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Effect of openings on infilled frame stiffness

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Professional paper

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Effect of openings on infilled frame stiffness

It is widely known that the stiffness and strength of frames increases by incorporation of masonry infill panels without openings. The behaviour of partly infilled reinforced-concrete frames is analysed, taking into account dimensions and locations of openings. A numerical parametric study of infilled reinforced-concrete frames is conducted, with an emphasis on wall dimensions, and dimensions and locations of openings. An appropriate analytical expression is presented for estimating the reduced stiffness of an equivalent diagonal compression strut.

Key words:
masonry infill wall, reinforced concrete frame, evaluation of stiffness reduction, opening ratio, opening location

Stručni rad

Fatih Cetisli

Utjecaj otvora na krutost ispunjenih okvira

Poznata je činjenica da se krutost i nosivost okvira povećava ugradnjom zidanih ispuna bez otvora. U ovom se radu analizira ponašanje djelomično ispunjenih armiranobetonskih okvira, pri čemu se u obzir uzimaju dimenzije i lokacije otvora. Provedena je numerička parametarska analiza ispunjenih armiranobetonskih okvira, s naglaskom na dimenzije zida te na dimenzije i lokacije otvora. Za procjenu reducirane krutosti ekvivalentne tlačne dijagonale u radu je dan odgovarajući analitički izraz.

Ključne riječi:
zidana ispuna, armiranobetonski okvir, procjena reducirane krutosti, koeficijent otvora, lokacija otvora

Fachbericht

Fatih Cetisli

Einfluss von Öffnungen auf die Steifigkeit ausgefachter Rahmen

Es ist bekannt, dass Mauerwerksausfachungen ohne Öffnungen Steifigkeit und Tragfähigkeit von Stahlbetonrahmen erhöhen. In dieser Arbeit wird das Verhalten von teilweise ausgefachten Rahmen analysiert, wobei Dimensionen und Position der Öffnung betrachtet werden. Parametrische numerische Analysen ausgefachter Stahlbetonrahmen wurden durchgeführt, mit dem Schwerpunkt auf Mauerwerksdimensionen, sowie Dimensionen und Position der Öffnung. Eine analytische Formel zur Bewertung der reduzierten Steifigkeit des diagonalen Ersatzstabes ist dargestellt.

Schlüsselwörter:
Mauerwerksausfachung, Stahlbetonrahmen, Einschätzungen reduzierter Steifigkeit, Öffnungskoeffizient, Position der Öffnung

1. Introduction

It is quite certain that ignoring infill panels may not be a safe decision when designing earthquake-resistant structures. Various researchers have shown that the stiffness of frames dramatically increases if they are fully infilled with masonry material. Infill walls act as a compressed diagonal strut if frames are subjected to lateral loads.
Modelling problems arise in the design of structures with masonry infilled frames due to many interacting parameters such as various possible failure modes, high level of uncertainty, composite behaviour of infilled frame, etc. Numerous analytical [1-10] and experimental [11-21] studies were conducted to propose a sustainable design procedure for structures with masonry infilled frames.
As a result of these studies, single and multiple diagonal strut models were defined in design codes [22-25] in order to take into account the effect of the masonry infill wall on the lateral resistance of the reinforced concrete frame. Although numerous parameters can be used to define behaviour of a masonry infilled reinforced concrete frame subjected to lateral loads, the major affecting parameters are considered to be the ratio and location of the opening, material characteristics of the infill wall and frame, and dimensions of the infill wall and frame.
A numerical parametric study is presented in this study so as to draw attention to the issues not covered by the existing literature. The stiffness of an infill wall that does not have any openings has already been defined in several design codes [22-25]. Hence, the results of this study are simplified and reduced to the calculation of the stiffness reduction factor (λ) so that they can be used in accordance with design codes. The stiffness reduction factor (λ) is defined in the literature as the ratio of the lateral stiffness of the infill wall with an opening to the lateral stiffness of the infill wall without an opening. In this study, the term "opening" is used to define the void regions (windows, doors, ventilation orifices, etc.) in an infill wall. Hence, the opening ratio (λ) is used to define the ratio of the area of void region to the area of fully infilled wall. As a result of this numerical parametric study, a new empirical formula (λ) is proposed to estimate the reduction in stiffness of the masonry infilled reinforced concrete frame due to the presence of openings, taking into account dimensions of the structural frame (L/h ratio), the location and the ratio of the opening (α).

2. Background

As mentioned in the introduction, several analytical, numerical, and experimental studies were conducted by various researchers in order to clarify the behaviour of the masonry infilled reinforced concrete frames subjected to lateral loads. The infill wall effect on the resistance of the reinforced concrete frame subjected to lateral deformations is simplified to the stiffness of a single or multiple diagonal struts. A detailed review of such studies is summarized by Moghaddam and Dowling [26] and Asteris et al. [27]. The clarification of some affecting parameters has led researchers to focus on and detail the behaviour.
Mondal and Jain [28] studied lateral stiffness of masonry infilled frames with central openings. A parametric study on a single-storey, single-bay frame was conducted by using the FEM. The influence of the cracked-uncracked flexural rigidity, separation at the frame-infill interface, and flexibility of end-offsets, was studied to provide a methodology in order to use the FEM while modelling frames infilled with masonry material. A linear relationship was proposed in order to present the effect of the opening ratio (α) on the stiffness reduction factor (λ)

$$\lambda = 1-2.47 \cdot \alpha \tag{1}$$

An early study on the effect of an infill wall opening subjected to lateral loads was presented by Syrmakezis and Asteris [29]. Syrmakezis and Asteris investigated the effect of the location and opening ratio through the linear-elastic analysis of a one-storey single-bay frame. They applied a lateral load in one direction and neglected the seismic oscillation effect. Hence, according to results presented by Syrmakezis and Asteris [29], if the opening is not on the diagonal and located in the corners (close to beam-column joints), the infill wall provides more resistance to lateral load.
Asteris et al. [30] proposed a simple formulation (polynomial) defined as the "stiffness reduction factor" Eq.(2), resulting from a numerical study (FEM). The stiffness reduction factor (α) is varied with the infill panel opening ratio (λ) in a single reinforced concrete frame infilled with masonry wall having a central opening. Similar to Asteris et al. [30], Nwofor [31] studied the relationship between the stiffness reduction factor (λ) and the opening ratio (α) for central openings in masonry infilled reinforced concrete frames. The stiffness reduction factor was defined in an exponential form Eq.(3). The effect of the location of the opening on the stiffness reduction factor was also studied by Nwofor [31] for three cases: opening position underneath, on, or above the compressed diagonal. Another study on the effect of the ratio and the location of the opening in a masonry infilled reinforced concrete frame was conducted by Rathi and Pajgade [32]. Similar to previous studies, Rathi and Pajgade [32] also defined three cases for the location of the opening in an infill wall without taking into account the oscillation effect of the earthquake. Both Nwofor [31] and Rathi and Pajgade [32] considered the lateral load applied in one direction only and, hence, they neglected the formation of strut when the movement is in the opposite direction.

$$\lambda = 1-2 \cdot \alpha^{0,54} + \alpha^{1,14} \tag{2}$$

$$\lambda = 0.95 \cdot e^{0,03 \cdot \alpha} \tag{3}$$

As mentioned previously, the effect of the opening ratio and the location of the opening in masonry infilled reinforced concrete frames on the lateral resistance of the frame were discussed by some researchers (i.e. Nwofor [31] and Rathi and Pajgade [32]). However, in these studies, the oscillation effect of the earthquake was not considered when the location of the opening was defined. They considered the applied lateral load in one direction; hence they neglected the formation of strut when the movement is in the opposite direction. Besides, the effect of frame dimensions on the stiffness reduction factor was also not discussed. These missing issues are taken into the consideration in the present study.

3. Analysis of the wall opening location effect

The effect of the location of the opening and dimensions of the infill wall on the stiffness reduction factor was studied through a finite element analysis (FEA). A non-linear analysis was performed on a planar single-storey single-bay masonry infilled reinforced concrete frame (with or without opening) using the SAP2000 software [33], in accordance with provisions contained in FEMA 356 [34]. Results were analysed in order to propose a simple empirical formulation for calculating the stiffness reduction factor in case an opening is present. The dimensions of the wall (L/h – wall length to wall height ratio for a constant wall height), the location of the opening, and the ratio of the opening area to the full infill wall area, were varied.

3.1. Development of the model

The diagonal compression strut, associated with the pounding effect of the reinforced concrete frame on the infill wall, was simulated in FEA in order to investigate stiffness of the masonry infill wall with an opening. Hence, the single-storey single-bay planar (X-Z) reinforced concrete frame used in the analyses had the constant storey-height of 275 cm. However, the bay lengths (from c.g. of the columns) of the frame varied and amounted to 210, 330, 390, 450, 570, and 750 cm (Figure 1).

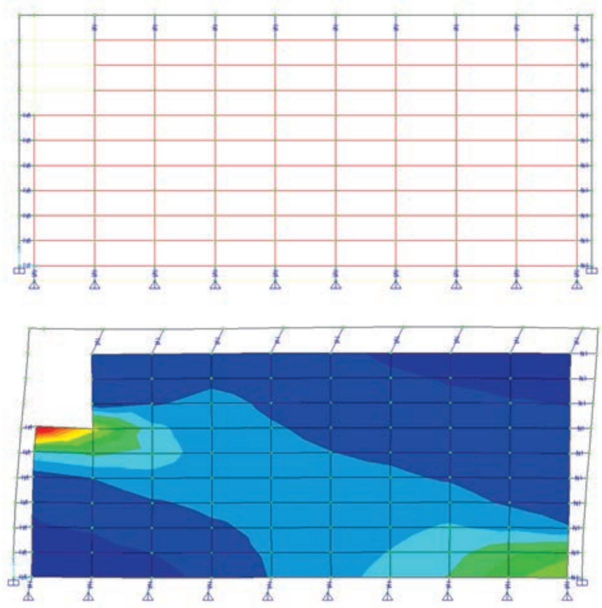

Figure 1. Undeformed and deformed view of the model (case 411)

The frame consisted of two 30 x 30 cm square columns and a 25 x 50 cm rectangular beam. The columns and beam were defined using straight frame sections. Although the stiffness of the bare frame was subtracted from the total stiffness of the infilled frame in order to determine the stiffness of the infill wall, minimum section requirements had to be satisfied. Hence 30 x 30 cm square columns were preferred as the vertical structural member. Similarly, the minimum width requirement was used for the beam. 50 cm was chosen for the depth of the beam, which is a common size that is used in the construction of building type structures [35, 36]. Since the beam cross-sections are commonly constant in a single building type structure, and as only the stiffness of the infill wall was considered in the analyses (by subtracting the stiffness of the bare frame), the same cross-sections were used for columns and beams in the analysis matrix.

Table 1. Material Characteristics

Characteristics [MPa]	**Concrete**	**Infill wall**	**Reinforcement Gr60**
Modulus of elasticity	25000	1500	200000
Compressive strength	30	5	620
Tensile strength	3,4	0,0	620
Poisson's ratio	0,2	0,2	0.00
Yield strength	---	---	420
Expected yield strength	---	---	455
Expected tensile strength	---	---	680

Two groups of reinforcement details were taken into consideration in order to investigate the effect of reinforcement details on the stiffness reduction factor. For the first group (Group 1 reinforcement), a total of eight ϕ20 longitudinal bars were used in the whole column cross-section, and these bars were equally distributed along each side of the column. The beam was reinforced using five ϕ20 longitudinal bars throughout the length of the beam at both the top and the bottom faces. Both the columns and the beam were confined using ϕ6 tie-bars spaced at 15 cm intervals along the entire length. The second group reinforcement (Group 2 reinforcement) consisted of a total of eight ϕ28 longitudinal bars, which were used throughout the column cross-section, and were equally distributed along each side of the column. Finally, ϕ12 tie-bars were spaced at 15 cm intervals throughout the length.

The reinforced concrete frame material was defined as C30 (30 MPa) concrete and Gr60 steel reinforcement (Table 1). The uniaxial compression (-) and tension (+) concrete material model, developed and used by SAP2000 in the analyses, is presented in Figure 2. Strain values presented in Figure 2 are in the range of 10^{-3} mm/mm. The uniaxial compression (-) and tension (+) steel reinforcement material model, developed and used by SAP2000 in the analyses, is also presented in Figure 2.

The dimensions of the masonry wall bricks can vary highly in practice depending on the material type, technical qualifications of the country, and producers. Besides, the mesh profile and mesh element dimensions have always been considered as relevant parameters in FEA. The mesh element dimensions were chosen to represent a lightweight masonry brick type that is commonly used in Turkey for construction of exterior walls. Hence, the mesh profile was drawn by using 60 x 25 cm plane-stress area sections, 20 cm in thickness, in order to represent 1/1 scaled dimensions of the considered brick type (60 x 25 x 20 cm). The wall length to the wall height ratios (L/h) were 0.80, 1.33, 1.60, 1.87, 2.40, and 3.20. Special joints were drawn on the frame parallel to each corner of the area sections. The characteristics of the masonry infill wall material are listed in Table 1 and presented in Figure 2. It was assumed that the infill wall doesn't have a tensile load-carrying capacity while modelling the material as elastic-brittle material.

The cracking of concrete or infill wall was not considered in the analyses. Hence the opening and closing of cracks were not studied. But the separation at the interface between the reinforced concrete frame and the infill wall was modelled using gap elements.

3.2. Analysis options

The interaction between the reinforced concrete frame and the infill wall was defined by two-joint link elements. The two-joint link elements were defined as gap (contact) elements with a zero gap and the 1.0E8 N/mm^2 stiffness, which allows separation between the reinforced concrete frame and the infill wall in case tensile forces occur at the interface between the frame and the infill wall [33, 37]. According to the Analysis Reference Manual SAP2000 [33], the use of gap elements having very stiff properties is recommended when modelling the pounding effect (in which the compression (-) is the only case). In addition, the effective stiffness for gap elements should be defined as zero and the non-linear stiffness property for a given degree of freedom should be defined. Hence, unidirectional (longitudinal direction of link element in the present study) extremely stiff gap link elements with zero gap were used in between the corners of the plane stress elements and centroids of frame elements. It was assumed that the frame elements were not deformed in the cross-sectional plane due to the pounding effect.

Since the reinforced concrete frames are mostly used in structures constructed with a reinforced concrete slab, a rigid diaphragm constraint was defined for the beam-column joints of the frame. The columns were restrained with a fixed support. The translation about Y axis and rotation around X and Z axes were not allowed in order to obtain a 2D analysis of the R/C frame. By defining a rigid diaphragm constraint, the shortening in the longitudinal direction of the beam was prevented, and the lateral stiffness of the frame was related to the lateral stiffness of the columns and infill wall (if any) only. Hence the pounding of one column on the infill wall, and the separation of other column from the infill wall, was provided.

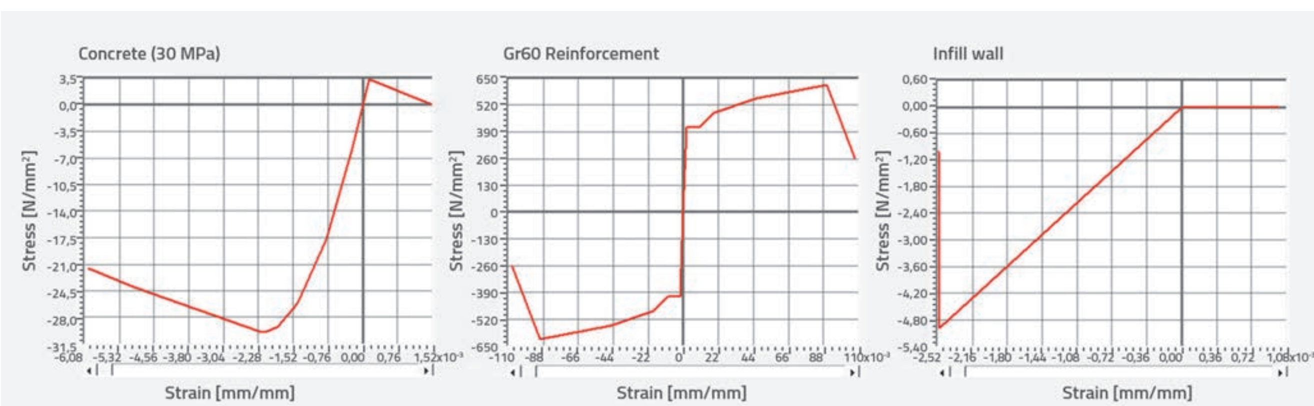

Figure 2. Material characteristics for concrete and infill wall

A non-linear static load case with displacement control (pushover analysis) was defined for the non-linear analysis of the masonry-infilled reinforced concrete frame. Beam-column joints of the reinforced concrete frame were deformed by up to 6.0 cm to observe the plastic hinges and capacity curve of the frame. The 6.0 cm drift of the beam column joints was chosen as the target displacement in order to see the complete non-linear behaviour of the structure. As a result, the formation of plastic hinges at beam, plastic hinges at columns, immediate occupancy capacity of the beam, and immediate occupancy capacity of the columns, were observed in addition to the failure of the structure, and this respectively for each analyzed case. As expected, the maximum drift at beam column joints were varied for each analyzed case. The plastic hinges were automatically generated in accordance with the FEMA 356 provisions (P-M2-M3 for columns and M3 for beam) [34].

3.3. Analysis Matrix

Since various numerical and experimental investigations have revealed that the infill masonry wall exhibits a strut effect in the frame, it was considered that the plane of the infill masonry wall exists of nine regions (Figure 3) in order to investigate the opening location effect on the resistance of the infill masonry wall.

Because the earthquake load is a reversible effect on a structural frame, the formation of the strut changes in accordance with the direction of the lateral deformation and different regions exhibit

Table 2. Analysis Matrix

ID	L/h	O.L.	O.R.	ID	L/h	O.L.	O.R.	ID	L/h	O.L.	O.R.
1bare			100.00	2bare			100.00	3bare			100.00
1full			0.00	2full			0.00	3full			0.00
111			4.44	211			3.70	311			3.17
112		1(BCJ)	13.33	212		1(BCJ)	14.81	312		1(BCJ)	15.87
113			17.78	213			18.52	313			19.05
121			4.44	221			3.70	321			3.17
122		2 (MB)	13.33	222		2 (MB)	14.81	322		2 (MB)	15.87
123	1.33		17.78	223	1.60		18.52	323	1.87		19.05
131			4.44	231			3.70	331			3.17
132		3 (MC)	13.33	232		3 (MC)	14.81	332		3 (MC)	15.87
133			17.78	233			18.52	333			19.05
141			4.44	241			3.70	341			3.17
142		4 (C)	13.33	242		4 (C)	14.81	342		4 (C)	15.87
143			17.78	243			18.52	343			19.05
ID	**L/h**	**O.L.**	**O.R.**	**ID**	**L/h**	**O.L.**	**O.R.**	**ID**	**L/h**	**O.L.**	**O.R.**
4bare			100.00	5bare			100.00	6bare			100.00
4full			0.00	5full			0.00	6full			0.00
411			3.70	511			3.70	611			3.70
412		1(BCJ)	14.81	512		1(BCJ)	14.81	612		1(BCJ)	14.81
413			18.52	513			18.52	613			22.22
421			3.70	521			3.70	621			3.70
422		2 (MB)	14.81	522		2 (MB)	14.81	622		2 (MB)	14.81
423	2.40		18.52	523	3.20		18.52	623	0.80		22.22
431			3.70	531			3.70	631			3.70
432		3 (MC)	14.81	532		3 (MC)	14.81	632		3 (MC)	14.81
433			18.52	533			18.52	633			22.22
441			3.70	541			3.70	641			3.70
442		4 (C)	14.81	542		4 (C)	14.81	642		4 (C)	14.81
443			18.52	543			18.52	643			22.22

O.L. – opening location, O.R. – opening ratio (%)

similar behaviour (Figure 3). Hence, the nine regions of the infill wall plane can be reduced to four, which are shown in Figure 4 as 1 (BCJ) beam-column joint corner (Region 1, Region 3, Region 7, and Region 9), 2 (MB) mid-span of the plane adjacent to the beam (Region 2 and Region 8), 3 (MC) mid-height of the plane adjacent to the column (Region 4 and Region 6), and 4 (C) the centre of the plane (Region 5).

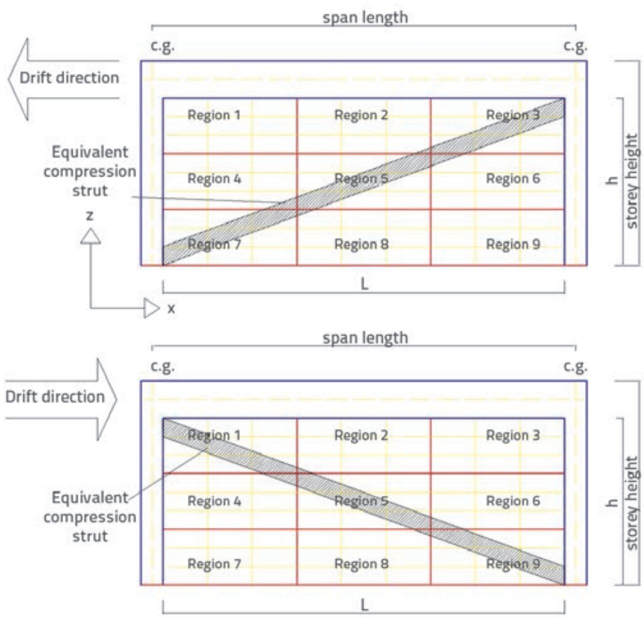

Figure 3. Equivalent diagonal compression strut effect of infill wall

Figure 4. Model for analysis matrix

It is a common fact that the span lengths can vary greatly in a single building type structure. According to the studies presented by Hancilar et al [35] and Ozmen et al [36], beam span lengths vary from 3.0 to 8.0 m. Hence, as presented in Table 2, six planar reinforced concrete frames were analyzed using the FEM. Three opening ratios for each of the four opening locations were studied for each of the six L/h ratios. In addition, in order to proportion the change in lateral stiffness, bare frame and fully infilled frame cases were also analyzed. Since it is known from literature that the lateral stiffness of infill wall decreases rapidly with an increase in the opening ratio, the opening ratios below 20% were taken into consideration in the present study. The opening ratios were chosen to be proportional with the infill wall block dimensions (60 x 25 cm). Hence, the studied opening ratios differed from the infill wall opening ratios commonly used in the literature. The details of the analyzed matrix are tabulated in Table 2.

4. Results and calculation of stiffness reduction factor

It was verified once again by the finite element analysis of the reinforced concrete planar frame infilled with masonry wall, with or without opening, that the contribution of the infill wall to the lateral stiffness of the frame is not negligible. However, it cannot be said that there is an easily definable relationship between the stiffness of the fully infilled frame ("full„ in Figure 5) and dimensions of the infill wall. This variation can be attributed to the single or multiple strut behaviour of the infill wall (Figure 5). Besides, the change in frame behaviour from flexural to shear for short span lengths (for L/h < 1.60 in the present study) affects resistance of the fully infilled frame. As presented in Figure 5, a slight (negligible) decrease was observed in the stiffness of the bare frame ("bare„ in Figure 5) as the span length in between the centre of gravities of the columns increased. As presented in Figure 5, "bare" and "full" are the lower and upper bounds, respectively. Since the investigated parameters (opening ratio, opening location, and wall dimensions) are coupled, it was not possible to draw a relationship for all other cases. Hence, the change in stiffness due to an infill masonry wall that has an opening was normalized with the change in stiffness due to the full infill masonry wall for all investigated parameters (opening ratio, opening location, and wall dimensions).

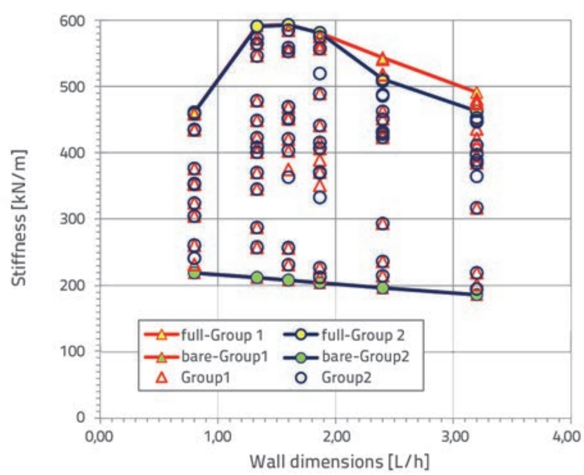

Figure 5. Effect of wall dimensions (L/h) on lateral stiffness

The lateral stiffness of the analyzed structures was determined by dividing the measured total horizontal support with the measured drift (Eq.(4)). The lateral stiffness was determined at the formation of the first plastic hinge on any of the reinforced

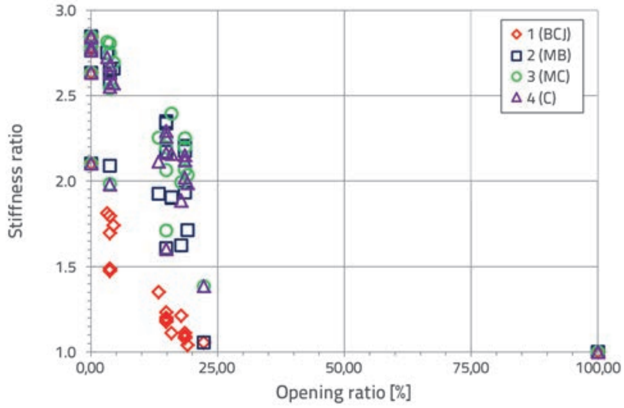

Figure 6. Effect of opening ratio on stiffness ratio

concrete frame members (Figure 5). The stiffness ratio is the ratio of the lateral stiffness of the analyzed structure to the lateral stiffness of the bare frame. The effect of the opening percentage on the stiffness ratio is presented for all analyzed cases in Figure 6 (presented for Group 1 reinforcement only).

As expected, the existence of an opening in the infill wall has an important effect on lateral resistance. The effect of the location of the opening on the stiffness ratio (ratio of stiffness of the infilled frame to the stiffness of the bare frame) is presented in Figure 7 for certain opening ratios with the variation in the dimensions (L/h ratio) of the frame. Figure 7 clearly illustrates that the stiffness ratio is extremely affected by an opening at the beam-column joint region (1 (BCJ)). In addition, if the dimensions (L/h) of the frame are less than 1.60, the masonry infilled frame becomes more sensitive to an opening in the infill wall. In order to present the stiffness reduction factor (Eq.(5)), the increase in lateral stiffness due to an infill wall without any opening was first normalized to "1" (one) after the stiffness of the bare frame was subtracted. Then, the influence of the ratios (Eq.(6)) and locations of the opening and dimensions of the infill wall was investigated.

$$\text{stiffness} = \frac{\text{total horizontal support reaction}}{\text{measured drift}} \quad (4)$$

$$\lambda = \frac{\text{stifness of frame infilled with a wall that have opening - stiffness of bare frame}}{\text{stiffness of fully infilled frame - stiffness of bare frame}} \quad (5)$$

$$\alpha = \frac{\text{area of the opening}}{\text{area of the full infill wall}} \quad (6)$$

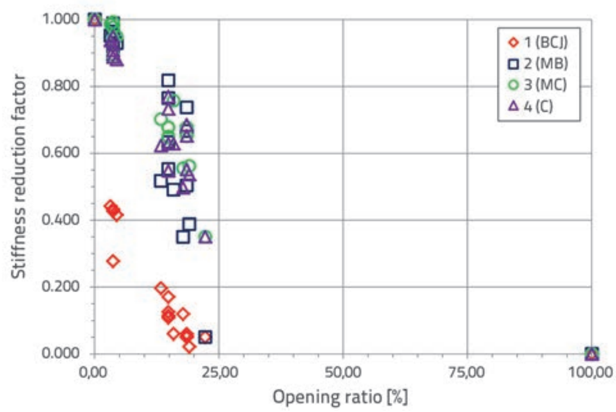

Figure 8. Variation in stiffness loss with respect to opening ratio and opening location

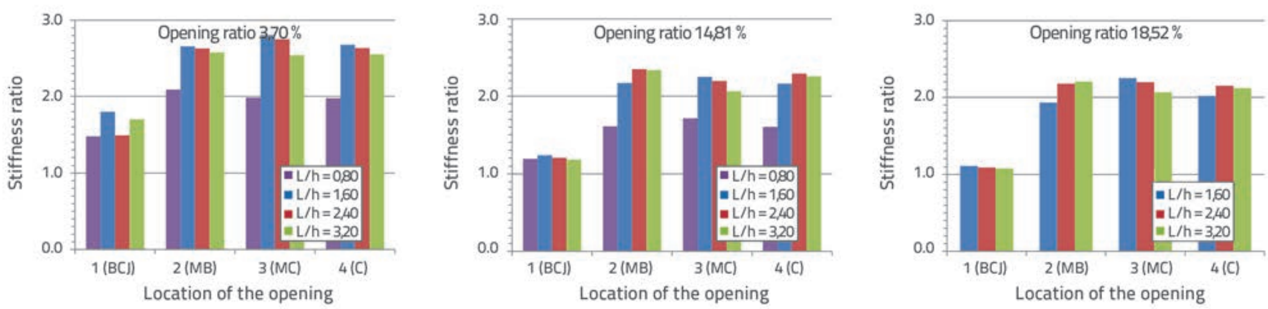

Figure 7. Effect exerted by location and percentage of opening on stiffness ratio

Table 3. Results of regression analysis for stiffness reduction factor

Parameter	Openings location	Result of regression analysis	Proposed
k_1		k_1 = 1,0084 + 0,3973 · (L/h)	k_1 = 1,0 + 0,4 · (L/h)
k_2	1 (BCJ)	0,2	0,2
	2 (MB)	0,9	1,0
	3 (MC)	1,1	1,0
	4 (C)	1,0	1,0

The results of the analyses (Figures 7 to 10) show that the opening ratio (α) is not the only parameter that affects the stiffness of the reinforced concrete frame that was infilled with masonry wall. The presented results brought the opening location (Figure 7 and 8) and the dimensions of the infill wall (L/h ratio) front in addition to the opening ratio while determining the stiffness reduction factor.

The nonlinear behavior of the infilled frame was determined in order to see the first plastic hinge formation at any of the reinforced concrete frame members with the Group 1 reinforcement detail (Figure 9). As shown in Figure 9 (only L/h = 1.60 illustrated as an example), both the opening ratio (Eq.(6)) and the opening location play an important role in nonlinear behaviour of the reinforced concrete frame infilled with masonry wall. As the opening ratio increases, the opening location plays a vital role on the resistance of the infilled reinforced concrete frame. Among four investigated locations, an opening in the beam-column joint region (1 (BCJ)) extremely affects the resistance. As the opening ratio increases, the contribution of the infill wall to the lateral resistance of the frame decreases almost to zero if the opening is located at the beam-column joint region.

A regression analysis was conducted In accordance with the results of the finite element analyses of the masonry infilled reinforced concrete frame. As a result of the regression analysis, an empirical formulation (Eq.(7)) was obtained for prediction of the stiffness reduction factor. The proposed empirical formula takes

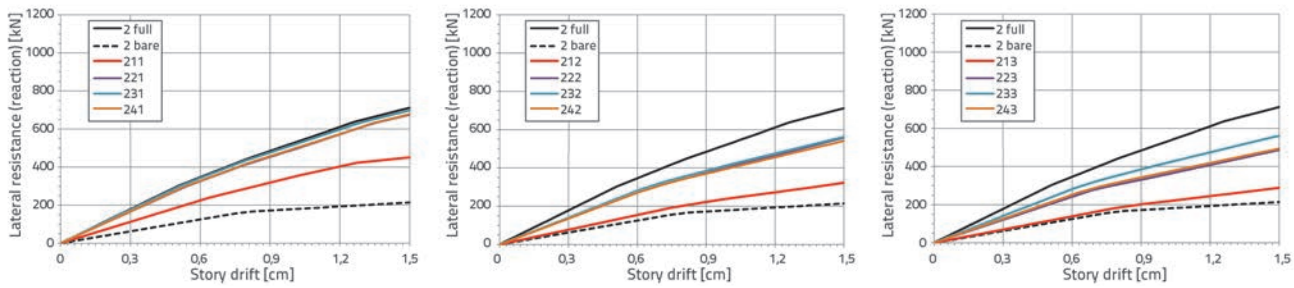

Figure 9. Effect of location and opening ratio on nonlinear behaviour (L/h=1.60)

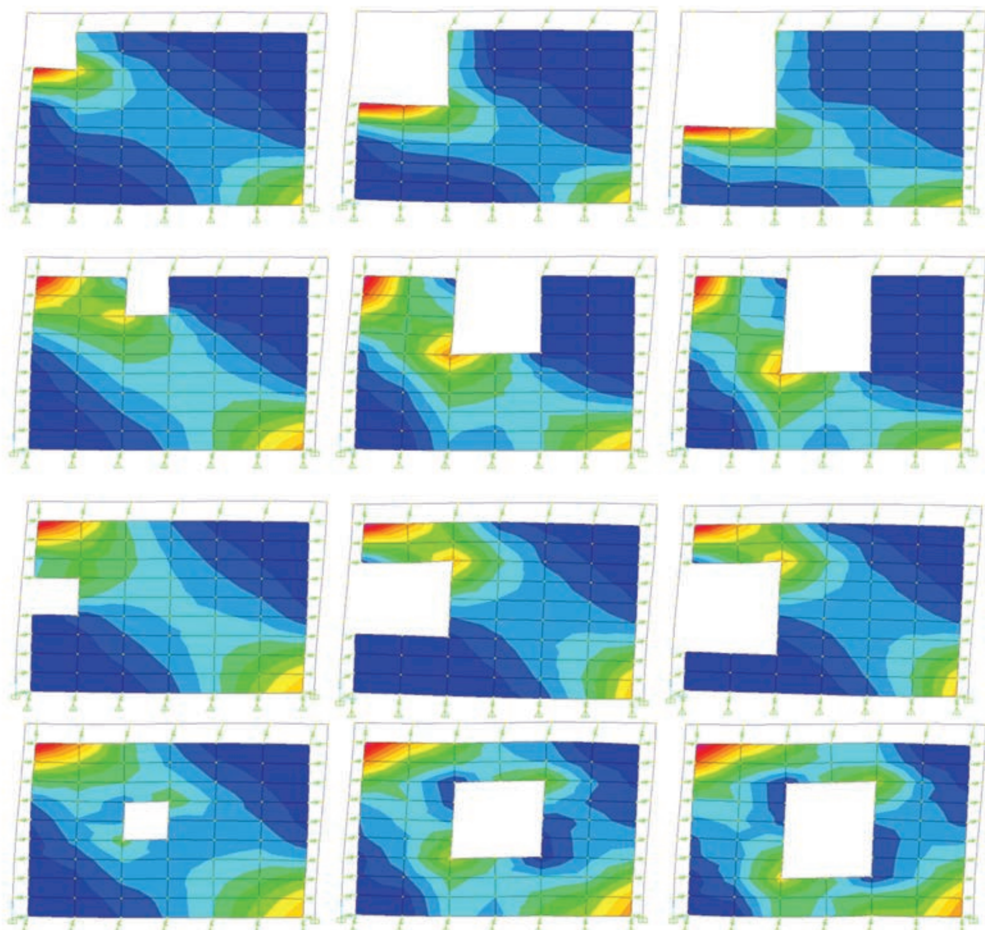

Figure 10. Stress distribution for infill wall with opening (L/h=1.60)

into account dimensions of the infill wall (L/h ratio) and location of the opening, and this in addition to the opening ratio. The effect of infill wall dimensions (L/h ratio) on the stiffness reduction factor was formulized with the constant k_1. The regression analysis showed that the effect of the dimensions of the infill wall can be simplified as a linear relationship (k_1 Eq.(8)) to be used as the power of opening ratio. The regression analysis results and the values recommended for the parameter k_1 are presented in Table 3.

The role of the opening location, which may disturb formation of the equivalent diagonal compression strut (Figure 10), is also significant. As shown in Figure 10, any opening at 1 (BCJ) (Regions 1, 3, 7, and 9) extremely disturbs formation of the equivalent compression strut. Hence, the contribution of the infill wall to the stiffness of the structure is highly limited. Although an opening

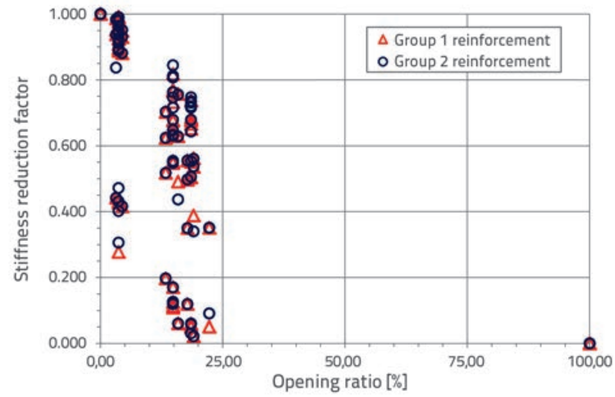

Figure 11. Effect of reinforcement detail on stiffness reduction factor

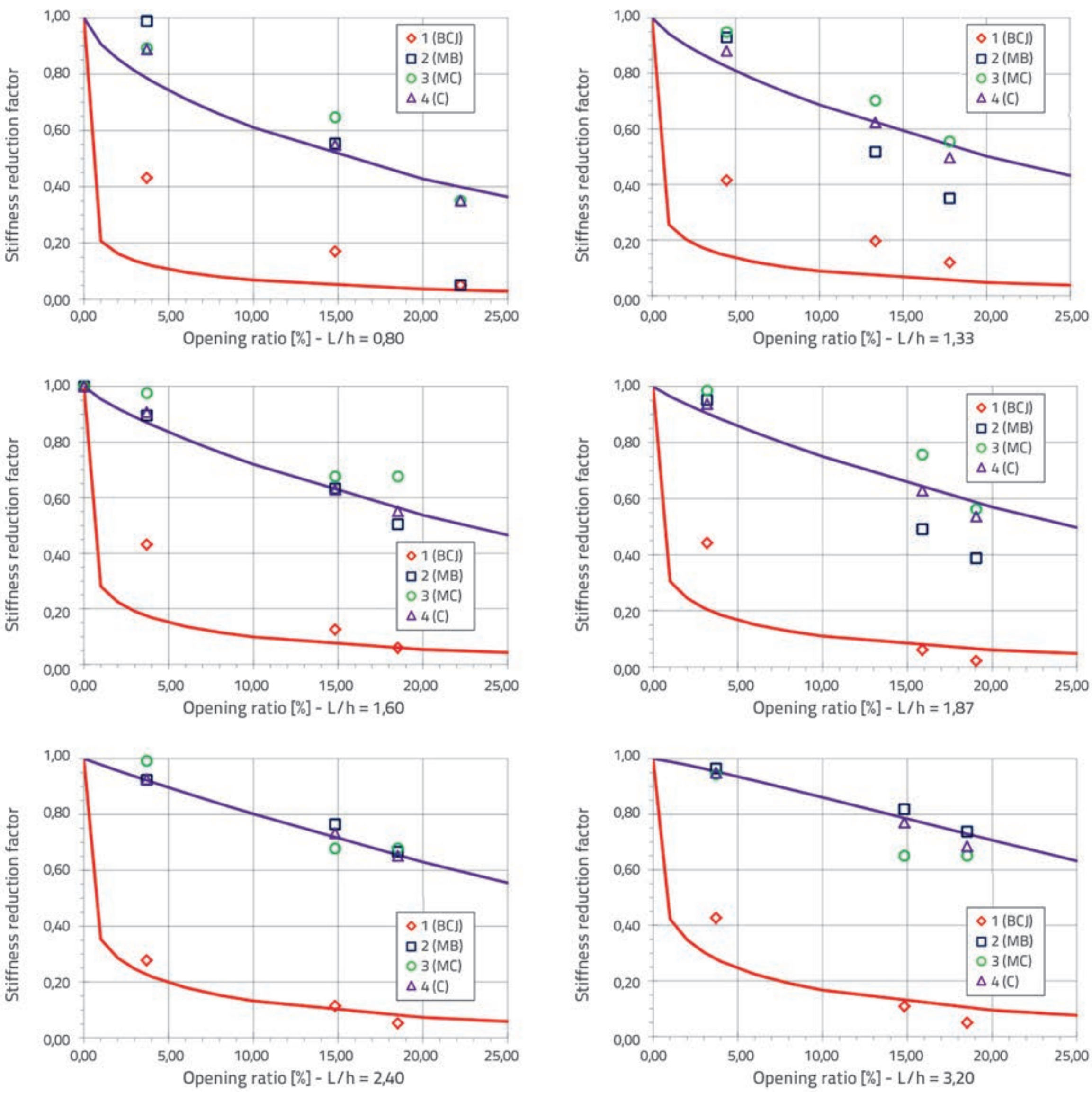

Figure 12. Proposed stiffness reduction factor (λ)

at 4 (C) (Region 5) will also be on the equivalent compression strut, the infill wall tends to behave, due to its nature, as multiple compression struts. When comparing the opening locations 2 (MB) (Regions 2 and 8) and 3 (MC) (Regions 4 and 6), the stiffness of the reinforced concrete frame infilled with masonry is more sensitive to an opening at 2 (MB) locations. In accordance with the obtained results, the effect of the opening location on the stiffness reduction factor (λ) is taken into the consideration as the constant k_2 to be used as the power of the opening ratio. The results of the regression analysis and the proposed values for the parameter k_2 are also presented in Table 3.

Although the stiffness reduction factor (λ) is affected by the opening ratio (α), opening location, and wall dimensions (L/h), it was observed that the reinforcement details of the column and the beam did not affect the stiffness reduction factor considerably (Figure 11). The proposed "stiffness reduction factor" equation, which was obtained from the multiple regression analysis in form of Eq.(7) in order to obtain the best data fit, is compared both with the finite element analyses (Figure 12 for Group 1 reinforcement) and formulations previously proposed by various researchers [28, 30] (Figure 13).

$$\lambda = 1 - 2 \cdot \alpha^{0.5 \cdot k_1 \cdot k_2} + \alpha^{k_1 \cdot k_2} \quad (7)$$

$$k_1 = 1{,}0 + 0{,}4 \cdot (L/h) \quad (8)$$

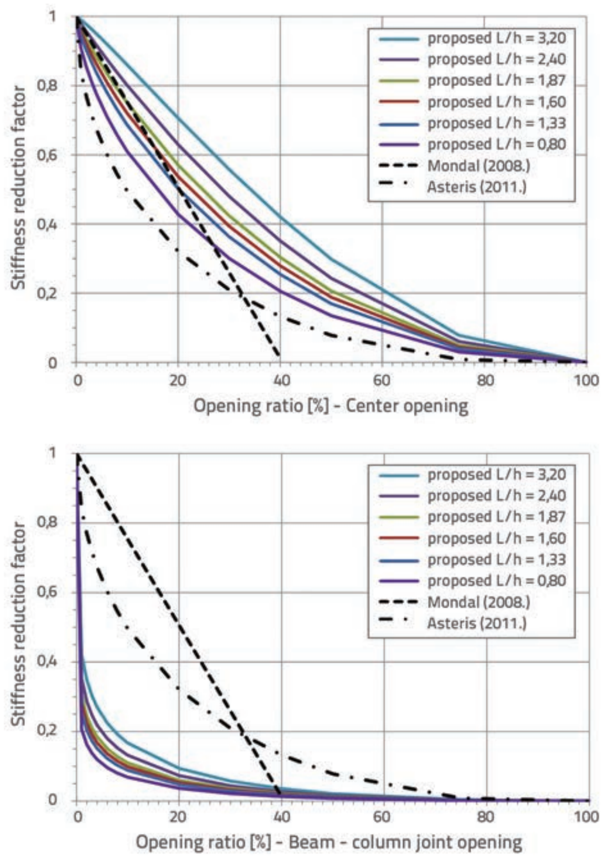

Figure 13. Comparison of proposed model (λ) and models from literature

As recommended by several codes, such as in Turkish Seismic Code [22], it can be observed that the effect of the opening (if not located at the beam - column joint) can be neglected if the opening ratio is less than 5%. The proposed reduction factor is applicable for infilled frame with normal openings. Extreme cases, i.e. cases where openings are extended to full height or full width of the infilled frame cannot be covered by the proposed equation for the stiffness reduction factor. In addition, opening dimensions may vary. The openings with narrow widths or narrow heights are not presented in this study. Hence, the proposed equation may not be valid for the narrow-width or narrow-height openings. According to these results and recommendations, the stiffness of the equivalent diagonal compression strut (k_{iw}) can be calculated using the Eq. (9), into which the proposed stiffness reduction factor (λ Eq.(7)) is incorporated,

$$k_{iw} = \lambda \frac{a_{iw} \cdot t_{iw} \cdot E_{iw}}{r_{iw}} \quad (9)$$

where

$$a_{iw} = 0.175 \left(\rho_{iw} \cdot h_c \right)^{-0.4} \cdot r_{iw} \quad (10)$$

$$\rho_{iw} = \left[\frac{E_{iw} \cdot t_{iw} \cdot \sin 2\theta}{4 \cdot E_{fr} \cdot I_c \cdot h} \right]^{\frac{1}{4}} \quad (11)$$

In Eq.(9) to Eq.(11) from the Turkish Seismic Code [22], the required parameters are; a_{iw} is the width of the equivalent diagonal compression strut, E_{iw} is the modulus of elasticity of infill wall, E_{fr} is the modulus of elasticity for the concrete material of the reinforced concrete frame, h is the height of the wall, h_c is the height of the column, I_c is the moment of inertia for the column, r_{iw} is the length of the equivalent diagonal compression strut, θ is the angle of the diagonal strut to the horizontal, and t_{iw} is the infill wall thickness.

4. Conclusions

The idealized strut characteristics have already been defined in relevant provisions of some characteristic design codes [22-25]. Hence, in the present study, the results are summarized for the prediction of the "stiffness reduction factor (λ)" in order to idealize the strut effect of the infill wall with openings. Although the "stiffness reduction factor" has already been discussed by various researchers, the effect of the location of the opening and the dimensions of the wall on the stiffness reduction factor has not been fully explored.

This study shows that the effect of reinforcement details of the structural reinforced concrete frame members on the stiffness reduction factor is negligible. However, the stiffness reduction factor is affected by location of the opening and wall dimensions, in addition to the opening ratio. Although the stiffness reduction factor varies at each location, the location of the opening can be simplified by adopting two out of nine regions: opening at beam-column joint, or opening at any other location.

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