Numerical Modelling of Masonry Infill Walls in Existing Steel Frames Against Experimental Results

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Abstract. The presence of masonry infills may significantly affect the seismic behaviour of existing steel moment-resisting frames, characterised by low lateral force resistance and inadequate energy dissipation capacity due to the lack of seismic detailing. Masonry infills may cause variation of internal force distribution along beams and columns, resulting in large local seismic demands at beam-column joints and consequently leading to soft-storey mechanisms. Several numerical models have been developed to account for the effects of masonry infills, among which the equivalent strut models were most widely used. However, it has been argued that despite its ability to capture the global response of structures, the single-strut model may not be adequate to correctly simulate the internal forces distributions in steel members. To this end, the present study investigates modelling strategies of infilled steel frames using both single- and three-strut models. The results from different modelling approaches are compared among them and with experimental tests, providing insights on the influence of the modelling strategies both at global and local levels.

Keywords: Masonry infills · Existing steel frames · Equivalent strut models

1 Introduction

Many existing steel multi-storey frames in Europe were designed before the provisions of modern seismic design codes; therefore, they often exhibit low resistance to earthquakes due to their insufficient energy dissipation capacity [1]. In addition, the presence of masonry infill walls has been found to significantly affect their seismic performance [2, 3]. On the one hand, masonry infill walls considerably increase the lateral stiffness, strength, and energy dissipation capacity of the bare steel frames. On the other hand, upon the failure of masonry infills, the larger seismic force previously attracted by the masonry infills is transferred to steel members, hence inducing high

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local demands in the structural elements and triggering soft-storey mechanisms. Therefore, it is of vital importance to correctly account for the presence of masonry infill in the seismic assessment of steel buildings. A popular way of numerically simulate the presence of masonry infill walls in finite element analysis is the so-called equivalent strut model, in which the masonry wall panel is simulated by one or more compressive struts in each diagonal direction. Most of previous studies [*e.g.*, 4–7] focused on using a single-strut model, where only one strut was used in each diagonal direction to achieve great simplicity without losing too much accuracy of the structural response at global level. Nevertheless, all the single-strut models were developed based on the behaviour of reinforced concrete (RC) frames; hence their reliability in the case of steel frames cannot be guaranteed due to their larger flexibility and the complexity of the detailing at connections, which may impact the wall-frame interactions.

Previous analytical, numerical, and experimental studies have been conducted on masonry-infilled steel frames [*e.g.,* 8–12], but designated proposals of strut models for steel frames are still very limited. One of the earliest studies was conducted by El-Dakhakhni *et al.* [8], who reported that the surrounding steel frame was able to provide enough confinement to the infill panel through the contact lengths over beams and columns, allowing it to continue carrying lateral loads after cracking. Since it is not possible to simulate this behaviour by adopting the single-strut model, the authors employed three-struts in each diagonal direction to account for the presence of contact lengths. Over a decade later, Yekrangnia and Mohammadi [11] and Pashaie and Mohammadi [12] proposed another two three-strut models based on numerical analyses, which considered the fundamental parameters of masonry-infilled steel frames, including the aspect ratio, wall-to-frame relative stiffness and friction between brick units.

The present paper investigates the use of a single-strut model and a three-strut model and compares the estimated structural response provided by each model. The assessment includes the comparisons between numerical and experimental results of the global response of steel frames. Successively, the internal force distributions in columns obtained from the single-strut model and the three-strut model are compared with each other to investigate the necessity of adopting multiple struts over the use of single strut.

2 Strut Models

This section briefly describes the considered equivalent strut models *i.e.,* the single-strut model by Liberatore and Decanini [6] and the three-strut model by Pashaie and Mohammadi [12]. A schematic view of both models is provided in Fig. 1 and Fig. 2, respectively, along with the force-displacement relationship of the masonry struts.

The Liberatore-Decanini model, as shown in Fig. 1, utilises one strut in each diagonal direction to simulate the geometry of masonry infill walls. The struts have the same thickness as the infill wall they represent and have identical width determined based on the wall-frame relative stiffness. Moreover, the proposed monotonic force-displacement relationship of the struts contains four segments representing the un-cracking stage, the post-cracking stage, the post-peak strength deterioration stage, and the residual strength stage. A major advantage of this model is that the constitutive law of the struts is determined considering four different failure modes, including corner crushing, sliding shear, diagonal tension, and diagonal compression. However, it is noteworthy that this single-strut model was developed for RC frames, *i.e.,* the strut width and the strut strength corresponding to each of the four failure modes were calibrated based on experiments conducted on RC frames.

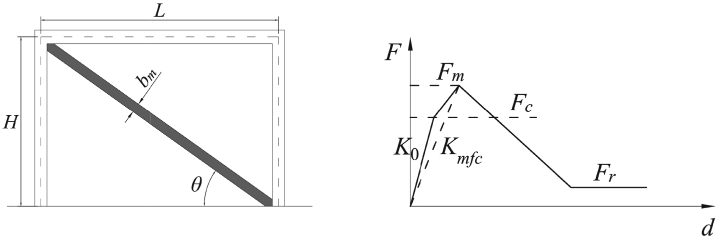


Fig. 1. Geometry and force-displacement relationship of the single-strut model developed by Liberatore and Decanini [6].

The Pashaie-Mohammadi model, as shown in Fig. 2, is one of the latest development of strut models for masonry infills confined by steel frames. The model was formulated based on a comprehensive parametric analysis. In particular, the proposed model accounted for the influence of different types of connections (*i.e.,* pinned, semi-rigid, and rigid connections), which is an essential characteristic of steel frames compared to RC frames. This study highlighted that a single diagonal strut forms at a low level of drift, which splits into several off-diagonal struts as the drift increases. The off-diagonal struts gradually converge into two main off-diagonal struts at large drifts, characterised by different widths. The main advances of this model are that the two off-diagonal struts are no longer identical (*i.e.,* different widths and mechanical properties) and that the effects of rigidity of connections are also accounted for.

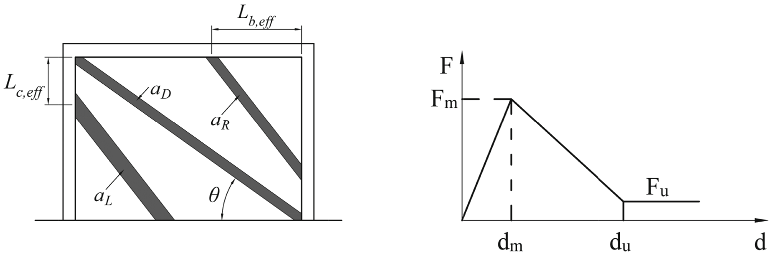


Fig. 2. Geometry and force-displacement relationship of the three-strut model developed by Pashaie and Mohammadi [12].

3 Comparisons of the Equivalent Strut Models

In this section, the aforementioned strut models are evaluated by comparison with the results of a recent pseudo-dynamic (PsD) test [13]. The structure tested was a large-scale two-storey existing steel moment frame with perimeter masonry infills constructed along the minor axis of columns. Numerical models of the steel frame were established in *OpenSees* [14], where the masonry infill walls were simulated using the two aforementioned strut models, respectively. The numerical models were then subjected to the displacement history recorded during the experimental test.

Table 1 reports the fundamental natural period of the infilled steel frame obtained numerically and experimentally, showing that the single-strut model underestimates the fundamental period by 33%, while the three-strut model overestimates it by more than 100%. Provided that accurate storey masses were used in the numerical models, the initial lateral stiffness of the infilled steel frame is greatly overestimated by the single-strut model and underestimated by the three-strut model. In addition, Fig. 3 shows the response of the numerical models against the measured behaviour of the infilled steel frame showing that both models significantly underestimate the maximum base shear.

Table 1. Fundamental period of the infilled steel frame.

	PsD test	Single-strut	Multi-strut
Fundamental period T_1 (sec)	0.144	0.096	0.327

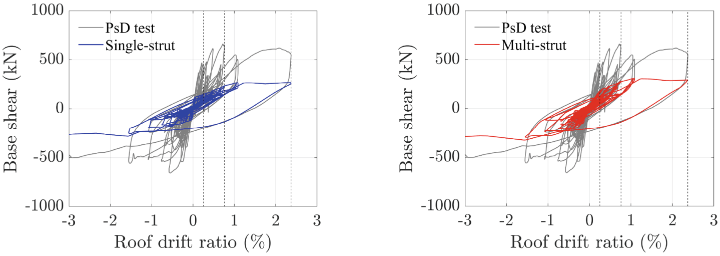
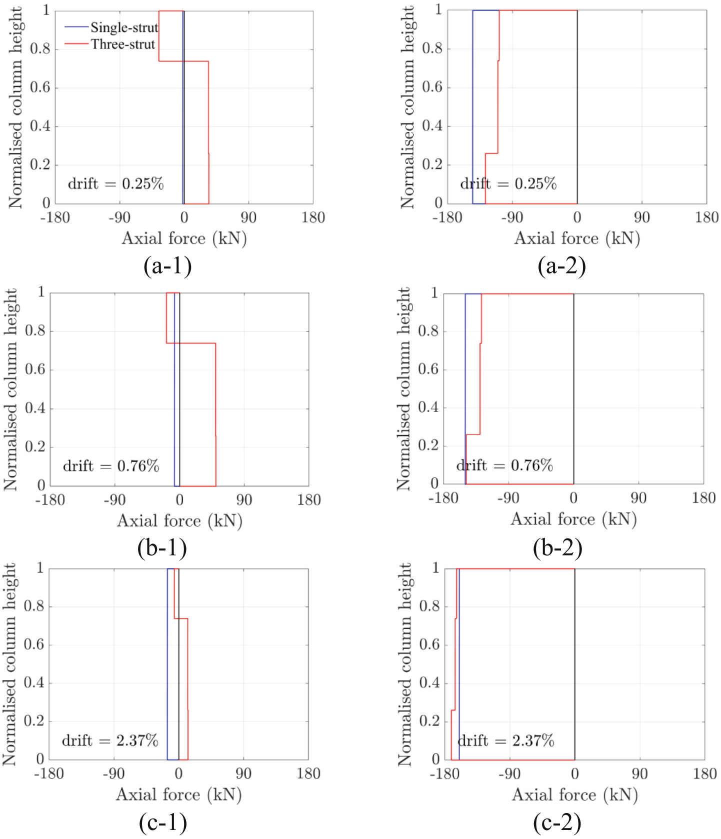


Fig. 3. Comparions between the behaviour of the numerical models and the behaviour of the test infilled steel frame.

Figure 4, 5 and 6 show the comparison of internal forces (*i.e.,* axial force, shear force, and bending moment) distribution along both the windward and leeward columns on the ground floor, considering three displacement levels, as indicated in Fig. 3, which are individually 0.25, 0.76 and 2.37% roof drift ratio. The three displacements correspond to the experimentally measured peak roof drifts of the infilled steel frame under ground motions with increasing intensity levels.

It can be seen in Fig. 4 that in general the windward column sustained considerably smaller axial loads than the leeward column. It is also noticed that the axial forces in both columns increased with increasing displacements, with the exception of the windward column in the three-strut model, where the axial force decreased at larger displacements due to the failure of masonry struts. Moreover, the off-diagonal struts also led to tension in that column outside the contact region as a result of equilibrium, while the windward column in the single-strut model was purely under compression. On the other hand, both strut models yielded similar estimation of compressive force in the leeward column. When comparing with the case of single-strut model, the maximum compression estimated by the three-strut model was initially around 10% lower at small displacements, but eventually became around 7% higher at large displacements. At 0.76% roof drift raio, nearly identical estimations of maximum compression were provided by the strut models.



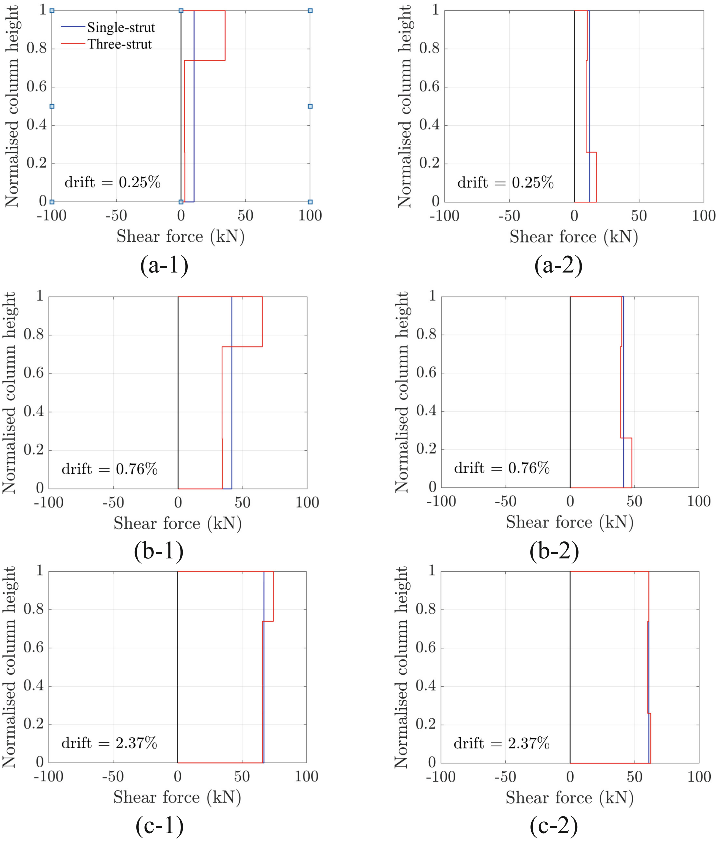
(a-1) (a-2)

(b-1) (b-2)

(c-1) (c-2)

Fig. 4. Axial force distribution of the windward (x-1) and leeward (x-2) columns on the ground floor at increasing roof drifts from (a) to (c).

Figure 5 shows the shear force distributions in columns obtained from the numerical simulations. It is found that at small displacements, the three-strut model leads to shear force over the contact length of the column (*i.e.,* the top part of the windward column and the bottom part of the leeward column) which are significantly larger than the shear force in the remaining part of the column. However, when the steel frame is subjected to larger displacements, as the masonry infills eventually lose their load-carrying capacity, the shear force distribution over the columns became more uniform. In addition, when compared with the results of the single-strut model, it can be concluded that at 2.5% roof drift ratio of the steel frame, the difference between the estimated maximum shear force is as large as 240% in the windward column, as shown in Fig. 4(a-1), and around 45% in the leeward column, as shown in Fig. 4(a-2). Nevertheless, the differences became smaller with increasing roof drifts, and as shown in Fig. 4(c) where the two strut models yield almost identical shear force distribution in both columns.



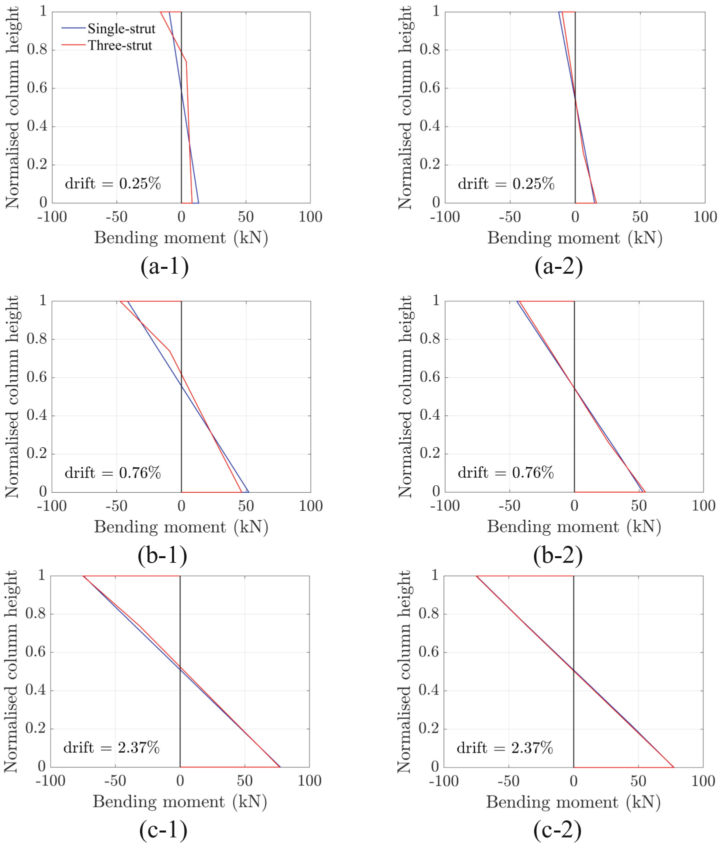
(a-1) (a-2)

(b-1) (b-2)

(c-1) (c-2)

Fig. 5. Shear force distribution of the windward (x-1) and leeward (x-2) columns on the ground floor at increasing roof drifts from (a) to (c).

The bending moment distribution reported in Fig. 6 show approximately the same trends as the shear force distribution. Firstly, at small displacement, as shown in Fig. 6 (a), the bending moment distribution obtained from the single-strut model also differs from the three-strut models. The difference between estimated moment at column base is as high as 37% in the windward column, as indicated in Fig. 6(a-1), but much smaller in the leeward column at around 10%, as shown in Fig. 6(a-2). It is also interesting to see from Fig. 6(a-1) and 6(b-1) that the inclusion of off-diagonal struts effectively increases the bending moment demand within the region of contact length of windward column, which is similar to the case of shear force demand. Lastly, as the displacement demand increases, the bending moment distribution obtained from both strut models became closer to each other after the complete failure of masonry struts.



(a-1) (a-2)

(b-1) (b-2)

(c-1) (c-2)

Fig. 6. Bending moment distribution of the windward (x-1) and leeward (x-2) columns on the ground floor at increasing roof drifts from (a) to (c).

4 Conclusions

This paper investigated the numerical modelling of infilled steel frame using both single- and three-strut models to simulate the masonry infill. Comparisons were made between a single-strut model and a three-strut model to investigate the variation of internal force distribution in columns due to the different number of struts adopted. The major conclusion was that for the case study building considered in this paper, the response of columns estimated by the three-strut model differed from the prediction of the single-strut model, when the structure was subjected to small displacement demand and the masonry struts were actively carrying the seismic loads. The differences were particularly pronounced at connections where plastic hinges were to be formed in a moment frame. However, at large displacement, the three-strut model provided fairly similar estimation of response of column to the single-strut model, which was due to the failure of masonry struts.

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