Sensitivity of the Strut Model for an RC Infill-Frame to the Variations in the Infill Material Properties

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Abstract

Extensive research has been carried out on the behaviour of infill-frames when laterally loaded. This paper focuses on the analysis of infill-frames using the equivalent strut modelling method. Even though several different strut models are available in the literature, recent studies have shown that it is not possible to apply one strut model to all infill-frame structures. This means that by changing properties of the infill-frame, the geometric properties of struts namely, width, location and number of struts, will also change. A finite element model at a micro level available from the literature has been used to perform a sensitivity analysis on an infill-frame by varying the material properties of the infill. Since the principal stresses in the panel, which are used to define the struts, change as the lateral drift increases, an optimal drift value is suggested for each analysis at which the geometric properties of the strut model can be determined. Based on the results of the sensitivity analysis, one strut model is proposed which is shown to be suitable for all of the cases considered in this study.

Keywords: finite element, infill-frame, strut model, masonry, concrete, ANSYS, OpenSees

1 Introduction

Masonry is commonly used as a construction material worldwide. When a masonry panel is built within a reinforced concrete or steel frame, the structure is referred to as an infill-frame. The structural interaction between the masonry and frame is complicated and has been the subject of extensive research (e.g., Fiorato et al. (1970), Mehrabi et al. (1994), Al-Chaar (1998) and Al-Chaar et al. (2002). For this reason, masonry is usually not considered as a structural element in design calculations, and only the weight of the infill panel is used in such analyses. However, the behaviour of such structures during past earthquakes (e.g., Kafle et al. (2008), Kam and Pampanin (2011), Marius (2013)) and in experimental research studies (e.g., Al-Chaar et al. (2002), Mehrabi et al. (1994), Abdel-Hafez et al. (2015)) indicate that the behaviour of bare frames and infill-frames is substantially different.

The high nonlinear nature of the structural interaction between the frame and infill makes nonlinear finite-element modelling an attractive option for understanding their behaviour. However, the finite-element (FE) modelling of such structures can be too complex, urging for some simplified methods to be used by engineers for design purposes. Equivalent-strut models are commonly used as a replacement for FE models. Single-strut models were initially proposed (e.g., Holmes (1961), Stafford Smith (1962), Mainstone (1971), Priestley and Paulay (1992) and Durrani and Luo (1994)). However, one of the shortcomings of single strut models is that the shear force/bending moment diagrams of the frame members are not accurately represented. Consequently, many other models with multiple struts were suggested to better represent infill-frame structures (e.g., El-Dakhakhni et al. (2003), Crisafulli and Carr (2007), Rodrigues et al. (2010), Chrysostomou (1991)).

Mohyeddin (2011) developed a generic three-dimensional FE model of a one-storey one-bay reinforced concrete frame with (or without) an infill panel that can be generated in the ANSYS software. A more detailed explanation of the verification of the FE model can be found in Mohyeddin (2011) and Mohyeddin et al. (2013a). In the latter study, by examining the principal stresses in the infill panel at specific drift values, it was observed how the compressive struts formed in the panel. It was concluded that since the number, width and location of struts are dependent on both the infill-frame properties and the drift level, it is not possible to apply one strut model to all infill-frames. It was suggested that "case-specific" strut modelling would be the best approach to represent such structures, whereby some or all of the geometric properties of struts (location, number and width) may change from one infill-frame to the next. Mohyeddin (2011) and Mohyeddin et al. (2013b) performed a series of sensitivity analyses on Specimen 8 of Mehrabi (1994) shown in Figure 1 by varying masonry material properties; these are used in this study to explore "case-specific" equivalent strut modelling further.

2 Strut Modelling – Specimen 8

In this study, seven of the analyses from Mohyeddin (2011) and Mohyeddin et al. (2013b) are selected (see Table 1). One of these analyses was developed to the emulate experimental results of Specimen 8 from Mehrabi et al. (1994). In the other six analyses, masonry properties are increased and decreased by a value of 25%. The masonry material properties that vary are: f'_{cm} (ultimate masonry compressive strength), f'_{tm} (ultimate masonry tensile strength) and ε_{0m} (strain at which the ultimate masonry compressive strength is achieved). Strut models are developed using the FE software OpenSees, and they are subjected to a monotonic displacement-controlled lateral load pattern. At least five strut models are analysed for each

infill-frame to test their suitability to represent the behaviour of the infill-frame. The nonlinear behaviour of masonry, concrete and steel material is considered in these models. The material models used in the frame members to represent the concrete cover "Concrete01" and the concrete core "ConfinedConcrete01" are modeled by a "non-linear beam-column" element. The Kent-Scott-Park (Scott et al., 1982) stress-strain relationship is used for the reinforced concrete models mentioned above. The material model "Concrete01" is also used to define the masonry material and incorporates a non-linear stress-strain relationship proposed by Hashemi and Mosalam (2006). This material model has a parabolic equation (Eq. 1) for the ascending part of the stress-strain curve and a linear relationship for the descending part. The parabolic equation for the ascending part of the curve is given below:

$$\sigma = \frac{-f'_{cm}}{\varepsilon_{0m}^2}\varepsilon^2 + \frac{2f'_{cm}}{\varepsilon_{0m}}\varepsilon \qquad (1)$$

where f'_{cm} is the maximum compressive strength of the masonry, ε_{0m} is the strain corresponding to f'_{cm}; ε is the strain, and σ is the stress.

For each of the analyses, the geometric properties of struts are determined based on the location of the load paths (principal compressive stresses) in the infill panel at a specific drift level (see Figure 2). The range of drift chosen for this purpose is 0.38% to 0.80%. This range includes the value of 0.63%, which was suggested for Specimen 8 (without changing any of the material properties) in previous studies (Mohyeddin et al., 2017a and b). Table 1 shows the drift value used in each of the analyses that produced the closest force-displacement curve to that of the FE analysis.

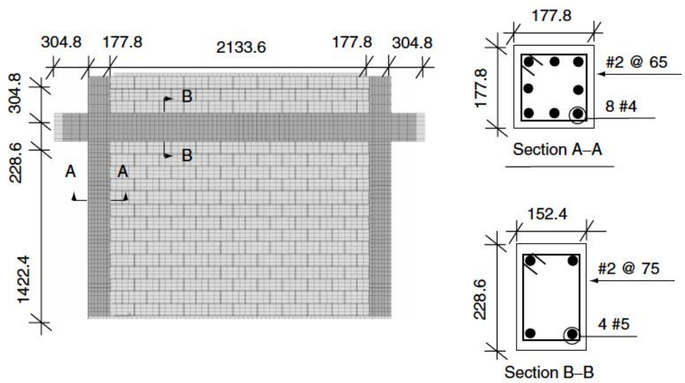

Figure 1: Geometric properties of the infill-frame used in Specimen 8 (Mehrabi et al., 1994)

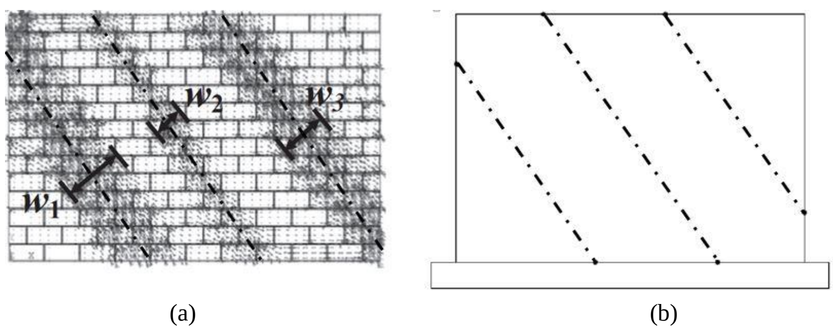

Figure 2: (a) Principal compressive stresses in the infill panel used to determine the strut locations (Mohyeddin et al., 2013a), **(b)** strut model developed based on (a)

Table 1: Masonry property values for each infill-frame and the drift for the chosen strut model.

Analysis No.	f'_{cm} (MPa)	ε_{0m}	f'_{tm} (MPa)	Drift value which provided the best strut model (%)
1	9.5	0.0027	0.95	0.63%
2	1.25*9.5	0.0027	1.25*0.95	0.67%
3	0.75*9.5	0.0027	0.75*0.95	0.76%
4	9.5	1.25*0.0027	0.95	0.76%
5	9.5	0.75*0.0028	0.95	0.50%
6	9.5	0.0027	1.25*0.95	0.59%
7	9.5	0.0027	0.75*0.95	0.71%
AVERAGE				**0.66%**
Coefficient of Variation				14.37%

In all cases, a drift value in the range of 0.5-0.76% produced the strut model that best represents the behaviour of the infill-frame. Figure 3 presents a comparison between force-displacement curves from the strut model, the original detailed FE model, and the experimental result for Specimen 8. In Figure 4, a comparison is made between the results from detailed FE models and the case-specific strut models when changing material properties. For all cases, the case-specific strut model closely matches the FE analysis and captures the highly nonlinear behaviour of the infill-frame. The largest difference in the ultimate strength between the strut model and the detailed FE model is 7%, and it occurs in the model with a lower value of ε_{0m}. The same model has the most substantial difference between the drift at the ultimate strength, being 0.46% for the detailed FE model and 0.81% for the strut model; however, it perfectly captures the behaviour at drift values higher than 1.5%. The strut model with a lower masonry tensile strength has the best match for the drift at the ultimate strength: only 1% difference. Furthermore, the strut model with a higher tensile strength has the same ultimate strength value as the detailed FE model. Examining the post-failure behaviour up to collapse, the strut models closely match the detailed FE analyses. The strut model with higher masonry compressive and tensile strength (analyses no. 2) differs the most from the detailed FE model at drifts higher than 1.5%. In this case, the strut model underestimates the forces in this part of the analysis.

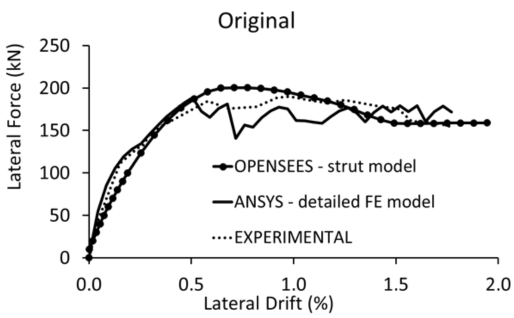

Figure 3: Comparison between the results from the experimental study on Specimen 8, the detailed FE model and the case-specific strut model (Mohyeddin et al., 2017a and b).

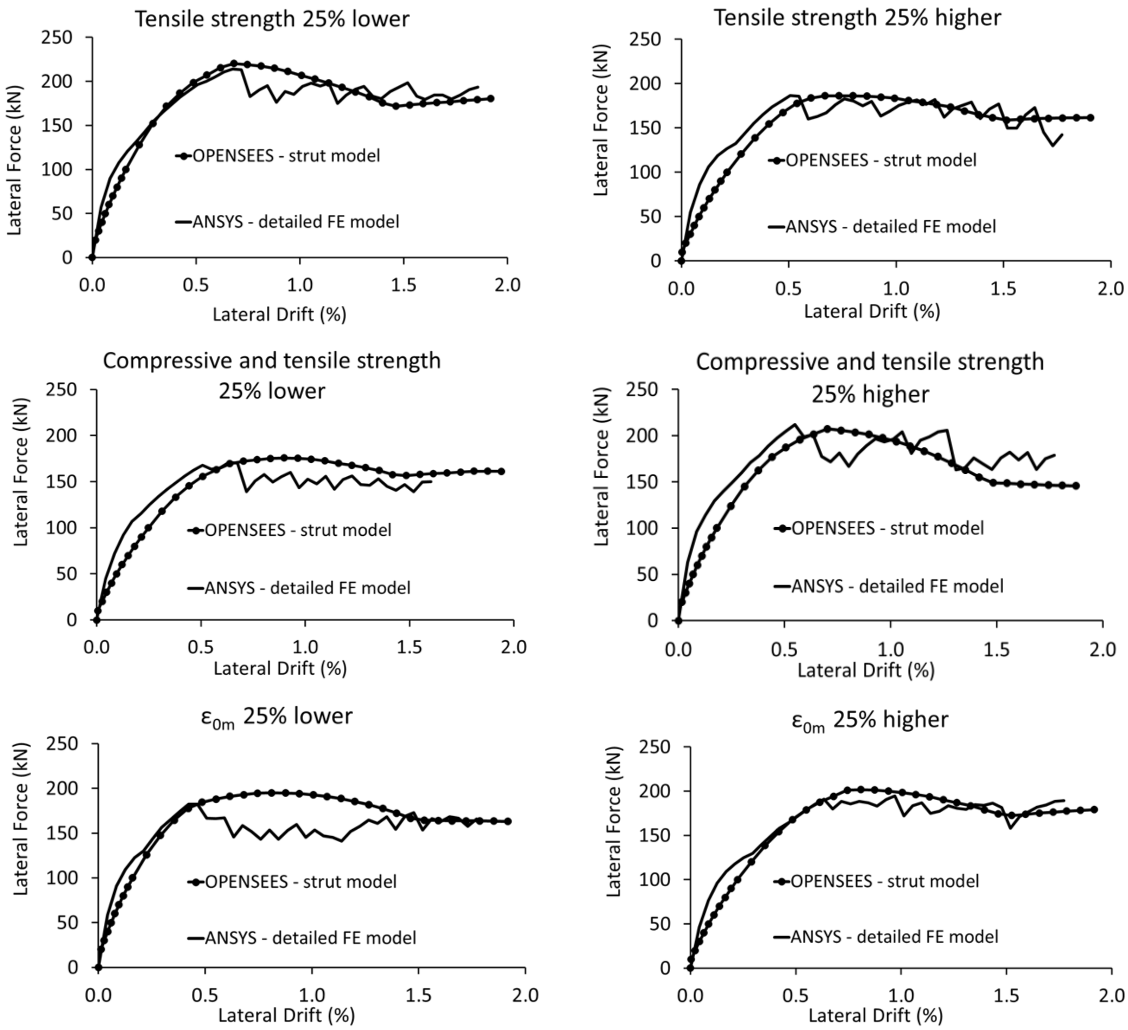

Figure 4: Comparison between the results from detailed FE models and the case-specific strut models when changing material properties.

2.1 Strut Width

In all cases investigated in this study, the strut models that provided the best match against detailed FE results have three struts (Figure 2). Furthermore, in most cases, the outer struts have almost an identical width (w_1 and w_3), and the middle strut (w_2) is narrower than the other two. The average width of the struts w_1, w_2 and w_3 is 14%, 8% and 13% of the diagonal of the infill panel, *d*, respectively. The average of the sum of the widths is 36% of *d* with a coefficient of variation (CoV) of 10%.

Mohyeddin et al. (2017b) calculated the strut cross-sectional area for Specimen 8 based on various equations available in the literature (single and multiple strut models) and found that the total strut width varied between 7% and 33% of *d*. Therefore, it can be concluded that the strut width proposed by Holmes (1961), which is *d*/3, gives the best match with the findings here, i.e. 36% of *d*. However, it should be noted that the strut model proposed by Holmes (1961) is a linear strut model based on a single concentric diagonal strut.

2.2 Strut Locations

Another significant property of equivalent strut models is the location of struts. Figure 5 shows the envelope of the struts for all seven analyses, and Figure 6 shows the position of struts, i.e. centrelines of struts. Figure 6 shows that despite significant variations in the masonry material properties, the strut positions remain similar.

Based on the average values of strut widths and positions (Figures 5 and 6), an equivalent strut model is created. Figure 7 shows the struts geometry of such a model. *h* and *l* in this figure are the height and span of the frame measured between the centrelines of the frame members.

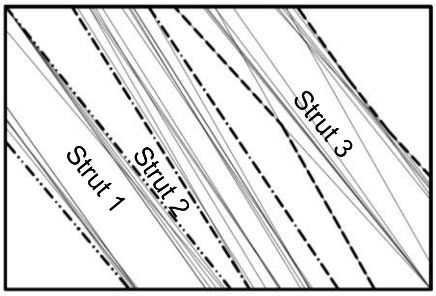

Figure 5: Envelope of all seven strut models

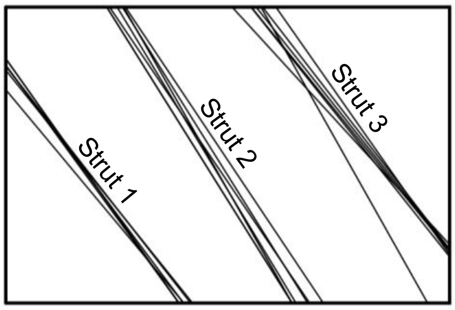

Figure 6: Middle position of all seven strut models

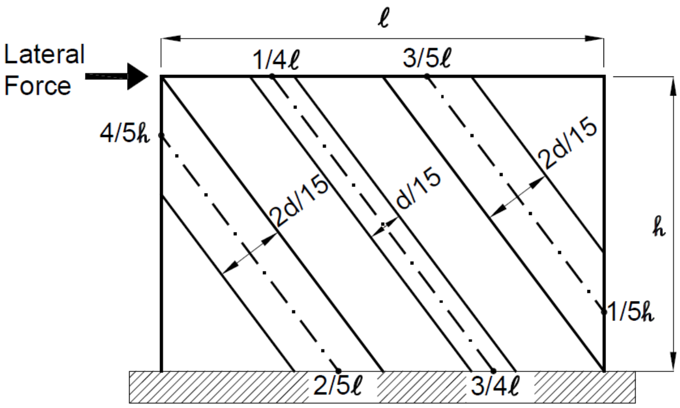

Figure 7: Average strut model for Specimen 8.

4 Average Strut Model – Specimen 8

The average strut model developed for Specimen 8 is applied to all seven infill-frames, including the original (no change in masonry material properties), and the results are shown in Figure 8 and 9. The strut models have identical geometrical properties (as presented in Fig. 6). Hence, the only variation between these analyses is the material properties of the struts (as given in Table 1). The figures show that the average strut model captures the nonlinear behaviour of all variations of Specimen 8. The difference in the ultimate strength of the average strut model when compared to the detailed FE model ranges from -5% (lower tensile strength) to +12% (higher ε_{0m}), which is slightly larger than the strut models seen in Figure 4. Similar to Figure 4, in all strut models the ultimate strength occurred at a higher drift value compared to the detailed FE analysis.

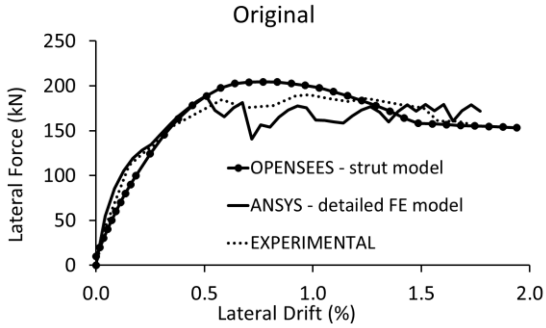

Figure 8: Comparison between the results of the experimental study on Specimen 8, the detailed FE models and the average strut models.

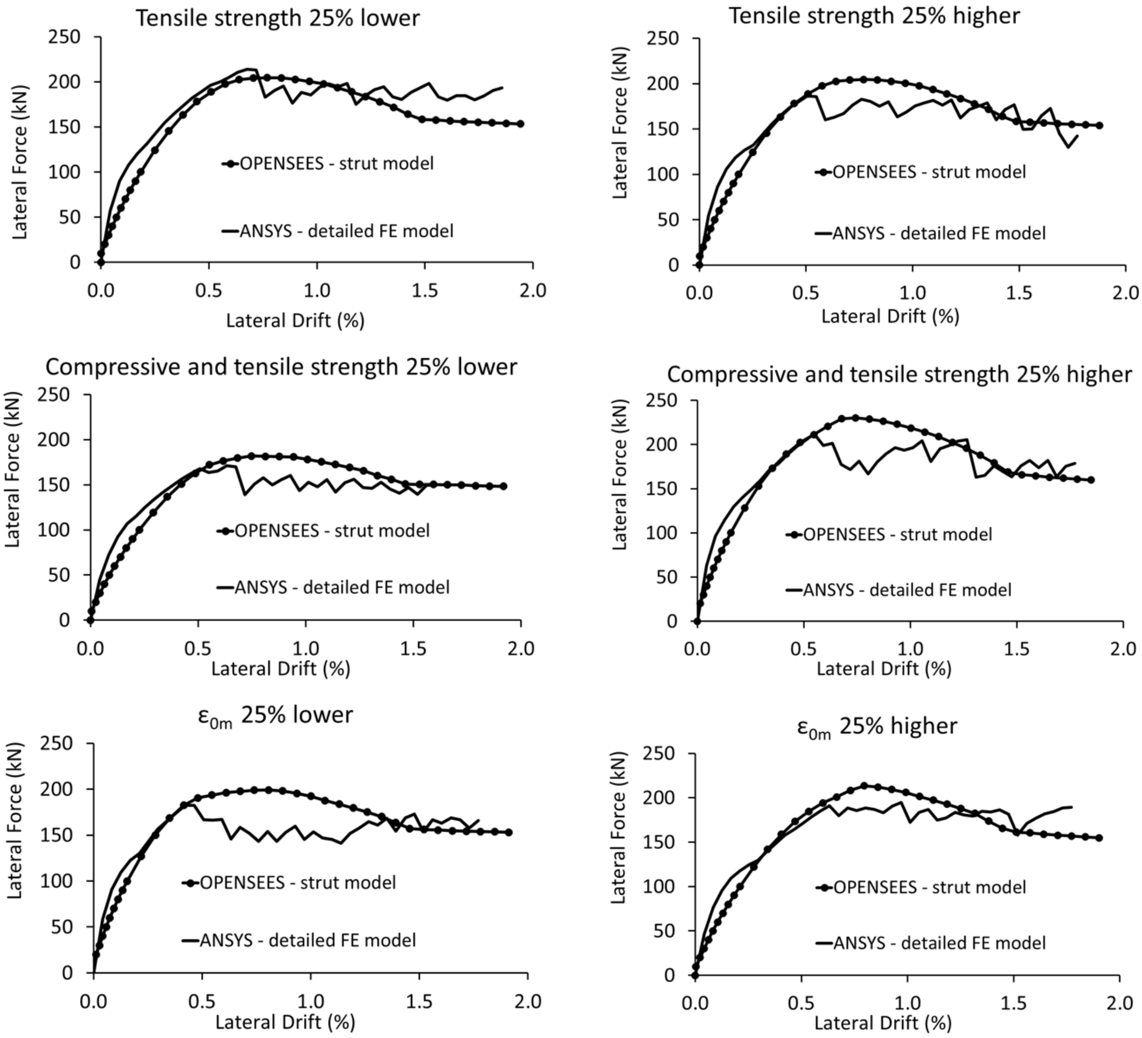

Figure 9: Comparison between the results from detailed FE models and the average strut models.

5 Discussion and Conclusions

The results of detailed FE analyses of a number of infill-frames were used to determine the geometric properties (number, width and location) of equivalent case-specific strut models for each of the infill-frames. The infill-frames had identical geometric properties (dimensions), but varying material properties. Several strut models were constructed for each infill-frame, and by using the detailed FE results at different drift values, the geometric strut properties were determined. Nonlinear stress-strain curves for masonry, concrete and steel were also incorporated in the strut models. It was demonstrated that, on average, the strut models corresponding to a drift value of 0.66% produced the best match with the force-displacement curves from the detailed FE models. It was further demonstrated that the geometric properties of the struts were not sensitive to a ±25% variation in the material properties of the infill panel. This means that once a case-specific strut model is created for an infill-frame structure, the same equivalent strut model can be applied to other infill-frames of the same geometric properties but different material properties within a 35% variation.

Considering that a detailed FE infill-frame analysis is very time-consuming, the equivalent strut modelling technique is a very practical and effective approach for structural design purposes. This research will continue by performing a large number of sensitivity analyses to produce case-specific strut models for a wide range of infill-frames and hence remove the FE analysis step.

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