reinforced concrete material

The 3D element SOLID65 was used to model the concrete parts. When associated with the CONCR material model of ANSYS® [26], the SOLID65 element is capable of cracking in tension and crushing in compression. The definition of the CONCR material model requires five main parameters which are listed in Table 2. The shear coefficients for opened and closed cracks, which control the amount of shear transferred across an opened or closed crack, range from 0 to 1, with 0 representing a smooth crack (i.e. with no shear transfer) and 1 representing a rough crack (i.e. with no loss of shear transfer) [27]. In this study, the values of 0.53 and 0.98 were assigned to β_t and β_c, respectively. The values of the tensile and compressive strengths were defined according to experimental data. Since the CONCR material model behaves as a linear elastic material, it is unable to represent the nonlinearity involved in the real behaviour of concrete. Therefore, the Kent-Park [28] model was used to define a multilinear kinematic hardening material model (MKIN) for the concrete behaviour in compression. To avoid the premature numerical failure of the concrete, the crushing capability of the SOLID65 element was deactivated. The structural behaviour of the reinforcement material was represented by a bilinear stress-strain relation. The bilinear material is defined by the steel yield stress and the post-yield tangent modulus. Those parameters were used to define a kinematic hardening material with a bilinear behaviour that accounts for the Bauschinger effect [29]. The values considered for the Poisson ratio were 0.2 and 0.3 for the concrete and the steel materials, respectively.

Table 2 – Concrete material parameters.

Item	Description
β_t	Shear transfer coefficients for an open crack.
β_c	Shear transfer coefficients for a closed crack.
f_t	Ultimate uniaxial cracking tensile strength
f_c	Ultimate uniaxial compressive strength (crushing stress)

2.2 Masonry infill wall material

The modelling strategies that were used to model the plain concrete were also considered to model the masonry material. The nonlinear stress–strain curve proposed by Hendry [6] was adopted to model the compression stress state of the brick material. The ANSYS surface contact element pairs CONCTA174 and TARGE170 were used to represent the interaction behaviour between the masonry courses and between the infill and the surrounding RC frame. The cohesive zone material (CZM) model was used to define the behaviour of the contact elements [26]. Bilinear models with mixed traction (mode I and mode II) were adopted for the CZM to account for the possibility of loss of contact in both tension and shear, as shown in Fig. 3 a) and b), respectively. The value of the Poisson ratio assigned to the masonry material was 0.19.

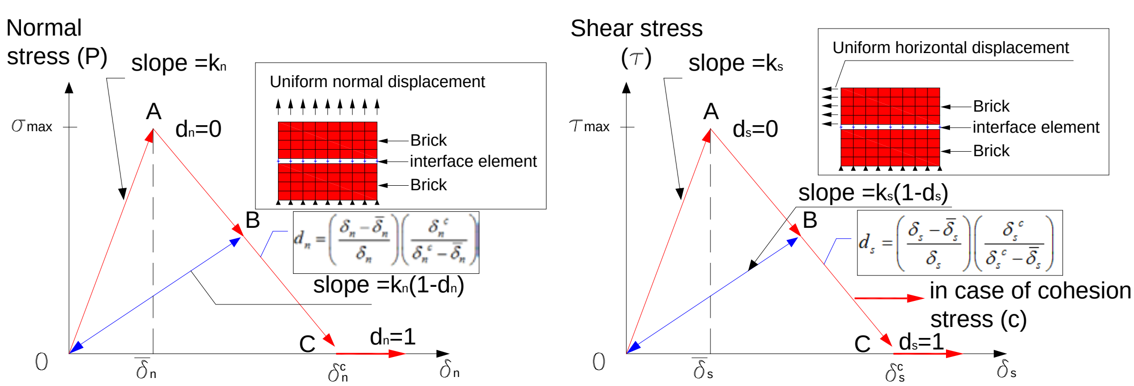


Fig. 3 – Bilinear behaviour of the CZM material: a) bilinear definition of cohesive zone model for tensile debonding (mode I); b) bilinear definition of cohesive zone model for shear debonding (mode II).

3. Micro-model results

In order to examine the capabilities of the proposed micro-model, the geometric and mechanical properties of three specimens from Kakaletsis [16] were analysed. One of these specimens has a fully infilled panel (termed specimen S) while the two other specimens (termed WX1 and DX1) have partially infilled panels with a window and door opening, respectively. The specimens are single-storey and single-bay frames built at a 1:3 scale that were subjected to reversed cyclic quasi-static horizontal loads up to a drift of 4%. Fig. 4 shows the numerical hysteresis curves of specimens S, WX1 and DX1, respectively, along with the corresponding experimental results. The results show that the numerical micro-models can provide a good agreement with the experimental data in term of the global behaviour (stiffness and strength) which are the more important parameters to calibrate the strut model. It is also noted that the proposed micro-modelling approach is also able to capture the non-symmetric nature of the experimental results. In addition to the hysteresis curves, the diagonal force in the infill and the contact stress between the infill and the RC frame were also analysed to calibrate the strut parameters.

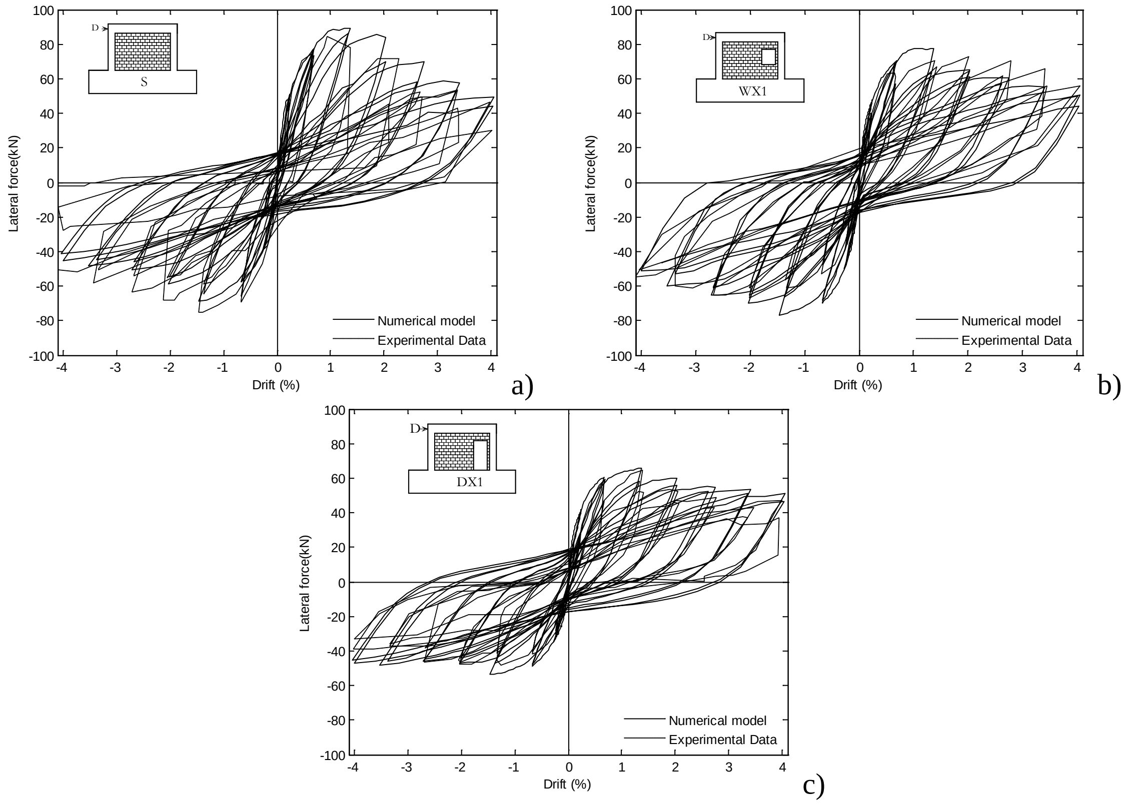


Fig. 4 – Hysteresis curves obtained from the numerical micro-models along with the experimental data: a) specimen S, b) specimen WX1, c) specimen DX1

4. Macro-model calibration

Even though macro-models (i.e. strut models) are efficient computational approaches to model the behaviour of masonry infills, using the direct stiffness-based or strength-based analytical calibration methods can lead to large errors. These are mainly due to the heterogeneity of the infill panel, loading paths, and failure mechanisms of the infill panel which can't be generalized into a single formula. On the other hand, by using experimental data, the contribution of the infill to the structural response can be fully defined. In this section, the use of micro finite element models is suggested as a proxy to experimental data for the calibration of single strut models. This section focuses on the calibration of a single strut element which is considered to be the preliminary component to represent the global infill model. The idea behind the calibration of this single strut element is to get a reliable representation of the in-plane infill panel behaviour which can then be further detailed to introduce other structural aspects of the global behaviour (e.g. the action of infills on the RC column which can be modelled by dividing the single strut into multiple struts). This reliable strut model can then be also associated with other elements or modelling features to account for the infill out-of-plane response.

Micro-models were used to represent the diagonal forces of the infill wall and the contact length between the infill panel and the RC structure (Fig. 5). The numerical data was then used to improve the stiffness- and strength-based approaches. For the stiffness-based approach, the maximum compressive diagonal strength obtained from the analysis was then divided by the strut area obtained by a specific formula from the literature. By establishing the compressive strength of the masonry using this approach, issues related with the definition of an equivalent masonry compressive strength which appear frequently with the stiffness-based method are solved. Table 3 presents the masonry compressive strength obtained for the macro models for the selected stiffness-based methods. These compressive strengths were then used to establish constitutive materials for the equivalent strut which are shown in Fig. 6 for specimen S. These compressive strengths are also compared with experimental values of the characteristic masonry strength (i.e. the brick unit compressive strength f_{br} and the average masonry strength $f_m^{'}$). It should also be noted that by using this approach based on micro-model results to evaluate the strength of the equivalent strut, the strength reduction effect due to the existence of openings can easily be considered. For the strength-based approach, a trilinear curve was fitted to the force-displacement relation of the infill panel which was then used to define the structural behaviour of the diagonal strut using the model proposed by Ibarra [30]. Figure 7 shows the idealization of the experimental force-displacement curves and the cyclic behaviour used for the strut model in the improved strength-based approach.

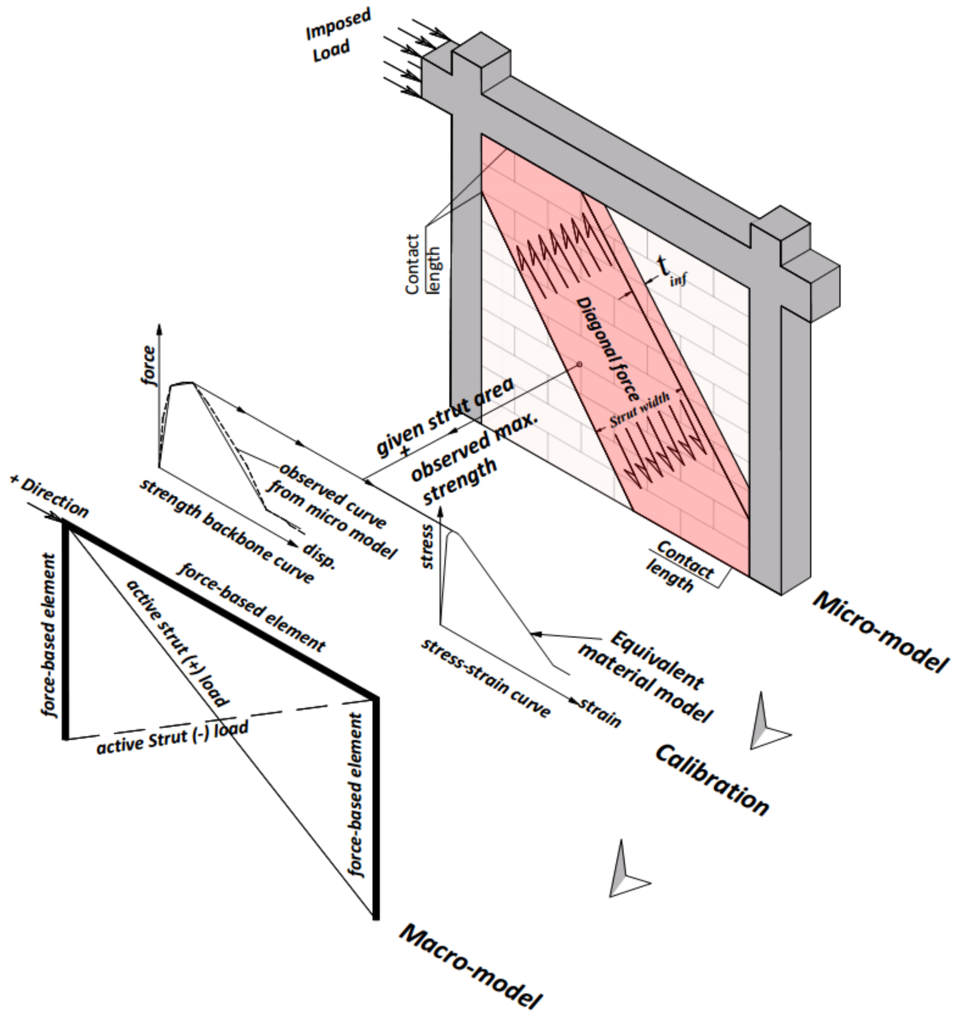


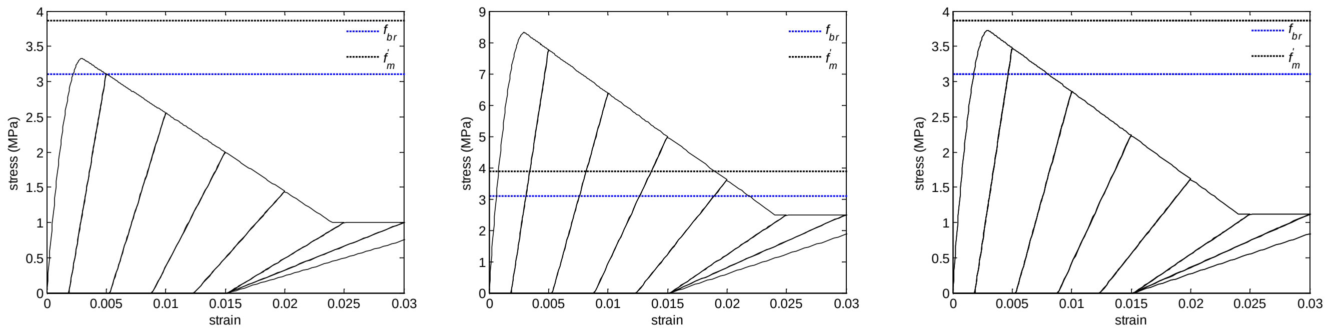
Fig. 5 – Equivalent compression strut to be used for the force transfer mechanism in masonry infilled RC frames calibrated using micro-models.

Table 3 – Compressive strength of the equivalent masonry material for stiffness-based approaches

Specimen	Measured data		Effective area of strut[2] (m^2)			Compressive strength for the equivalent material[3] (MPa)		
	Force (kN)	Strain (ε_m)[1]	Holmes [4]	Mainstone [5]	Hendry [6]	Holmes [4]	Mainstone [5]	Hendry [6]
S	54.08	0.003	0.0162	0.0065	0.0145	3.33	8.32	3.73
WX1	45.96	0.0032				2.837	7.07	3.17
DX1	33.00	0.0026				2.037	5.08	2.28

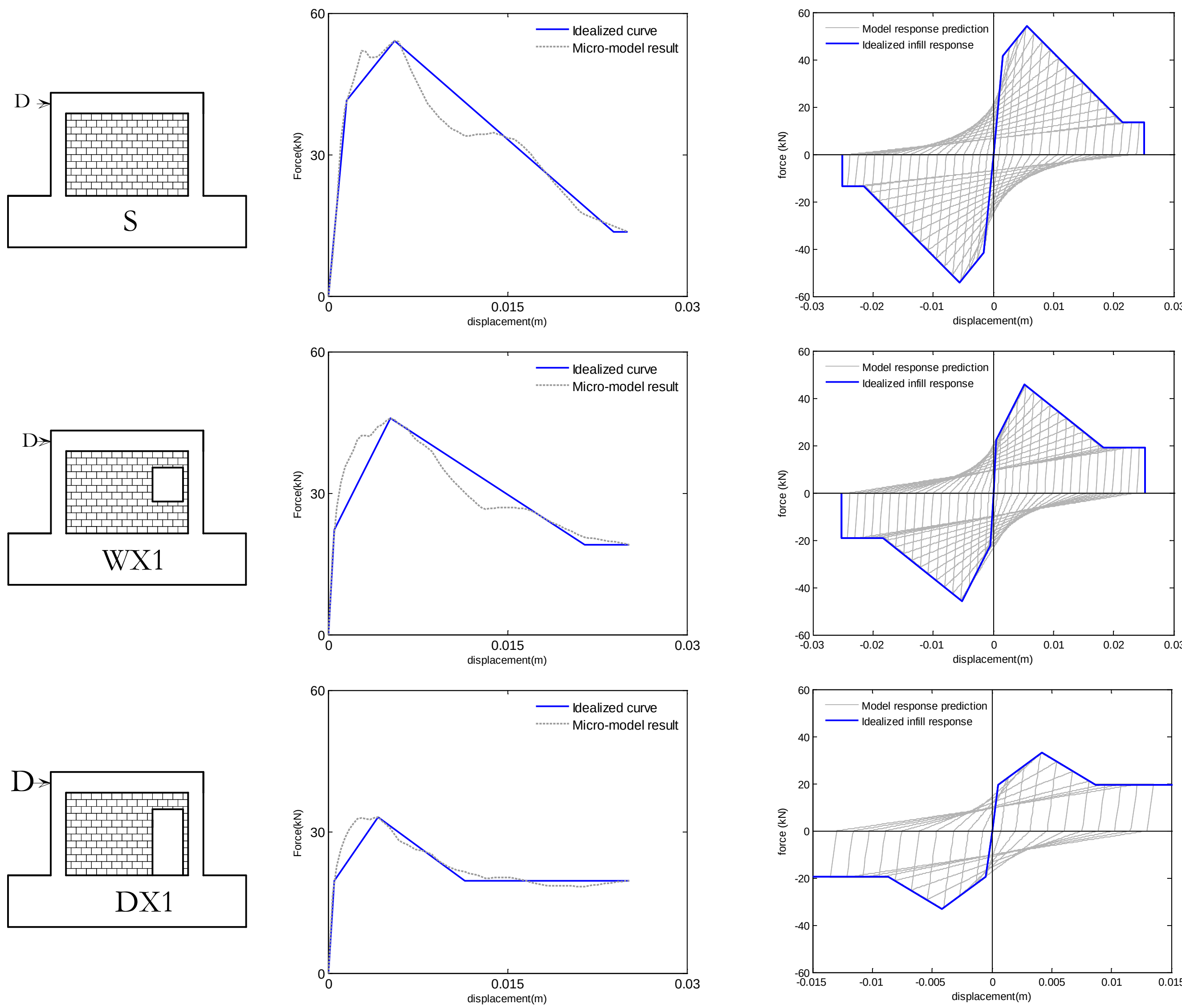
1) Strain corresponding to the maximum force
2) The net thickness of the infill wall was used to compute the area

[3)] Strength = measured maximum diagonal strength / effective area of the strut



a) b) c)

Fig. 6 – Constitutive model for the strut element with the strut width computed based on three different formulas a) Holmes [4], b) Mainstone [5] and c) Hendry [6] compared to the masonry strengths (f_{br} and f'_m).



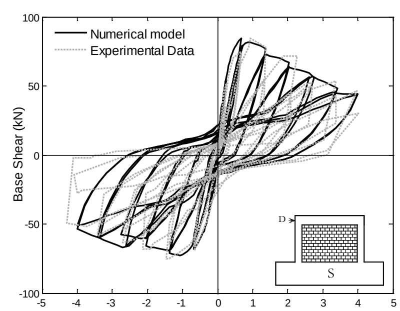
a) b) c)

Fig. 7 – a) Specimen configurations, b) quantified force-displacement curve along with the idealized strut element response, c) cyclic response curve for the infill strut model

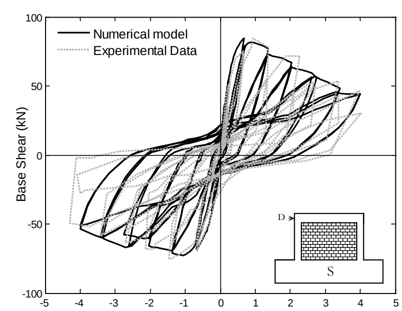
5. Simulation of experimental tests with the calibrated macro models

The selected case studies were modelled in OpenSees [31] where the RC components were modelled using force-based elements while the infill panel was replaced by an equivalent compressive strut. In order to examine the proposed calibration procedures, the formulas proposed by Holmes [4], Mainstone [5] and Hendry [6] were used to quantify the single strut area by the stiffness-based method. The constitutive model of the material of the equivalent strut was defined based on the results obtained from the micro-model (Table 3). For the strength-based approach, the fully idealized backbone curve defined from the micro-model results was also used to define the behaviour of the strut element.

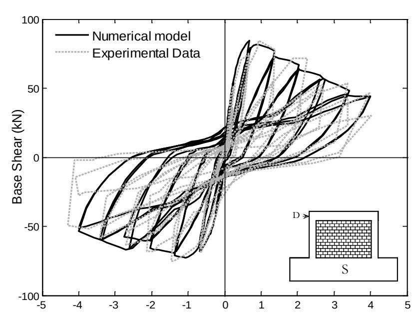
Figures 8 to 10 show the results obtained using the macro-modelling approaches for specimens S, WX1 and DX1, respectively. Each of those figures compares the experimental behaviour with the results obtained by the referred three different stiffness-based approaches and the strength-based method. As can be seen, using the proposed micro-models to simulate experimental results and determine the structural properties of the equivalent strut model generates numerical results with a good agreement with the experimental behaviour. Furthermore, calibrating the contribution of the infill wall from the micro-model results leads to almost identical results for all of the stiffness-based approaches even though they use different formulas to evaluate the strut width. However, the performance of the strength-based strut models calibrated using the backbone curve of the micro-modelling results is seen to be superior to that of the stiffness-based ones. As can be seen from Figs 9 and 10, the stiffness-based struts provide a good match with the positive experimental behaviour but a poorer match with the negative part of the behaviour. On the other hand, the strength-based struts can be seen to provide a better average match across both the positive and negative branches of the behaviour. It should be noted that the simplified formulation of these strut models is not able to capture the non-symmetric nature of the experimental behaviour. Finally, it should also be referred that the lack of agreement between numerical and experimental results is not just due to the masonry infill component. Part of this lack of agreement is also due to the inability to model the exact behaviour of the RC frame. Nevertheless, the presented results clearly show that using micro-model results to calibrate the properties of simplified strut models by improving existing analytical methods is useful to quantify the global response of masonry infilled RC frames when experimental results are not available.



a)



b)



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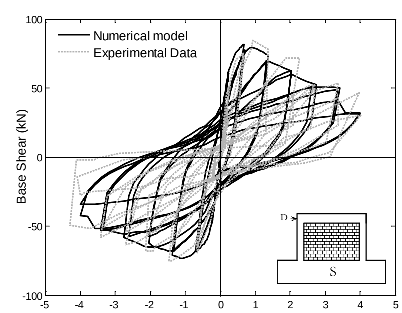

d)

Fig. 8 – Results obtained from a single strut element calibrated using micro- model results for specimen S using three different formulas for the stiffness-based method: a) Holmes [4], b) Mainstone [5], c) Hendry [6] and d) using the strength-based approach.

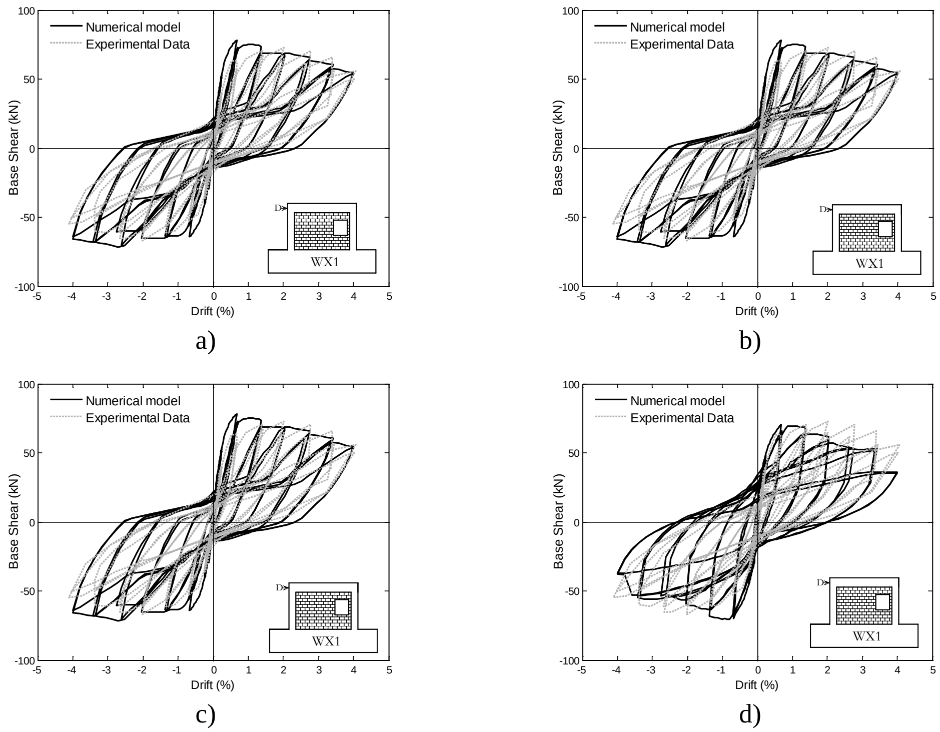

Fig. 9 – Results obtained from using a single strut element calibrated using micro- model results for specimen WX1 using three different formulas for the stiffness-based method: a) Holmes [4], b) Mainstone [5], c) Hendry [6] and d) using the strength-based approach.

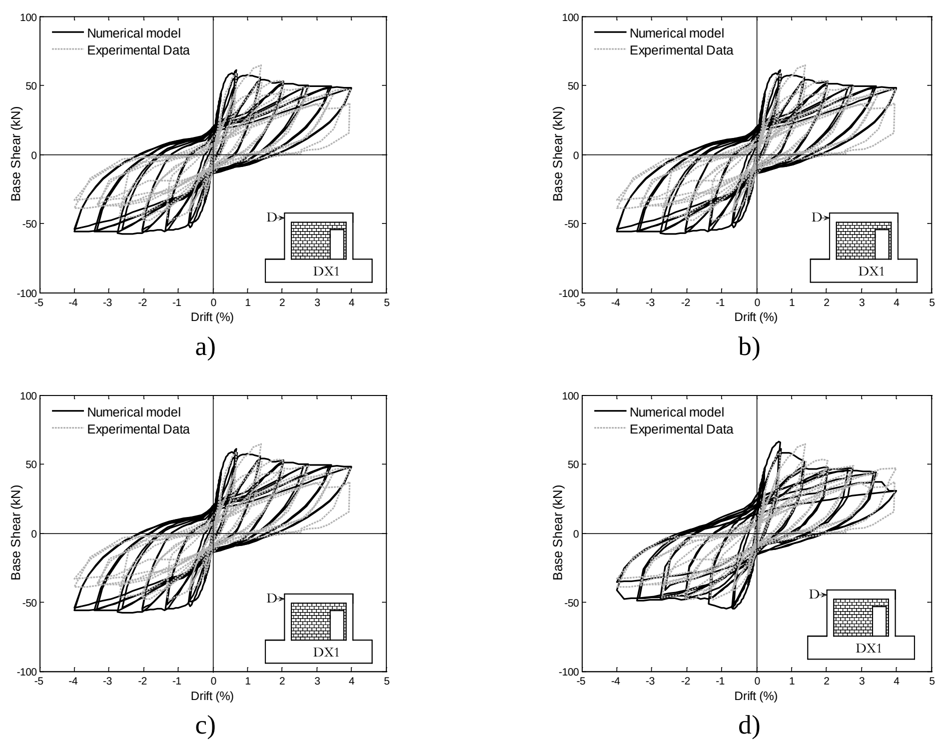

Fig. 10 – Results obtained from using a single strut element calibrated using micro- model results for specimen DX1 using three different formulas for the stiffness-based method: a) Holmes [4], b) Mainstone [5], c) Hendry [6] and d) using the strength-based approach.

6. Conclusion

This paper introduces the use of a detailed finite element modelling strategy to represent the cyclic behaviour of infilled RC frames as a proxy for experimental tests in order to calibrate the strut model. The proposed modelling approach was developed using the commercial software (ANSYS®) in order to be more easily replicated by other researchers. The presented case study examples show that the proposed micro-modelling approach is able to represent the structural behaviour of masonry infilled RC frame specimens using only the basic mechanical material properties of the structural components.

Macro-model calibration procedures based on data obtained from the micro-models that improve existing analytical proposals to establish the properties of strut-based macro models were also developed. Experimental results obtained from masonry infilled RC frames tested under cyclic loading were compared with numerical simulations of those tests involving strut models calibrated by the proposed approaches. The comparisons showed that the proposed macro-modelling approaches are able to capture the global structural behaviour of the physical specimens with adequate reliability. Therefore, if experimental data is not available to calibrate simplified models representing the behaviour of masonry infill walls under earthquake loading, the presented study recommends the use of numerical results obtained from detailed micro-models such as those presented herein combined with existing analytical proposals to calibrate the properties of strut models.

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