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Modeling of the lateral stiffness of masonry infilled steel moment-resisting frames

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Abstract. This paper presents an analytical model for the estimation of initial lateral stiffness of steel moment resisting frames with masonry infills. However, rather than focusing on the single bay-single storey substructure, the developed model attempts to estimate the global stiffness of multi-storey and multi-bay frames, using an assembly of equivalent springs and taking into account the shape of the lateral loading pattern. The contribution from each infilled frame panel is included as an individual spring, whose properties are determined on the basis of established diagonal strut macro-modeling approaches from the literature. The proposed model is evaluated parametrically against numerical results from frame analyses, with varying number of frame stories, infill openings, masonry thickness and modulus of elasticity. The performance of the model is evaluated and found quite satisfactory.

Keywords: masonry infills; steel frames; initial stiffness; analytical model; openings

1. Introduction

It is considered common practice, during design, to neglect the influence of infills on the structural response of frame structures, as a pro-safety procedure. However, this approach does not lead to a guaranteed outcome, especially in seismic design, when a shift of the fundamental period or stiffness irregularities may result in significantly increased seismic actions. On the other hand, modeling masonry infills for an integrated structural analysis, imposes certain difficulties in quantifying failure mechanisms and interaction phenomena between framing and infills, in addition to inherent uncertainties, related to either the characterization of the mechanical properties of masonry materials or workmanship. Thus, from a practical point of view, a quick evaluation of the expected influence of masonry infills in structural response, before a detailed and, in many cases costly, modeling effort is undertaken, would be quite helpful. In this context, a simplified analytical model for the prediction of lateral stiffness of steel moment resisting frames with masonry infills is presented herein.

Experimental testing or advanced finite element modeling of masonry infilled frames is invaluable in understanding their behavior, under either monotonic or cyclic loading conditions, particularly in terms of failure modes, influence of detailing and interaction with the framing. In comparison to the number of experimental studies for RC frames, the available data for steel frames is quite limited. Early studies, supported by experimental tests, were performed by Smith (1962, 1966). Later, Dawe *et al*. (1989), undertook an extensive experimental study on scaled and large-scale specimens. More recent contributions investigate, among others, steel frames with different types of infill blocks (Markulak *et al*. 2013), different steel bolted connection morphologies (Eladly 2017), the influence of combined lateral and vertical loading (Liu and Soon 2012, Liu and Manesh 2013, Chen and Liu 2016, Eladly 2017), the influence of infill openings (Tasnimi and Mohebkhah 2011), the behavior of repaired and reinforced masonries (Moghaddam 2004, Moghadam *et al*. 2006) and the seismic response of masonry infilled, concentrically braced frames (Jazany *et al*. 2013). Detailed and in-depth state-of-the-art reports can be found in the works by Asteris (2003, 2008), Chrysostomou and Asteris (2012), Asteris *et al*. (2011, 2013, 2017, Panto *et al*. (2018, 2019), Longo *et al*. (2018) and De Domenico *et al*. (2018).

From the earliest studies on the subject, it was recognized that the presence of masonry infills significantly alters the frame structural behavior. At first, the influence of infills was approximated with compressive diagonal struts (Polyakov 1960, Smith 1966), connecting the opposite beam-to-column joints at their centerlines. Many research studies have dealt with the width of the equivalent compressive strut. Holmes (1961) suggested a width, equal to the third of its length. Smith (1967) presented diagrams, taking into account the stiffness of the infill, relative to the column (parameter λ_h). Based on the same parameter, Mainstone (1971), proposed a formula that was included, in its revised form (Mainstone 1974), in FEMA-306 (ATC 1999) document. Many more contributions on this subject can be found in the relative literature (Hendry 1981, Liauw

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and Kwan 1984, Flanagan and Bennett 1999, Papia *et al*. 2003, Cavaleri *et al*. 2005, Amato *et al*. 2008).

Although infill modeling, with a single diagonal strut, is quite simple and straightforward to implement, it misses certain failure modes that may occur to the frame columns and beams, as a result of infill-framing interaction. Over the years, more elaborate multi-strut configurations have been proposed, such as, three strut-models, in diagonal direction (Chrysostomou *et al*. 2002, El-Dakhakhni *et al*. 2003, Yekrangnia and Mohammadi 2017) and two-strut models (Klingner and Bertero 1978). Additionally, single-struts, albeit eccentrically placed, have been proposed in order to capture corner failure modes to the column (Al-Chaar 2002). Departing from straight strut modeling, 4-node elements, consisting of bi-diagonal compression struts and shear or rigid elements, assembled in various connection schemes, have also been proposed (Crisafulli and Carr 2007, Rodrigues *et al*. 2010, Smyrou *et al*. 2011, Radić *et al*. 2016). Review studies on strut modeling of masonry infilled frames are also available by Tanganelli *et al*. (2017), Mohyeddin *et al*. (2017), Tarque *et al*. (2015), Asteris *et al*. (2011).

In the previously described strut models, the assumption of uniformity and continuity of the masonry is implied, for the transfer of compressive forces across the loaded diagonal, at least in the initial, prior to the development of crack, stage. This is not the case when openings are present, which is a common feature in most framed structures. The resulting lateral stiffness of the frame is reduced, depending on the size of the opening and its position in the panel. Models that take into account openings, either focus on restoring realistic force paths, using modified strut schemes, that bypass openings (Hamburger 1993, Kakaletsis and Karayannis 2008, Tasnimi and Mohebkhah 2011) or adjust the equivalent strut width, so that lateral strength or stiffness is calibrated (Mondal and Jain 2008, Al-Chaar 2002, Tasnimi and Mohebkhah 2011, Asteris *et al*. 2012, Nwofor 2012, Asteris *et al* 2016).

The number of research studies available on modeling of masonry infilled frames, is rather extensive. The aforementioned models, intend to describe the behavior of each infilled panel individually. However, their implementation in global frame modeling and analysis, practically requires that a finalized architectural and structural design has been achieved, so that input parameters related to framing, masonry and openings may be determined. On the other hand, there is often the need, to evaluate a number of different pre-designs. In that case, simplified methodologies that are cost-effective in terms of time and effort, are better suited, for the estimation of key response characteristics of the global structure, such as initial stiffness or base shear capacity. This study attempts to establish such a methodology, for the prediction of global initial stiffness of multi-storey frames with masonry infills. This methodology can substitute full-scale frame analysis, where the infills are modeled by equivalent struts. As such, a parametric investigation is firstly performed, employing full-scale frame analyses, of different frame configurations, as described in the following section.

Table 1 Assigned values for the examined parameters

Parameter	Values
Stories	4, 8, 10, 12
a_w(%)	0, 10, 25, 100 (bare frame)
E_w(MPa)	1150, 2255, 3400
t_w(cm)	9, 18, 27

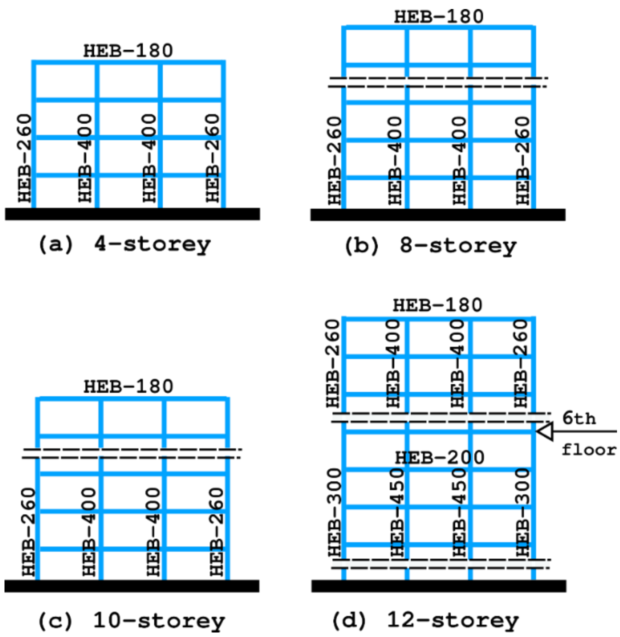

Fig. 1 Configuration of the test frames

2. Parametric analysis

2.1 Schedule

In order to evaluate the influence of masonry characteristics to the global frame behavior, and specifically to its lateral stiffness, a parametric analysis is performed. The following parameters are varied: a) the number of stories, b) the ratio of openings, a_w, c) the masonry modulus of elasticity, E_w and d) the masonry thickness, t_w. Table 1 enumerates the input values assigned to each one of the parameters. The selection of E_w values corresponds to the FEMA-306 (ATC 1999) guidelines for poor, fair and excellent masonry conditions covering a wide range of material, detailing and workmanship qualities, expected in the real structure. Similarly, the range of t_w values is quite extended, covering many common design situations. For the parametric analysis, that is performed in this paper, the masonry characteristics as well as the openings ratio are assumed constant throughout the structure. Also, the masonry is considered in full contact with its surrounding frame elements.

2.2 Design of test frames

Four 2D frames, with varying number of stories, ranging from 4 to 12 are evaluated (Table 1). Storey heights are 3m and bay lengths 5m. The frames are designed, according to Eurocodes 3 (CEN 2005a) and 8 (CEN 2004), ignoring infills, according to the commonly followed practice. The load cases, considered for the design, include both gravity and earthquake. In detail, for the gravity, uniform loads equal to 15KN/m and 20KN/m are applied to the beams, for the dead and live actions, respectively. On the other hand, seismic design is accomplished on the basis of Eurocode 8 (CEN 2004) acceleration spectrum, using the following design parameters: ground acceleration 0.24g, soil type B, behavior factor 5.0. Steel grade is S355 for all members. The software program SAP-2000 (CSI 2016) is used for the design. The lateral buckling of the beams is prevented as a possible failure mechanism, reflecting the presence of a stiff deck on top of them. Additionally, the requirements of EN1993-1-8 (CEN 2005b), for the resistance of the beam-to-column connections against shear, are checked, directly influencing the column cross-section selection. The geometry and the resulting member sections of the test frames are depicted in Fig.1.

2.3 Modeling of masonry infills

The influence of masonry infills to the global frame behavior is simulated through single diagonal compressive struts. While this method is not capable to capture nonlinear local interactions between the masonry and the column or the beam members, it is nonetheless less demanding in preprocessing effort to prepare the model, requiring quite less input parameters, compared to multi-strut models. Similarly, analysis post-processing and interpretation of the results is much less demanding. Expectedly, the multi-strut models are considered more accurate but it has also been demonstrated that the performance of single-strut models is quite satisfactory, to capture global frame response, against lateral pseudo-dynamic loading (Asteris *et al*. 2012), though at a reduced degree. Therefore, the adoption of single-strut modeling, in this work, is considered an acceptable compromise, further justified by the fact that only pre-yield state of the response is investigated.

The nonlinear force-deformation characteristic of each diagonal strut is presented in Fig. 2 (Fardis and Panagiotakos 1997). Only the compressive branch is active, while the tensile one provides a minimal non-zero stiffness, solely for numerical stability. The compressive branch on the other hand, is a multi-linear one, with its first segment representing the elastic range of the infill, with constant stiffness S_{ini}. This work focuses on the elastic response, therefore, only the initial compressive branch is of interest, however the frame analyses are performed using the complete material law (pushover analyses), in a more thorough research context.

2.3.1 Strut initial stiffness

The mechanical properties of the diagonal struts, representing a masonry infill, that is non-homogenous and multi-body structure, in a strict manner would be calculated, taking into account the properties of the individual composing materials, the bricks and the mortar, their interaction properties, along with influences from constructional workmanship and detailing. In a more pragmatic approach, the struts represent an equivalent homogenous infill, having modulus of elasticity E_w. With this assumption, the initial stiffness of the equivalent strut, can be defined as the axial elastic stiffness of an equivalent orthogonal bar, $S_{ini} = A_w E_w / d$, with length d is equal to the clear diagonal distance of the opposite beam-to-column joints, and orthogonal cross-area, $A_w = t_w w$, where t_w is the actual masonry thickness and w an equivalent infill width. For the calculation of width w, the following Eq. (1) is adopted, which was proposed by Mainstone (1974) and was included in FEMA-306 (ATC 1999):

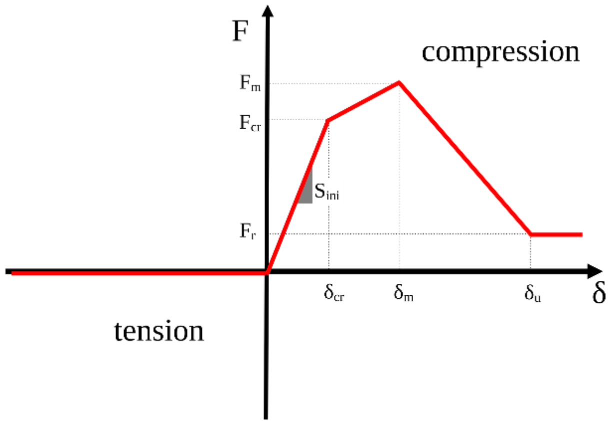

Fig. 2 Axial force-displacement characteristic of the diagonal struts

$$w = 0.175\,\lambda_h^{-0.4} d \qquad (1)$$

where λ_h is defined as:

$$\lambda_h = \sqrt[4]{\frac{E_w t_w \sin 2\theta}{4\,E\,I\,h_w}}\,h \qquad (2)$$

where h_w, the clear height of the infill, h, the storey height, $\theta = \tan^{-1}(h_w/L_w)$, L_w, the clear horizontal length of the infill, and *E, I*, the steel column modulus of elasticity and moment of inertia, respectively.

The above relations are valid for infills without openings. When openings are present the mechanical properties of the infill are significantly affected, depending on the proportion of the opening area, in relation to total infill panel area. Asteris *et al.* (2012) proposed an equivalent strut width for infills with openings, based on the well-established Eq. (1), but reduced through an empirical coefficient, λ, given by the next expression:

$$\lambda = 1 - 2\,a_w^{0.54} + a_w^{1.14} \qquad (3)$$

where a_w, the ratio of the opening area to the infill panel total area.

The multiplied by λ, width w, is applied in this work, when modeling masonry infills with openings.

2.4 Analysis results

Pushover analysis is performed, with gravity loads, imposed on the beams, preceding the application of lateral load. The lateral loading profile is uniform along the structure height. In the context of this paper, only the initial

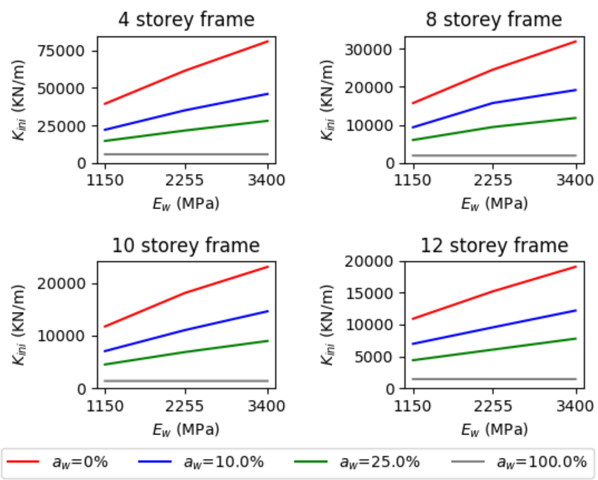

Fig. 3 Global frame lateral initial stiffness vs. masonry modulus of elasticity E_w from the pushover analysis results

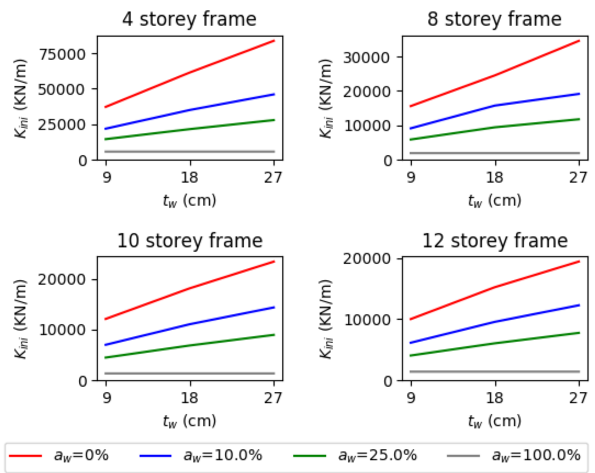

Fig. 4 Global frame lateral initial stiffness vs. masonry modulus of elasticity t_w from the pushover analysis results

stiffness of the pushover, base shear vs. roof drift ratio, curve is required. This is extracted from the whole curve, systematically, at a point where the internal equilibrium of diagonal struts has shifted from the gravity load pattern to the lateral one. No deterioration of the strut stiffness is modelled, assuming that in the context of the initial loading phase, that is of interest, no cracking has been occurred to the infills.

The diagrams in Fig. 3, illustrate how lateral initial stiffness, from all test frames is affected, as a function of the masonry modulus of elasticity E_w, for various ratios of openings a_w, while Fig. 4 illustrates the same diagrams, as a function of masonry thickness t_w. All other parameters are kept unchanged and specifically, for the vs. E_w diagrams, masonry thickness t_w is fixed to 18 cm, while for the vs. thickness t_w diagrams, masonry modulus of elasticity E_w is fixed to 2255 MPa.

The results indicate an almost linear increase against both E_w and t_w, of the lateral initial stiffness, uniformly for all frames and opening ratios. Compared to the bare frames, the masonry infilled frame lateral stiffness seems drastically increased, reaching ratios up to 17, if no openings are present. The influence of openings seems also very important. Even when their surface is quite low ($a_w = 10\%$), there is a substantial drop of the global lateral stiffness, compared to the respective infilled frame, without openings, approximately equal to 40-45%.

3. Simplified model for the initial lateral stiffness

3.1 Description

The initial lateral stiffness of a masonry infilled steel frame, according to the simplified model suggested here, is the result of two deformable sources: a) the bare steel moment resisting frame and b) the masonry infills, placed in a framing with no moment resisting capacity (hinged joints), so that lateral rigidity is provided by the axial resistance of the diagonal struts (Fig. 5a). Both are subject to the same lateral deformation, so an equivalent linking between them assumes a parallel connection scheme, as shown in Fig. 5b and is described by the following formula:

$$K_{ini} = K_{fr} + K_w \tag{4}$$

where, K_{fr} is the lateral initial stiffness from the bare moment resisting frame alone and K_w is the lateral initial stiffness from the masonry infills, placed in a framing without any moment resisting capacity.

The prediction of term K_w, is based on the schematic spring model, shown in Fig. 6. The infills belonging to the same storey, are represented by a single spring, having an equivalent stiffness $k_{st,i}$, modified by a multiplier s_i. These storey springs are connected in series and accordingly, equivalent stiffness K_w can be found from the following expression:

$$K_w = h \frac{1}{\sum_{i=1}^{N} \frac{1}{s_i k_{st,i}}} \tag{5}$$

where $k_{st,i}$ is the equivalent stiffness of storey i spring, s_i is a multiplier, for storey i, compensating for the different load applied to it, N is the number of stories and h is a correction factor, compensating for any portion of the applied lateral load that is transferred to the ground, through framing alone. Assuming a uniform lateral load, as implemented in our numerical study, it is taken equal to $N/(N-0.5)$.

The stiffness $k_{st,i}$ is the combined result of individual infilled panel stiffnesses in storey i. It is considered that all panels in the same storey are subject to the same lateral deformation, so a parallel connection scheme is employed (Fig. 7) to determine the equivalent stiffness $k_{st,i}$:

$$k_{st,i} = \sum_{b=1}^{nb} k_b \tag{6}$$

where k_b, the lateral stiffness of an individual infilled panel, at bay b, of storey i, and nb, the number of bays in

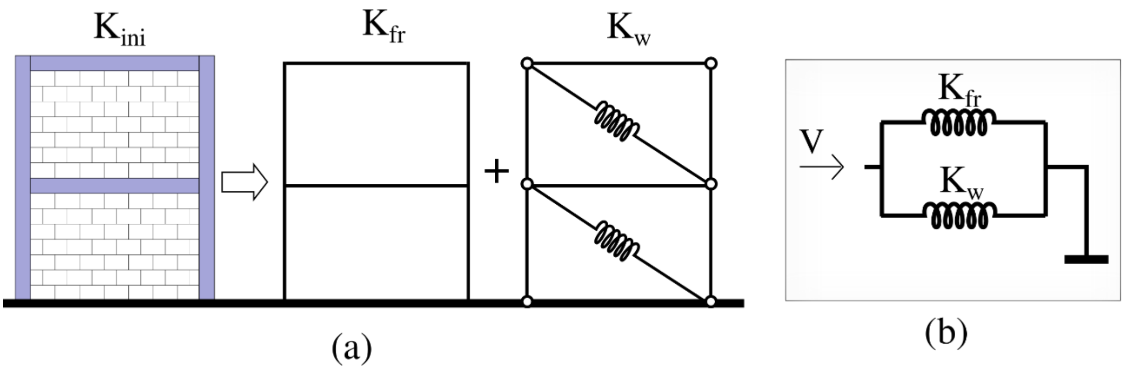

Fig. 5 Simplified model for the prediction of initial lateral stiffness K_{ini} of steel masonry infilled frames (a) and equivalent spring model (b)

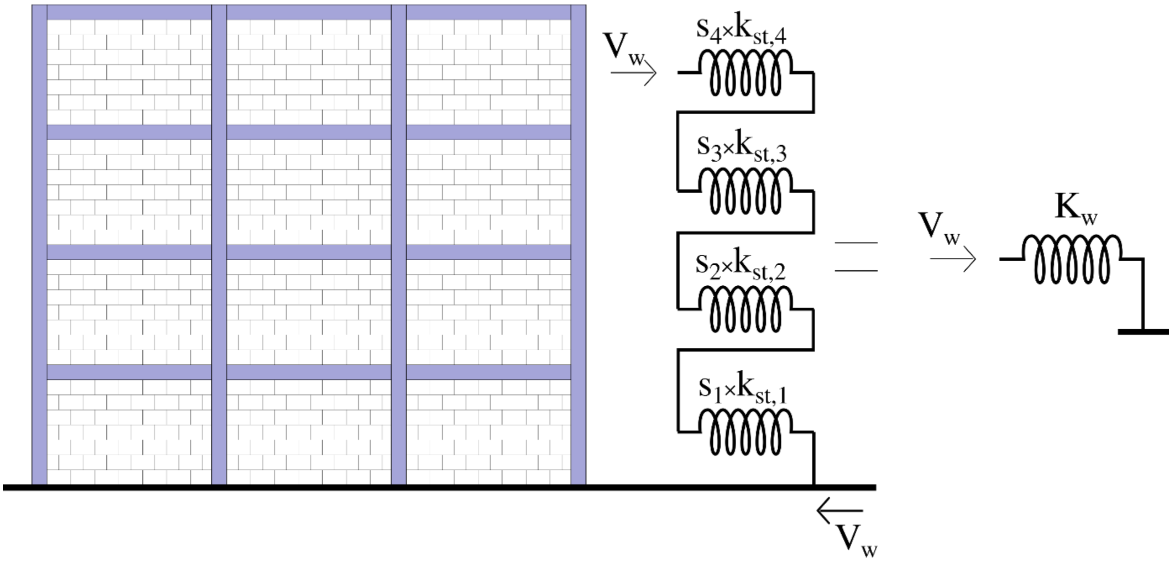

Fig. 6 Simplified model for the prediction of the component of initial lateral stiffness, K_w, contributed by infills

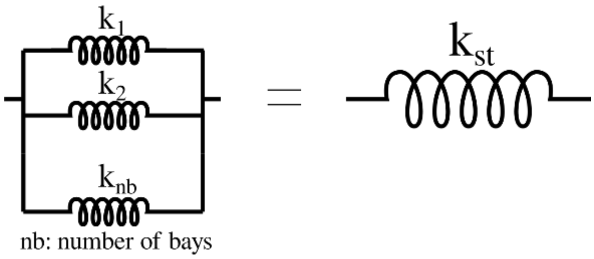

Fig. 7 Spring model for the equivalent stiffness, k_{st}, due to masonry infills in a single storey

the storey. Since the compressive strut is placed diagonally, while panel stiffness k_b is considered in a horizontal direction, a transformation of the strut axial stiffness $S_{ini,b}$ (Section 2.3.1) should be performed: $k_b = \cos^2\theta \times S_{ini,b}$.

For springs connected in series, like those in Fig. 6, it is expected that they should share a common load, through all of them. In the actual frame however, not all stories are subject to the same loading, hence the need introduce the stiffness multipliers s_i, in Fig. 6. In effect, the storey stiffness is magnified, when actually is subject to less than the total load V_w, so that a similar deformational behavior is simulated by the simplified spring model. The force through masonry in an infilled panel, under elastic conditions, is directly proportional to the lateral deformation of that panel. Therefore, appropriate values for the stiffness multipliers s_i, may be based on the distribution of interstorey drifts, along the height of the global frame:

$$s_i = \frac{1}{D(i)} \tag{7}$$

where, $D(i)$ is a shape function for the distribution of interstorey drifts on frame stories i.

Figure 8, presents the shape function $D(i)$ that is adopted in this paper, for the interstorey drift distribution of the examined test frames. Its maximum is set to unity, for stories 2 through n_1. The shape of lateral load pattern influences n_1 through the following semi-empirical procedure:

- determine and normalize to unity the function of externally applied load per storey $f(i)$; that is the sum of loads from storey i, upwards. Apparently, $f(1) = 1$ (assuming a pattern without reversed loads).
- set $f(1) = 0.5$
- distribute the difference 0.5 to the upper stories, beginning from the second one, without exceeding unity, to any of them

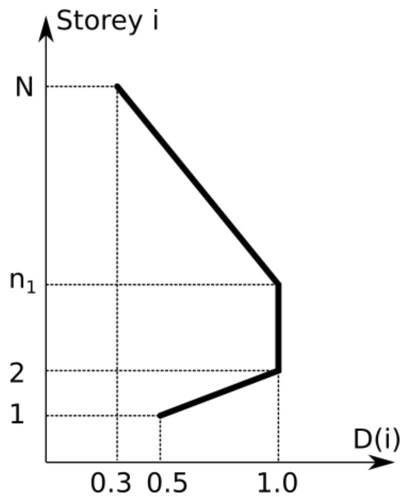

Fig. 8 Shape function $D(i)$ for the distribution of interstorey drifts

- n_1 is the upper storey, for which $f(n_1) = 1$

Based on the above procedure, the following formula can be derived, for the case of uniform lateral load pattern:

$$n_1 = \frac{1 + \sqrt{1 + 4\,N}}{2} \tag{8}$$

where *N* is the number of stories and n_1 is rounded off to the lowest integer.

An evaluation of the employed shape function $D(i)$, against the results from the numerical analyses, is presented in Fig. 9. A close match is generally evident, except for the base floor of the 4-storey frame, where the shape function underestimates recorded drifts at first storey.

4. Results

4.1 Discussion

Figures 10 and 11 display the relative error of the estimated global lateral initial stiffness, K_{ini}, according to the simplified model (Eq. 4), against the respective value from global frame analysis, for all the test frames and as varying parameters, the openings ratio a_w, and the masonry modulus of elasticity E_w or the infill thickness t_w, respectively. For the needs of Eq. (4), the lateral stiffness of the bare frame K_{fr} is found from the respective frame analysis results.

A very good performance of the simplified spring model is observed, with relative errors absolutely lower than 25%, for any combination of the varying parameters. The simplified model seems to rather underestimate the initial stiffness, particularly when openings are present. Generally, an increasing trend of the non-absolute relative error is observed, as the masonry becomes more strong, due to either a_w decrease or E_w, t_w increase. This suggests that the contributions from the framing and masonry stiffnesses are not exactly linearly additive, as proposed by Eq. (4). Nevertheless, for the extended range of parametric values examined here, the achieved accuracy is considered quite satisfactory, considering the simplicity of the model. The model performance for varying the number of stories seems consistent. Higher frames exhibit a more steep increase of the non-absolute relative error, for stronger masonry.

Table 2 Differentiated parameters for the verification study

Name	Differentiated parameter
LONG	bay length = 8m
5-BAY	five bays per storey
1-BAY	one bay per storey
G-HIGH	gravity loads: dead=30KN/m, live=40KN/m
G-LOW	gravity loads: dead=7.5KN/m, live=10KN/m
TRI	triangular load pattern

Table 3 Lateral initial stiffness, K_{ini} estimation for the verification study (in KN/m)

Name	Numerical	Model	% Error
LONG	33335	30849	-7%
5-BAY	44230	39623	-10%
1-BAY	5735	7123	24%
G-HIGH	28130	26128	-7%
G-LOW	16950	18415	9%
TRI	16400	20359	24%

4.2 Verification study

In this section, the proposed model is verified against numerical results, for frame configurations that are quite different than the parametric ones, used for calibration and evaluation. Specifically, the differentiated parameters are:

- the bay length
- the number of bays
- the gravity loads
- the lateral load pattern

Six more frame configurations are designed, inSAP-2000 (CSI 2016), following the same principles as described in section 2.2. This time however, the number of stories is fixed to 8. Table 2 lists the modified parameter for each of the new frame configurations. Only a single parameter is modified each time.

The final designs for the new frame configurations are illustrated in Fig. 12. The frames are designed neglecting infills. Next, the frames are analyzed with infills added, using pushover analysis, in order to determine their initial stiffness numerically. For the masonry infills, no openings are considered, while their properties are kept constant to these values: t_w=18cm and E_w=2255MPa.

Table 3 lists the calculated values of lateral initial frame stiffness, from the numerical models as well as the proposed simplified model. The simplified model seems consistent in its performance, achieving quite reasonable estimates. Worst relative error is 24%, for the single bay frame and the frame with triangular lateral load pattern.

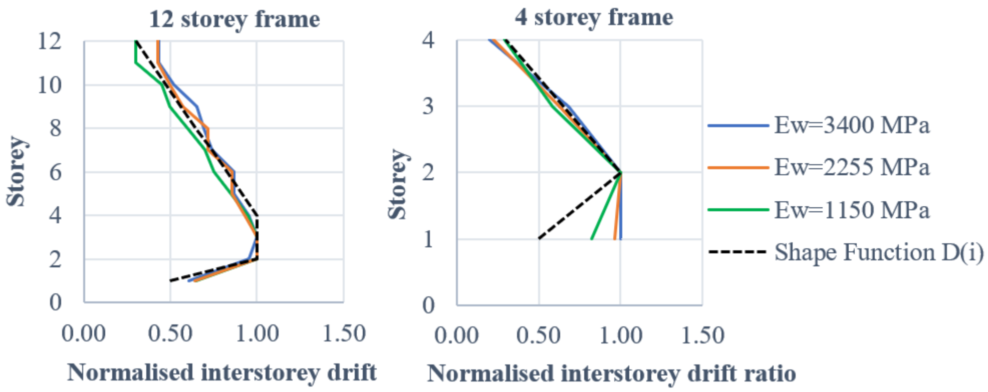

Fig. 9 Evaluation of shape function $D(i)$, against numerical frame analysis results

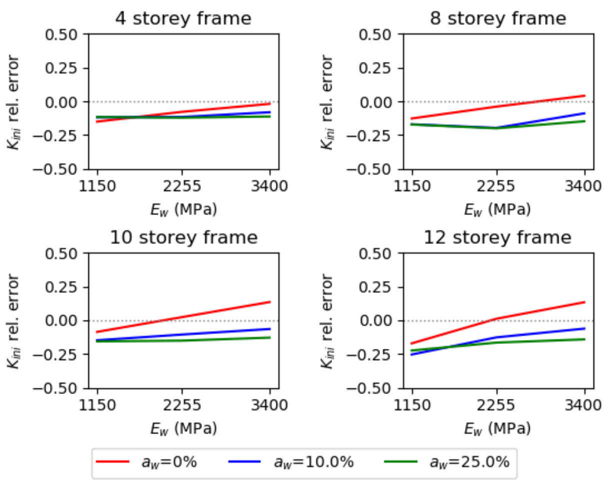

Fig. 10 Relative error on the estimation of K_{ini} vs. masonry modulus of elasticity E_w and opening ratio a_w

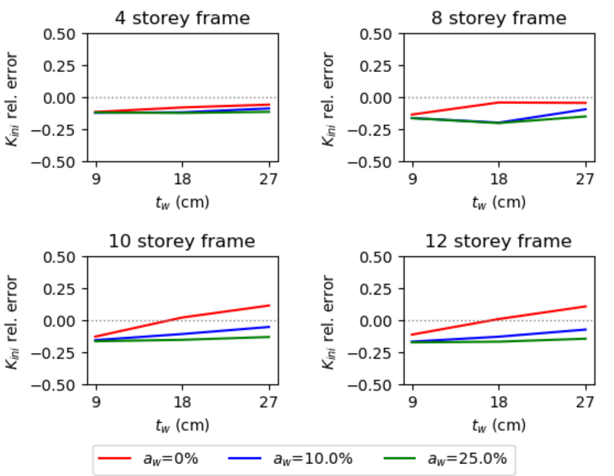

Fig. 11 Relative error on the estimation of K_{ini} vs. masonry modulus of elasticity t_w and opening ratio a_w

5. Conclusions

A simplified analytical model, for the estimation of the global lateral initial stiffness, of moment resisting frames, with masonry infills, has been described in this paper. The model has been evaluated against numerical results, from global frame analyses, parametrically, for different number of stories, opening ratios and masonry properties. Also, it has been verified against significantly differentiated frame configurations. The main findings of the research presented can be summarized in the following key points:

- the performance of the proposed model is quite satisfactory. The mean relative error is -10%, against all the test frame configurations, while its standard deviation is 0.08. The absolute maximum error is 25%. Practically, similar accuracy was achieved for the range of frame stories examined.
- the proposed model requires no complex calculations. It permits calculations by hand or it may be easily implemented in a spreadsheet. Therefore, it can be used at early stages of a project, to obtain a quick yet effective evaluation of different design solutions.
- the performance of the proposed model is consistent even for diverse frame configurations and loading patterns. No significant impact to the accuracy of the model has been detected, due to different bay lengths or gravity loads. For triangular loading pattern, which is more appropriate for seismic conditions, the error is higher, however within reasonable limits. Nevertheless, this issue deserves additional research and will be the subject of future investigations.
- even though it is not within the scope of this paper, it should be noted that the impact of the masonry infills, in relation to the lateral stiffness of the moment resisting steel frames, is drastic; increases over 15 times the bare frame stiffness have been detected in the numerical results and were closely matched by the proposed model. It is also confirmed that infill openings substantially affect frame stiffness. Even for low a_w ratios, reductions about 40-45% in lateral stiffness were recorded.

The evaluation of the proposed model was accomplished against regular frames, with uniform infill properties, throughout all their panels. No deterioration of the infill characteristics was considered. More research is necessary for frames with irregularities in their structural form or masonry, particularly in cases, where a soft-storey is formed. This will also be examined in a future investigation.

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