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DEVELOPMENT OF A FINITE ELEMENT MODEL FOR ALL-MASONRY INFILLED FRAMES UNDER LATERAL LOADING

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ABSTRACT

This paper presents the development of a finite element model in OpenSees to simulate the behaviour of all-masonry infilled frames subjected to lateral loading. All-masonry infilled frames refer to an infilled frame system where both the bounding frame and the infill panel are made of concrete masonry units. While masonry columns and beams can be constructed from large masonry boundary element units and are reinforced and fully grouted, the infill panel can be constructed with standard concrete masonry units with no reinforcement and grouting. The finite element model developed in this study is a macro-model consisting of multi-strut and special shear springs to consider the compressive and shear failure of the infill and its effect exerted on the bounding frame. The validation of the model, conducted through the comparison of experimental and numerical load vs. displacement responses and failure modes, showed that the proposed model is capable of providing accurate simulation results including the post-ultimate behaviour. The comparison between the proposed and other macro-models in the available literature showed that the proposed model performed better in providing estimates in stiffness, strength, and load vs. deflection responses.

KEYWORDS: *concrete masonry infills, masonry frames, finite element study, macro-model, shear spring, multi-strut*

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INTRODUCTION

Masonry infilled frames with either reinforced concrete (RC) or steel frames as bounding frames are commonly used in modern building construction. The behaviour of this type of structure is complex as the infill and its bounding frame, commonly made of two different materials, exhibit different behaviour but nonetheless all highly nonlinear inelastic. This nonlinear inelastic behaviour has been attributed to many factors, including (1) diagonal cracking and crushing of infill panel, (2) bond shear failure at the mortar joint, and (3) bounding frame cracking and yielding of the reinforcement. Hence, a robust and accurate computational model needs to consider these nonlinear effects and the extent of these effects as affected by the infill and frame interaction. Different techniques have been proposed and used for the analysis of infilled frames and they can be divided into two main categories: micro-, and macro-modeling. In terms of level of details considered for the masonry components and associated processing time and effort, they vary from being the most detailed to the most simplified technique. While the micro-modeling technique (or some form of simplified micro-modelling technique) models individual blocks and mortar using their respective constitutive relationships with the focus of capturing the localized stress and failure patterns [1-3], the macro-modeling technique uses simplified models to consider the infill effect based on a physical understanding of the overall system behaviour. In general, the former is often used when the objective of the analysis is to provide detailed stress and behaviour at a localized level and the latter is considered effective in simulating the global response and a more practical approach.

The "diagonal strut method" has been developed and established as the most commonly used macro-modelling approach. In its original version proposed by Polyakov [4] and Holmes [5], the entire infill panel is replaced with a diagonal strut connecting loaded corners. The infilled frame can then be treated as a braced frame and once the width of the strut is known, the stiffness and strength of the system can be determined through a simple frame analysis. Since its inception, much research has been dedicated to developing the strut geometry, in particular, strut width, to adequately simulate the overall behaviour observed in the experimental studies [6-9]. The refinement of the single strut geometry also led to development of multi-strut models in an effort to better represent the infill behaviour and infill-to-frame interaction. Several studies [10-13] proposed multiple compressive struts or a combination of compressive struts and some mechanism to account for shear behaviour. The results suggested that the macro-models, as a whole, can be used as a viable alternative to detailed but computationally costly micro-models and its accuracy can be significantly improved by implementing different strut geometry.

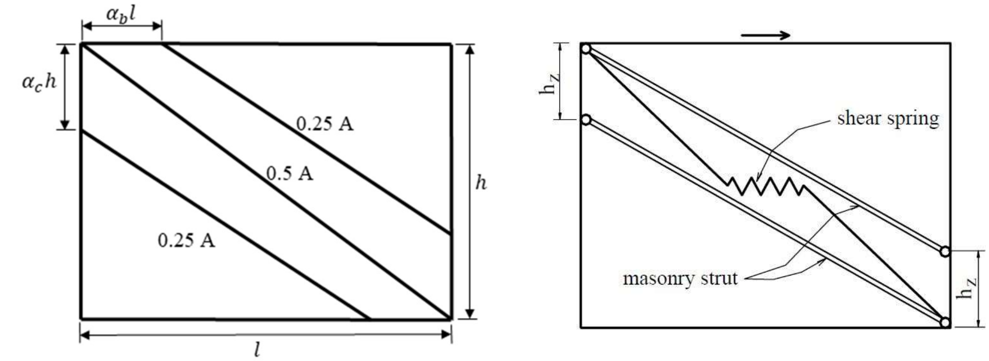
This study aims to develop a simplified and practical macro model to predict stiffness, strength and post-ultimate response of masonry infilled frames. This model considers a multi-strut configuration and implements a mechanism to account for shear behaviour in the infill panel. It is intended to provide a simple analysis tool for analysis of infilled frames using common commercial structural design programs.

ALL-MASONRY INFILLED FRAMES

The all-masonry infilled frame is a system where the masonry infill and bounding frame are all made of masonry units. In this case, masonry reinforced columns and tied beams form the masonry frame and they can be constructed with custom-made boundary element masonry units with thinner webs thus allowing a greater area for grouting and reinforcing. The masonry frame can be reinforced in the same manner as an RC frame. The masonry infill wall can be constructed with standard concrete masonry units. From both construction and design perspectives, all-masonry infilled frames are advantageous as design for the frame and infill can be carried out by structural engineers. The construction for the frame and infill can occur simultaneously and thus eliminating the need to coordinate with concrete or steel trades as in the case of steel or RC frames. It is recognized that while sharing some similarities with masonry infilled RC frames, the all-masonry infilled frame system could potentially exhibit different behavioural characteristics. While the model in this study was developed for all-masonry infilled frames, it can also be used in the analysis of masonry infilled RC frames with modifications made to the material properties of the bounding frame.

EXISTING MULTI-STRUT MODELS

Based on the diagonal strut concept, several researchers [10-13] proposed various forms of a multiple-strut model. Two representative models relevant to this study are described in the following. One is the three-strut model proposed by El-Dakhakhni et al. [11] and is shown in Figure 1(a). Their model proposed that three struts be used to reflect the infill effect over the length of frame beams and columns which can better capture the corner crushing failure of the infill. The limitation of the model is that it did not consider the shear behaviour of the infill within the three struts and thus cannot directly simulate the shear failure of the infill panel. The second is the multi-strut-spring model as shown in Figure 1(b). Proposed by Crisafulli and Carr [12], this model used two parallel struts for compression and a spring to model shear failure along mortar joints. The shear spring was assumed linear elastic with a stiffness defined through calibration with test



a) **b)**

Figure 1: Existing multi-strut models, a) El-Dakhakhni et al. [11], b) Crisafulli and Carr [12]

results. As the spring is configured to be parallel to the struts, the model implied that shear spring failure does not govern the failure of the infill. As shear sliding failure is a recognized failure mode anchored in design practice, the assumption of this model does not accurately reflect the shear sliding failure which are often observed in experiments.

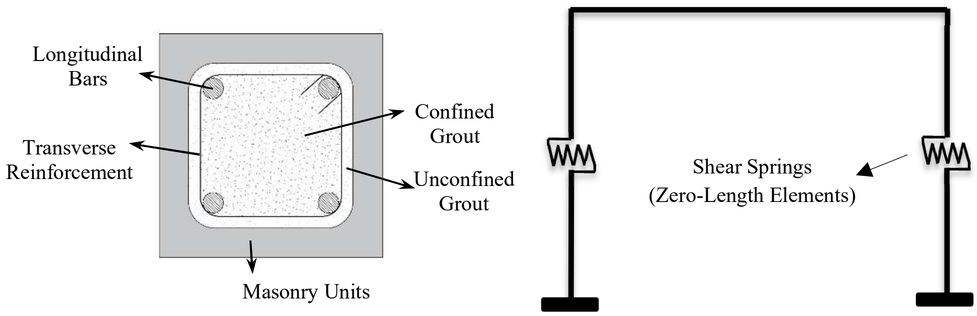
PROPOSED MODEL

Recognizing the limitations of the existing multi-strut models and using the multi-strut and spring model as a base, the model developed in this study proposed different configuration and geometry of the multi-strut and spring model with the aim to better capture the shear behaviour and shear failure of the masonry infill panel. The details of the proposed model are provided in the following sections. In general, the proposed model was developed and implemented using the OpenSees software. OpenSees is an object-oriented programming platform and has a large number of modeling classes ranging from linear elastic to nonlinear hysteretic material models. Different types of elements including zero-length elements, truss elements, and nonlinear beam-column elements along with a range of constitutive models for concrete, reinforcing bars, masonry, and mortar joints were considered and employed to simulate failure mechanisms of masonry infilled frames.

Masonry Frame

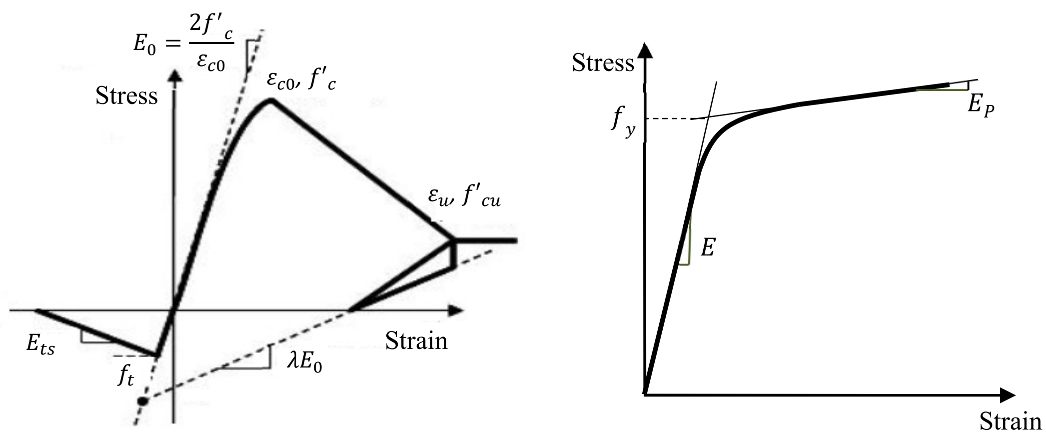
To accurately model the nonlinear response of masonry frames, the flexural, shear, and axial behaviour of frame members under lateral loading must be considered. Nonlinear Beam-Column Element in OpenSees was used to model frame beams and columns. This element assigns a fibre section to each constituent of the frame member with its specific uniaxial material model. The cross-section of masonry frame members consists of concrete masonry units, longitudinal and transverse reinforcing bars, unconfined grout, as well as the confined grout in the middle of the section (Figure 2a). The nonlinear behaviour of masonry units, unconfined and confined grout adopted the concrete material model proposed by Mohd-Yasin [14] (Concrete02) which includes tensile behaviour and gradual stiffness degradation under unloading situations in compression (Figure 3a). For the confined grout in the middle of cross-sections, strength and strain values of unconfined grout were modified based on the formulation proposed by Braga et al. [15] considering the arrangement of transverse reinforcement. To model longitudinal bars of beams and columns, the steel model with isotropic strain hardening behaviour (Steel02) proposed by Filippou et al. [16] was selected and used (Figure 3b). These material models are widely implemented in numerous studies on masonry/RC structures due to their simplicity and accuracy in formulation.

To capture the shear behaviour of frame members, shear springs were implemented in frame columns using zero-length elements (Figure 2b). These springs were intended to simulate both the initial sliding shear of mortar bed joints at the early loading phase as well as shear behaviour after cracking when the vertical reinforcement is engaged to confine further sliding. A similar technique involving the use of fibre section models and shear springs was used in previous studies [17,18].



a) b)

Figure 2: a) Cross-section of a reinforced masonry frame element, b) Proposed model for masonry frame



a) b)

Figure 3: Constitutive material models; a) Concrete02, b) Steel02

In this study, a symmetric constitutive model, shown in Figure 4, was assigned to these zero-length shear springs. The shear behaviour was assumed linear elastic up to the sliding shear strength of the mortar. In determination of the sliding strength, the compressive stress applied to the mortar joints needs to be considered. The sliding strength of mortar bed joints including the effect of compressive stress was computed in accordance with CSA S304-14 [19] as shown in Equation (1).

$$\tau_m = 0.16\sqrt{f'_m} + \mu\sigma_n \tag{1}$$

After reaching the sliding strength, the shear strength was assumed to decrease to 15% of the peak point with an increased shear strain (assumed to be $2\gamma_m$ in this case). At this point, it can be assumed that the vertical reinforcement becomes engaged to arrest further sliding, and the relative displacement of shear surfaces becomes zero with only rigid body movements until the end of lateral loading.

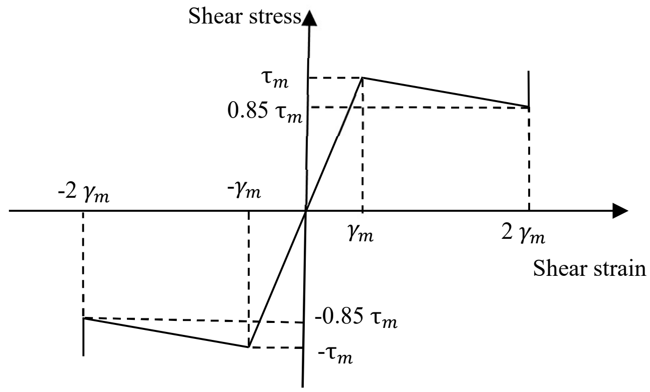


Figure 4: Proposed constitutive model of column shear springs

Masonry Infill

A modified multi-strut-spring model was proposed to represent the infill. As shown in Figure 5, this model consists of a sliding shear spring in the middle region of infill and two groups of equivalent strut elements. The strut elements are intended to transfer loads to the frame beams and columns as well as to the beam-column joints. The total width of the strut group is assumed to be equivalent to the uniformly diagonal loaded area which can be approximated using the width based on the single strut concept.

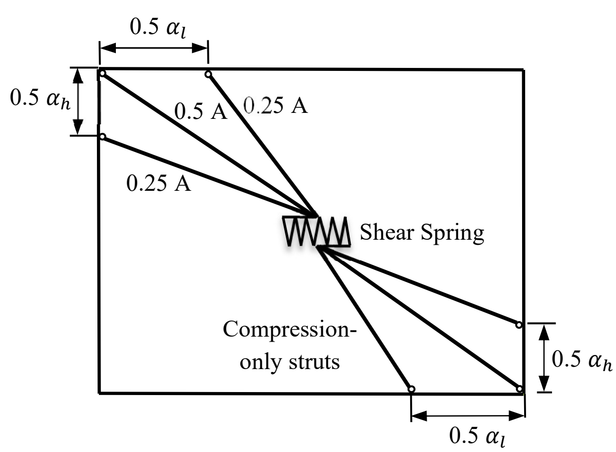


Figure 5: Proposed strut-model configuration

In this study, the strut width specified in the current Canadian masonry design standard CSA S304-14 [19] (Equation 2) was used as the total width of the strut group. The division of the area among three strut followed the same manner as proposed by El-Dakhakhni et al. [11], namely, 50% of the total width was assigned to the center diagonal and 25% of the total area was assigned to each of the off-centre diagonal. The difference from El-Dakhakhni et al.'s model is that the contact points were assumed to be at the middle of contact lengths as opposed to the full length.

$$w = 0.5\sqrt{\alpha_h^{2} + \alpha_l^{2}} \tag{2}$$

Where α_h and α_l are the infill to column and beam contact lengths, respectively, and are computed using equations contained in CSA S304-14 [19] and shown in Equation (3).

$$\alpha_h = \frac{\pi}{2}\sqrt[4]{\frac{4E_f I_c h_m}{E_m t_m \sin 2\theta}}, \quad \alpha_l = 2\alpha_h \sqrt[4]{\frac{l_m}{h_m}} \tag{3}$$

The effect of loading direction on the compressive strength and the associated Young's modulus of the three struts was considered using the relationship suggested by El-Dakhakhni et al. [11].

The shear spring connecting the diagonal struts is critical in accurately capturing the stiffness and strength of the infill. In this study, a symmetric three-branch load-displacement model was assigned to the shear spring to represent the sliding shear behaviour of mortar bed joints. As shown in Figure 6, the first line represents the uncracked phase up to the maximum shear strength of mortar (τ_m). The value of τ_m can be determined using Equation (1) or experimentally through masonry triplets test. The descending second line corresponds to the post cracking and sliding of mortar joints up to the friction-only sliding shear strength of mortar bed joints (τ_r) where all the cohesive capacity of mortar joints is lost. The flat third phase shows the residual shear strength of bed joints due to the friction between sliding surfaces. The values of γ_m and γ_r can be determined through triplet test on masonry samples and were assumed to be in the ranges of 0.0025 to 0.003 and 0.009 to 0.011, respectively. The shear behaviour was assigned to the zero-length element in the proposed model using Pinching4 material of OpenSees. The Pinching4 material is defined by 2 to 8 load and deformation or stress and strain values to construct a uniaxial material which has a pinched load-deformation response with strength and stiffness degradation under cyclic loading.

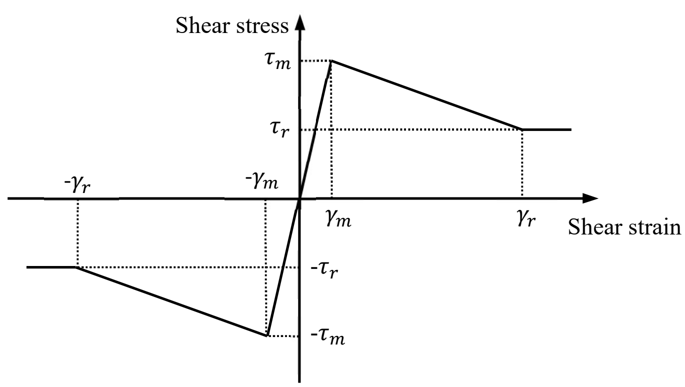


Figure 6: Load-displacement constitutive model for sliding shear behaviour of masonry

Overall, this model adopts the existing modeling methodology of using discrete struts to model compressive behaviour of the infill and spring to model the mortar joint shear behaviour. However, for shear behaviour modeling, unlike the Crisafulli and Carr's model [12], this model suggests that bed joints sliding and compression of equivalent struts act in a serial manner and failure of either of them causes the failure of the infill panel.

NUMERICAL IMPLEMENTATION

The proposed model was used to simulate the behaviour of two frame specimens, including one masonry bare frame and one all-masonry infilled frame. Both specimens were tested under monotonic lateral loading at Dalhousie University [20]. The masonry frame was constructed with C-shaped boundary element concrete masonry units and grouted and reinforced. The masonry infill was constructed with custom-made half-scale 200 mm standard concrete masonry units (CMUs) laid in a running bond. Mechanical properties of all materials, including masonry units, mortar, grout, masonry prism, and steel rebars were obtained experimentally and incorporated as input parameters in the material models described previously.

Modeling of the Masonry Frame

The cross-sectional dimension and reinforcement details of the masonry bare frame specimen are shown in Figure 7. Figure 8 shows the numerically and experimentally obtained load vs.

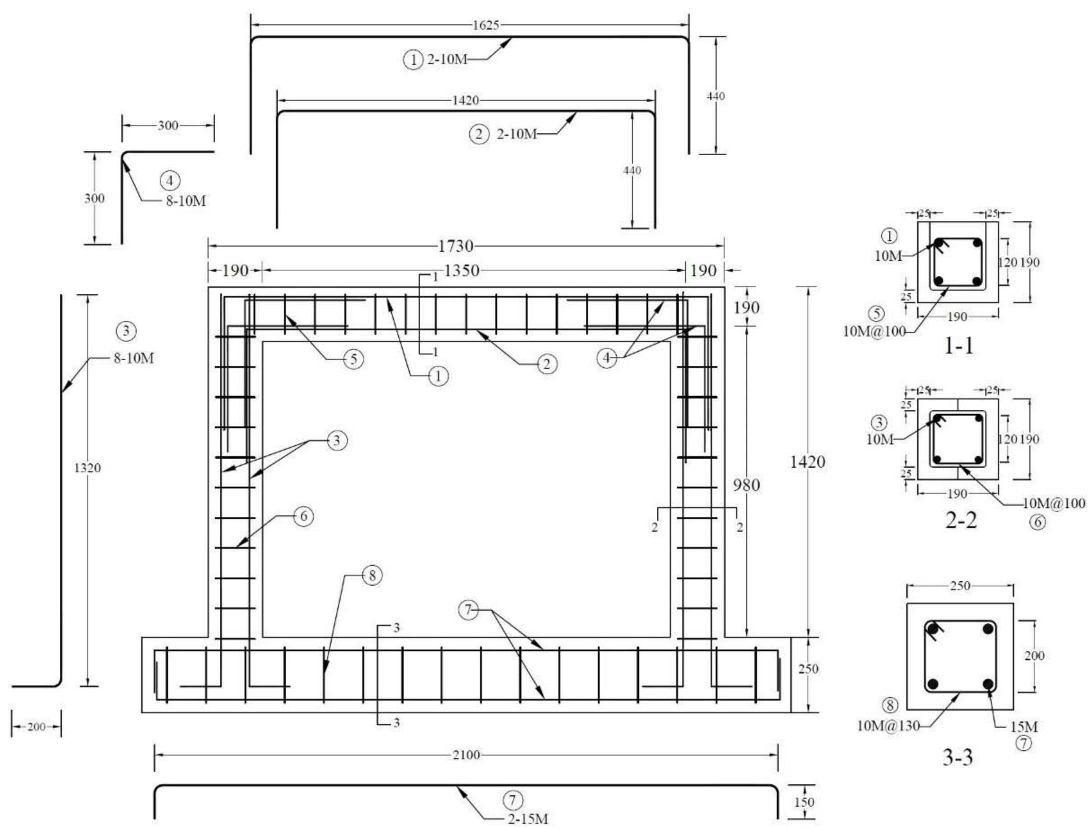


Figure 7: Reinforcement and geometry details of masonry frame specimen

displacement curves.The numerically obtained curves also included one without the use of the shear springs. It shows that while both numerical models provided similar ultimate strength, the model with the shear springs showed a much-improved stiffness prediction when compared with the test results. Around the load of 32 kN, the first crack was observed in mortar bed joints along the left column of the frame which caused a load drop. This load reduction and stiffness degradation thereafter were accurately captured by the model.

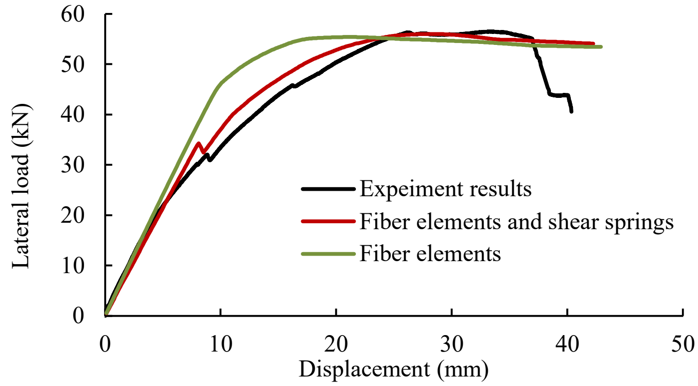


Figure 8: Lateral load vs. displacement curve comparison of masonry frame specimen

Modeling of the All-Masonry Infilled Frame

The experimental load vs. displacement response of the all-masonry infilled frame specimen is compared with the response curve obtained using the proposed model in Figure 9. Also included are the response curves obtained using models proposed by El-Dakhakhni et al. [11] and Crisafulli and Carr [12] for comparison. As can be seen, the proposed model performed better in predicting stiffness, strength, and post-ultimate behaviour. The much-improved accuracy of the proposed model is believed to be a result of implementing the shear spring such that the sliding shear behaviour of bed joints is reflected on the stiffness and strength degradation. By adding this component through shear springs in the model resulted in a closer strength estimate to the test result than that predicted by other models which significantly overestimated the strength and stiffness.

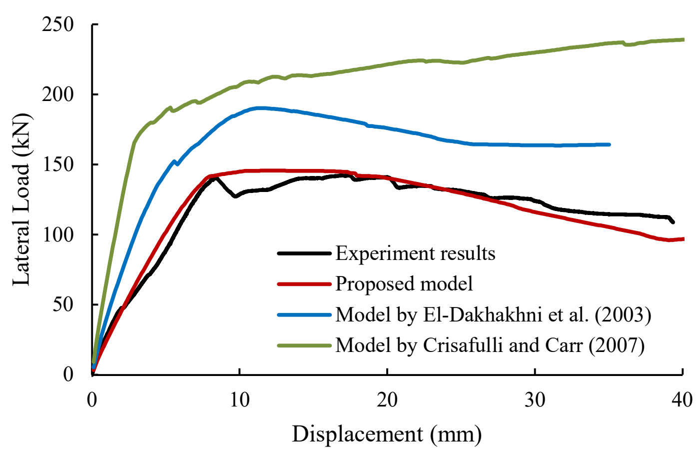
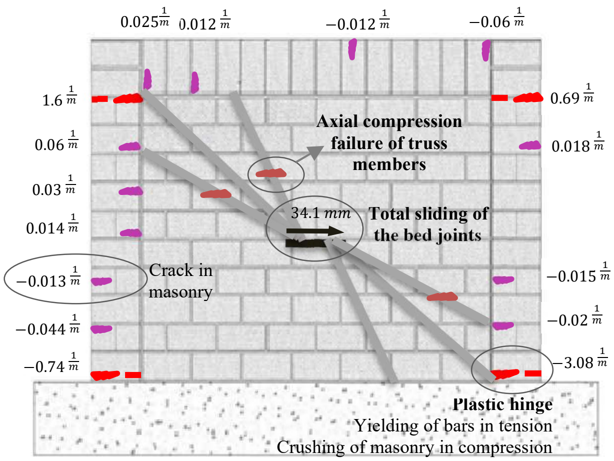
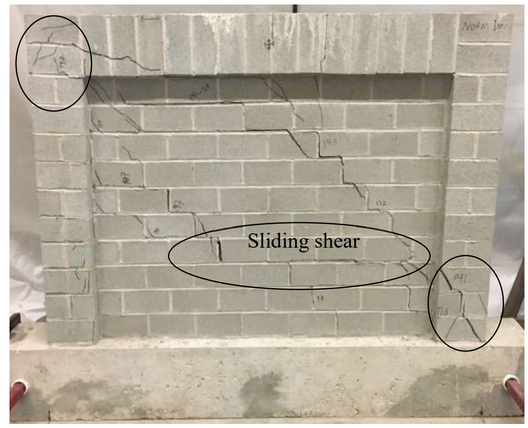


Figure 9: Load-displacement curves for masonry infilled frame specimen

The FE failure mode of the specimen is indicated in Figure 10(a). The model showed cracking along the frame members and forming of the plastic hinge of the frame, as well as failure of the shear spring and strut members. In comparison with the experimental failure mode shown in Figure 10(b), the global failure location and mode was accurately predicted. For example, the model predicted the development of plastic hinges at bottom right and top left corners of the frame with the highest curvature deformation. The compression failure of the truss members and deformation of shear spring indicates the development of diagonal cracking and shear sliding.





a) **b)**

Figure 10: Failure mode and cracking pattern; a) Proposed model, b) Experiment result

CONCLUSION

This paper presents the development of a finite element macro model for the analysis of masonry infilled frames. Implemented in OpenSees, this model was intended to provide an effective analysis tool for infilled frames when the global response is the objective of the analysis. The model replaces the entire infill panel with multiple compressive struts and a shear spring. The compressive struts were intended to model the compressive behaviour of the infill panel and its exerted effect on the bounding frame by connecting the off-diagonal struts to the frame at discrete points. The shear spring was modeled with zero-length element to capture the shear behaviour of infill panel, in particular, shear sliding and cracking in the mortar joints. The material models used for compressive and shear behaviour were described. While the model was developed particularly for the all-masonry infilled frames, it can be adapted to RC frames by modifying the material model for the bounding frame. The efficacy of the proposed model was verified with the test results of two specimens. The verification showed that the proposed model can accurately predict stiffness, ultimate strength, and post-ultimate behaviour of both masonry bare frame and all-masonry infilled frames. When compared with the existing multi-strut models, the proposed model performed better in capturing the stiffness and overall behaviour of infilled frames. The proposed model's capability in the simulation of cyclic loading behaviour will be studied in future work.

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