Structural Engineering and Mechanics, Vol. 38, No. 2 (2011) 249-259
DOI: http://dx.doi.org/10.12989/sem.2011.38.2.249

How to reduce short column effects in buildings with reinforced concrete infill walls on basement floors

Murat Bikce*

Department of Civil Engineering, Mustafa Kemal University, Iskenderun, Turkey

(Received April 28, 2010, Accepted February 21, 2011)

Abstract. Band windows are commonly used in reinforced concrete structures for the purpose of ventilation and lighting. These applications shorten the lengths of the columns and, consequently, they are subject to higher shear forces as compared with those of hollow frames. Such short columns may cause some damages during earthquakes. Hence, these effects of short columns should be minimized by choosing the dimensions of the band windows properly in order to prevent serious damages in the structure. This can be achieved by taking into account the parameters that are crucial in causing short column effect. Hence, in this study, the effects of those parameters such as the widths and heights of the band windows, the number of bays and storeys within the frame, and the heights of storeys are examined. The effects of the parameters are analyzed using time history analysis. One of the important results of these analyses, is that, the widths of the band windows should be less than 60% of the clear span between the columns, whereas, their heights should be greater than 35% of the clear storey height in order to decrease the short column effects substantially during the design of the reinforced concrete structures.

Keywords: short column effect; band windows; reinforced concrete buildings; shear force; infill; earthquake.

1. Introduction

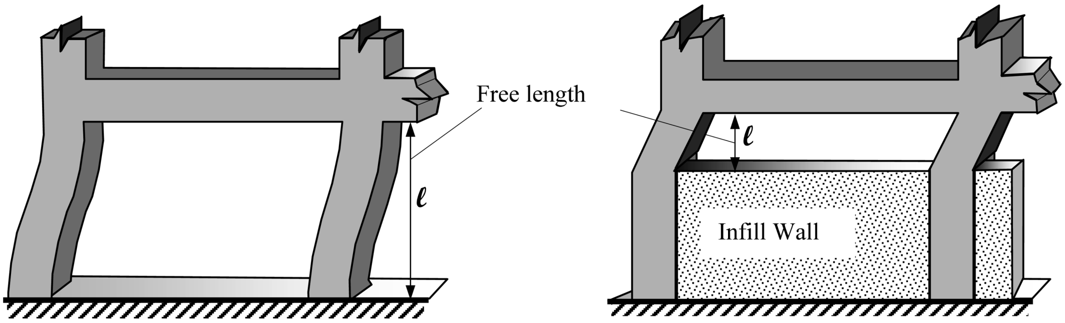
There can be two cases causing the appearance of short column effect within a structure. In the first case, the columns are produced shorter than the other columns on the same floor, such as, columns that carry a suspended ceiling, columns to which stairs are fixed and shorter columns on the first floor in an inclined construction field. In the second case, the columns have restricted free lengths due to the existence of band windows or soil infill up to road level causing constraints on the columns of the basement floor. The walls of the basement floors of reinforced concrete dwelling buildings and some of the side walls of either basement or other floors of industrial buildings are usually designed by leaving gaps in them. These gaps, called band windows, are left in order to provide air ventilation or more light as shown in Fig. 1.

An infill wall between two columns can be constructed either using a reinforced concrete wall up to the bottom of the band window (Fig. 1(a)) or one can use one of the following kinds of building blocks: cored brick, hollow brick, panel, etc. (Fig. 1(b)) to construct it.

*Corresponding author, Assistant Professor, E-mail: muratbikce@yahoo.com

(a) (b)

Fig. 1 Infill wall under the band window (a) reinforced concrete, (b) masonry



(a) (b)

Fig. 2 (a) Freely bending hollow frame, (b) partially infilled frame with shortened column heights

Recently, for providing enough rigidity at the base of framed reinforced concrete buildings in medium and high rise buildings, the outer walls in the basement floors are designed as reinforced concrete shear walls. Structural behaviors of reinforced concrete infill walls are different from masonry infill walls. Reinforced concrete walls constructed as an integral part of a supporting system display a ductile behavior in resisting lateral and vertical loads, whereas, infill masonry walls, generally, behave in a brittle manner.

If the infill walls are constructed as short walls and attached to the frames, the adjacent columns of the main frame cannot bend freely due to the rigidities of the walls during the earthquakes that apply lateral forces on the structure. These columns are, then, forced to deform only along their free lengths above the wall. As a consequence, they are subjected to high shear forces (Figs. 2(a) and 2(b)).

When infill walls under band windows are not extended along the complete column height, short column effect creates severe damages to load carrying structural members during earthquakes. In this study, the effects of various parameters causing short column effect in reinforced concrete frame buildings with band windows and reinforced concrete infill walls are investigated. The effects are presented in the form of graphics and tables and several recommendations are given for reducing the abovementioned catastrophic effect.

2. Previous research

Numerous experimental and analytical studies have been conducted on the investigation of the effects of infill walls on framed RC structures since 1960s (Polyakov 1956, Blume *et al.* 1961, Stafford 1966, 1967, Uzsoy and Citipitioglu 1972, Klingner and Bertero 1976, Umehara 1984, Dowrick 1987, Hendry 1990, Wood *et al.* 1991, Paulay and Priestley 1992, Gülkan and Wasti 1993, Fardis *et al.* 1999, Sezen *et al.* 2000, Al Chaar *et al.* 2002, Asteris 2003, Cagatay 2005, 2007, Guevara and Garcia 2005, Guney and Boduroglu 2006). However, to the best of the author's knowledge, the contribution of the rigidity of infill walls to the overall structural rigidity of a structure is not taken into account at the design stage. Some of the abovementioned studies (Blume *et al.* 1961, Wood *et al.* 1991, Gülkan and Wasti 1993, Cagatay 2005) showed that framed structures having infill walls with different layouts behave more rigidly and are more ductile under earthquake excitations than those that are in the form of plain framed structures. The method of equivalent virtual compression struts is proposed by Stafford (1966, 1967) in order to predict the effects of infill walls on the structural behavior of RC structures subjected to horizontal loads caused by earthquakes. The results of these studies revealed that there are considerable differences between the structural behaviors of completely infilled frames and partially infilled frames (Dowrick 1987). Later, Hendry (1990) developed a relation between the width of the effective virtual compression strut and the vertical and horizontal contact lengths of the infill wall.

A number of analytical and experimental studies on the investigation of short column effect have been carried out up to now (Umehara 1984, Gülkan and Wasti 1993, Sezen *et al.* 2000, Cagatay 2005, 2007, Guevara and Garcia 2005). In the work of Gülkan and Wasti (1993), an investigation was conducted by testing a single bay frame with one storey. Their results showed that masonry infill walls start affecting frame behavior when the heights of the infill walls get greater than one third of the frame height. The authors explained that effect by the change in the column shear force. They found four or five times higher column shear forces than those of plain framed structures for some extreme cases. The reduction in the free height of captive or short columns increases the lateral stiffness. Hence, these columns are subjected to larger shear forces during an earthquake since the storey shear is distributed in proportion to the lateral stiffnesses of the columns. If these columns are reinforced with conventional longitudinal and transverse reinforcement and subjected to relatively high axial loads, then they will fail by the splitting of concrete along their diagonals. If the axial loading level is low, the most probable mode of failure is by shear sliding along full depth cracks at the ends of the members. Moreover, in the case of a captive column caused by adjoining non-structural walls, the confinement provided to the lower part of the column is so effective that damage is usually shifted to the short non-confined upper section of the column (Guevara and Garcia 2005).

Cagatay (2007), investigated the variation in the shear force of a portal frame with constant height and span by changing the height of the masonry infill wall. The band window heights were set as 17, 33, 50, 67, 83 and 100% of the clear storey height. It was shown that the highest shear force value occurred for the structure with 17% band window height ratio. From the results of their experimental study Kakaletsis and Karayannis (2007) found out that in order to provide an improvement in the performance of an infilled frame, the location of the opening in the infill must be as near to the edge of it as possible. Cagatay *et al.* (2010) claimed that, in their work, additional infill walls on the two sides of a short column decreased the shear force in it, appreciably.

Band windows should be avoided, whenever possible, in the design of frames for the prevention of short column effect. However, the use of band windows is unavoidable in the external frames of the basement floors of buildings due to ventilation and lighting needs. Various national and international regulations have specified limits for controlling short column effect (ACI 318-71, ICBO 1973, Eurocode 8, TEC 2007). For example, according to 2007 Turkish Earthquake Code (2007), the transverse reinforcements should be continued along the complete clear storey height and the following equations should be satisfied (TEC 2007)

$$V_e = 1.4\ (Mr_b + Mr_t)\ /\ \ell \leq V_r \tag{1}$$

$$V_e = 1.4\ (Mr_b + Mr_t)\ /\ \ell \leq 0.22\ A_w f_{cd} \tag{2}$$

3. Short column model

In this study, the basement floors of RC frame buildings with band windows and RC infill walls are considered. Only the variation of one physical parameter is considered, at a time, while the others are kept constant and the lateral soil pressure acting on the RC infill walls are neglected.

The plan of the model structure investigated in this study is seen in Fig. 3(a). Fig. 3(b) shows the vertical section of axis C and Fig. 3(c) shows cross-section F-F. In order not to have torsional effect, the structure is chosen to be symmetric with respect to B axis. The parameters considered are ℓ, L, ω, W, N, and K. Many analyses were carried out by varying the foregoing parameters and observing how they changed the short column effect. The structure in Fig. 3 was modeled in SAP2000 Structural Analysis Program representing columns and beams with frame elements and shear walls with shell elements. The Time-History Analysis of the model is carried out in x direction by employing the acceleration of Izmit Earthquake (August 17, 1999), El Centro Earthquake (May 18, 1940) and Northridge Earthquake (January 17, 1994). As a result of these analyses, the maximum

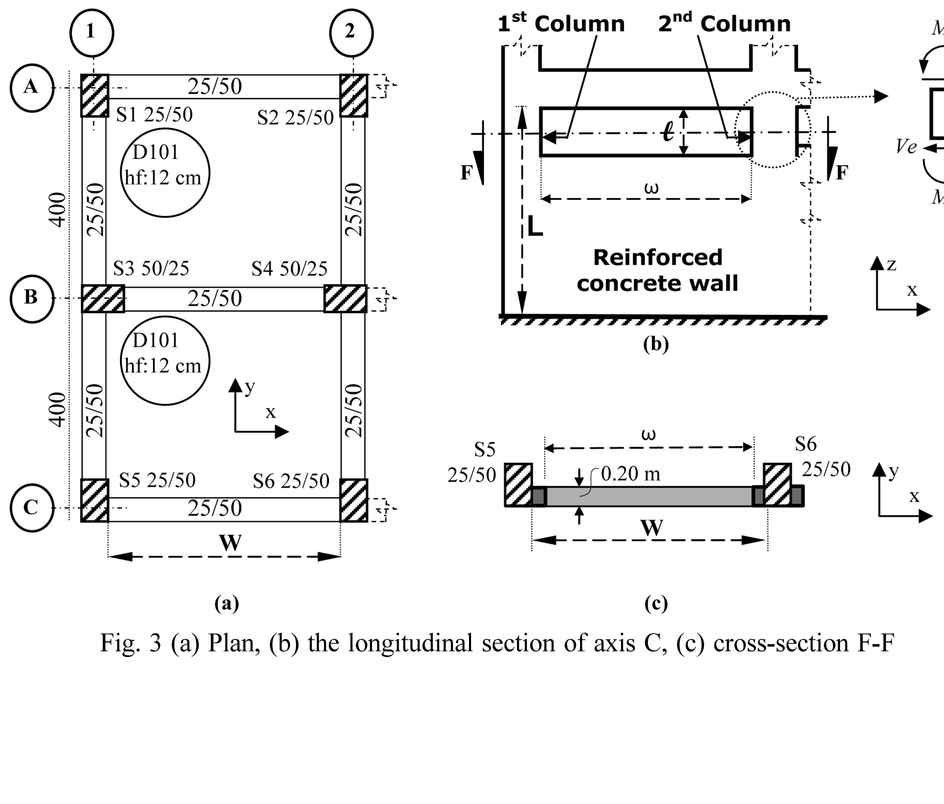


Fig. 3 (a) Plan, (b) the longitudinal section of axis C, (c) cross-section F-F shear forces obtained is taken into account. The shear force results in the free lengths of the 1st and 2nd columns (see Fig. 3) were normalized with the shear force obtained in the hollow frame for easy comprihension.

The material properties and the element cross-sections are assumed to be constant throughout the elements. The modulus of elasticity of concrete was taken as 28500 MPa, Poisson's ratio as 0.2 and the yield strength of the reinforcement as 420 MPa. It was assumed that the model structure was in a first degree seismic zone.

4. Investigation of the effects of the parameters causing short column effect

The analyses were repeated by changing the parametric values under investigation within the measurement ranges frequently encountered in practice. Upper floors when included in the calculations were assumed to have no infills. Some intermediate values yielding very close results were excluded to prevent crowdedness in the graphics.

4.1 Effect of band window height

The calculations were repeated by taking the band window height (ℓ) as 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100% of the clear storey height (L) in a single storey one bay structure for detecting the effect of band window height ratio on the shear force of the short column (i.e., for 10% the band window height ratio (ℓ/L) is 0.1). The analysis was repeated for each value of band window height ratio and the shear force obtained from each analysis was divided by the shear force for the corresponding hollow frame to calculate the shear force ratios (for example, the shear force ratio for $\ell/L = 0.1$ is $V|_{\ell = 0.1 \times L}/V|_{\ell = L}$). Fig. 4 shows the shear force ratios obtained versus the band window height ratio (ℓ/L). Observing that for a constant band window height ratio, the shear force ratio varied with the clear storey height (L), shear force ratio curves were found for a number of clear storey height (L) values and the results are presented in Fig. 4.

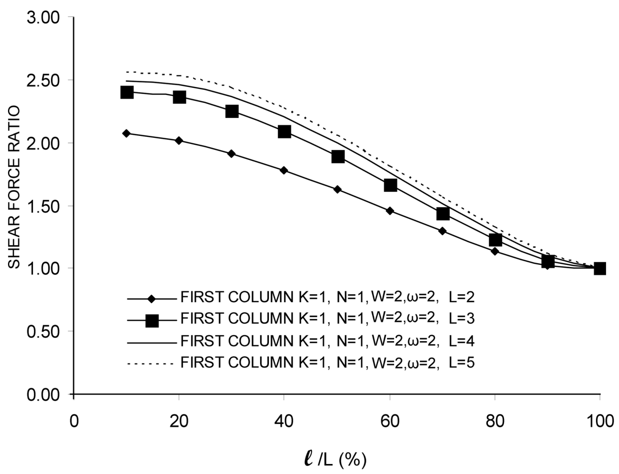


Fig. 4 The variation of short column shear force ratio with storey height ratio

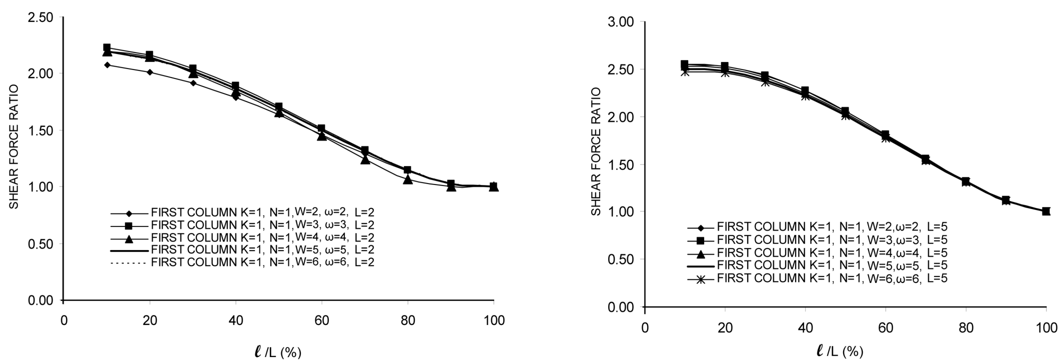
Shear force values obtained for the 1st and 2nd columns in the analysis for a single storey single bay frame are, as expected, identical. As seen in Fig. 4, shear force ratio starts to increase appreciably after the height of the RC wall in the frame exceeds approximately one third of the clear storey height. This result is similar to that found in the literature for masonry infill walls (Gülkan and Wasti 1993, Cagatay 2005, Guney and Boduroglu 2006). The highest shear force ratio occurs when the band window height ratio is minimum (ℓ/L = 0.1). The shear force ratio increases monotonically as the band window height ratio gets smaller and smaller.

4.2 Effect of frame width

The same analysis was repeated by varying the frame width for detecting its effect on the shear force ratio and Figs. 5(a) and 5(b) show the results obtained. An increase occurs in the shear force as the frame width increases. However, the variations in the storey height and the frame width increase the shear force in the short column by 2-2.5 times within the ranges selected for a single bay and single storey structure, whereas, this ratio reaches 4-5 times for buildings in which the section under the window was constructed of masonry infill walls (Gülkan and Wasti 1993). The difference between them is caused by the fact that the RC infill wall inside the frame behaves like a coupled shear wall as it gets taller and, consequently, takes over most of the shear force of the short column. Hence, short columns in frames with RC infills are affected less by shear forces compared with those in frames with masonry infills.

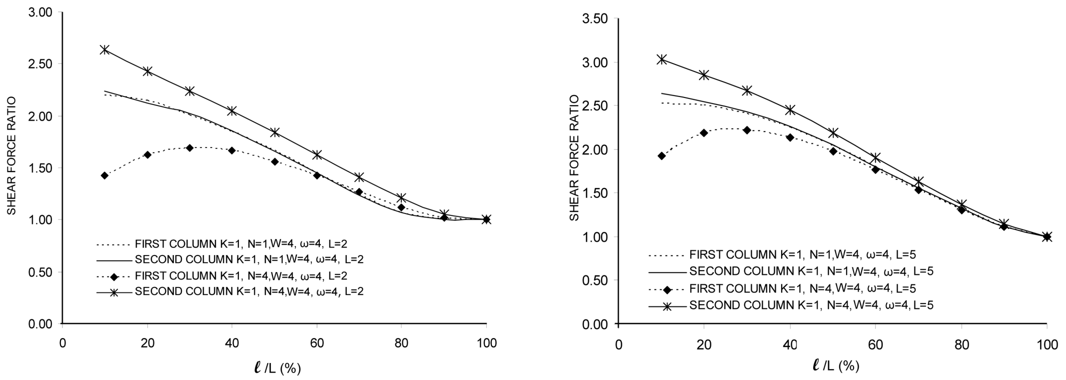
4.3 Effect of number of bays

The same analysis was repeated by varying the number of bays and changing the frame width for detecting their effects on the shear force ratio due to short column effect and Fig. 6(a) and 6(b) show some of the results obtained. Short columns are subject to identical shear forces in one bay structures independent of the frame width. However, shear force ratio decreases in the 1st column and increases in the 2nd column as the bay number increases. In the case where the seismic load is applied in the opposite direction, these effects will be reversed. A change in the bay number causes a change in the shear force ratio. However, this change is not similar for the 1st and the 2nd



(a) (b)

Fig. 5 The effect of variation in band window width on the short column shear force ratio for (a) L = 2 m and (b) L = 5 m



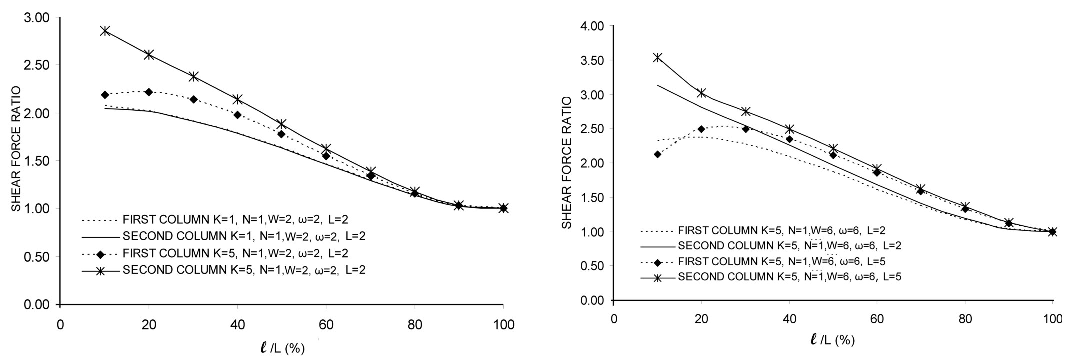
(a) (b)

Fig. 6 Variation in the shear force ratios in the 1st and 2nd columns depending on the increase in the number of bays for (a) L = 2 m and (b) L = 5 m

columns. As seen in Fig. 6(a) and 6(b), interior short columns are subjected to higher shear forces compared with the end ones.

4.4 Effect of number of stories

The same analysis was repeated by increasing the storey number and changing the frame width for the detection of the effect of the variation in the storey number on the shear force ratio due to the short column effect and Fig. 7(a) and 7(b) show some of the results obtained. As seen in Fig. 7(a), the shear force is distributed equally to the columns in the single storey. However, the shear force ratio decreases in the 1st column and increases in the 2nd column depending on the number of stories. For a 5 storey frame the rise in the shear force in the short column is 4 times compared with the hollow frame (Fig. 7(b)). Variation in the frame width does not change this factor appreciably.



(a) (b)

Fig. 7 (a) Variation in the shear force ratios in the 1st and 2nd columns depending on the increase in the number of stories (b) Variation in the shear force ratios in the 1st and 2nd columns depending on the variations in the frame width in a 5-storey building

4.5 Effect of band window width

Similar analyses were conducted for $\ell = 0.3 \times L$ and $W = 2, 4, 6$ m by changing the band window width for detecting the effect of variations in band window width on the shear force of short columns. The analysis was repeated by decreasing the band window width by 50 cm at each step starting from the case in which band window width ω was equal to the frame clear width in such a way that the window would be symmetrical with respect to the midpoint of the clear span. The calculations were carried out for each case and the variation of the shear force ratio (normalized by the shear force in the frame with $b = B$ and $\ell = 0.3 \times L$) for the upper end of the short column are presented in Figs. 8-10.

As expected, the highest shear force occurs for $b = B$ (see Figs. 8-10). In all cases with ℓ/L less than 0.6, almost the entire shear forces are transfered to the RC infill walls (see Figs. 8-10). As it can be observed, the curves are nearly horizontal with the shear force ratios which do not need special attention. Designers may take this ratio into consideration for buildings requiring band windows on the basement floors for ventilation and lighting.

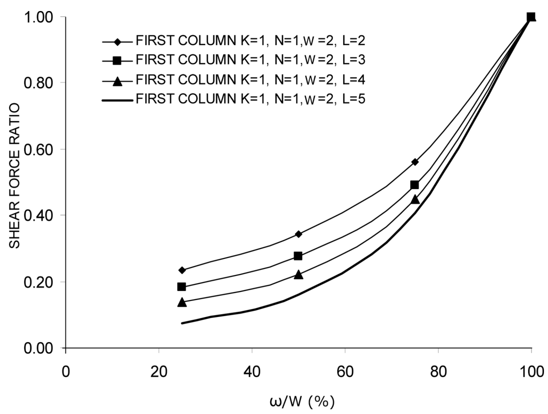


Fig. 8 The effect of band window width on the shear force for $W = 2$ m

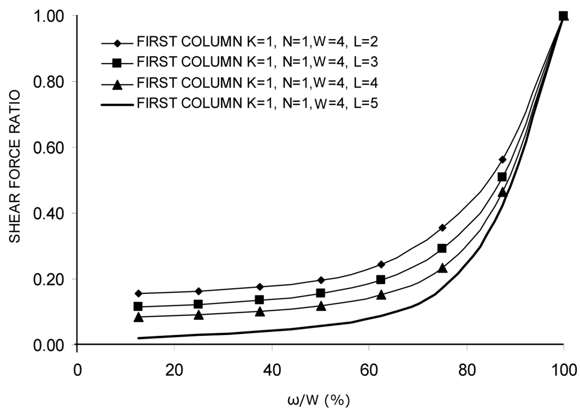


Fig. 9 The effect of band window width on the shear force for $W = 4$ m

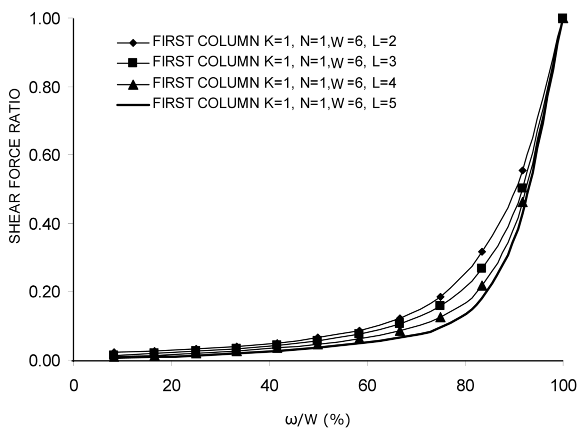


Fig. 10 The effect of band window width on the shear force for $W = 6$ m

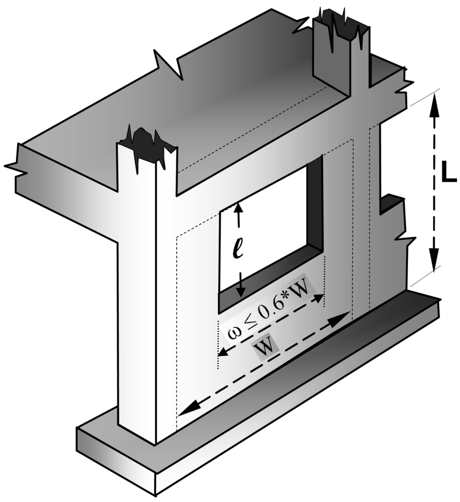


Fig. 11 Band window design in a reinforced concrete frame infill

5. Conclusions

In this study, the effects of parameters such as band window width and height, number of bays and storeys on the short column effects on buildings with RC infill walls in the exterior frames of their basement or ground floors, are presented in the form of graphs. From the results obtained, the following conclusions are drawn:

- With changes in the parameters under consideration, the shear force affecting the short column may go up to four times that of the hollow frame.
- A reinforced concrete infill wall inside a frame starts to affect the shear forces of the adjacent columns, substantially, when its height reaches one third of the storey height Short column effect increases monotonically as the band window height decreases.
- The short column effects of RC infill walls increase when the number of storeys and bays in a frame increase. Despite the fact that the increase in the shear forces of the columns of a portal frame are equal, in the cases of higher bay and storey numbers the interior short columns are subject to higher shear forces than the edge short columns.
- In cases where the width of the band window is less than 60% of the internal width of the frame, almost the total shear force of the short columns is transfered to the reinforced concrete infill which behaves like a coupled shear wall (Fig. 11).

References

Al Chaar, G., Issa, M. and Sweeney, S. (2002), "Behavior of masonry - infilled nonductile reinforced concrete frames", *J. Struct. Eng.,* **128**(8), 1055-1063.

Asteris, P.G. (2003), "Lateral stiffness of brick masonry infilled plane frames", *J. Struct. Eng.,* **129**(8), 1071-1079.

Blume, J.A., Newmark, N.M. and Corning, L.H. (1961), *Design of Multistory Reinforced Concrete Buildings for*

Earthquake Motions, Portland Cement Association, Chicago.
Cagatay, I.H. (2005), “Failure of an industrial building during a recent earthquake in Turkey”, *Eng. Fail. Anal.,* **12**, 497-507.
Cagatay, I.H. (2007), “Investigation of parameters affecting short column effect in buildings”, *Sixth National Conference on Earthquake Engineering*, Istanbul.
Cagatay, I.H., Beklen, C. and Mosalam, K.M. (2010), “Investigation of short column effect of RC buildings: failure and prevention”, *Comput. Concrete,* **7**(6), 523-532.
Committee 318 (1971), American Concrete Institute (ACI), *Building Code Requirements for Reinforced Concrete (ACI 318-71)*, Detroit.
Dowrick, D.J. (1987), *Earthquake Resistant Design for Engineers and Architects*, John Wiley & Sons, New York.
European Committee for Standardization 223, Eurocode 8: *Design of Structures for Earthquake Resistance*, Part 5: Specific Rules for Concrete Buildings, Brussels.
Fardis, M.N., Bousias, G., Franchioni, G. and Panagiotakos, B. (1999), “Seismic response and design of RC structures with plan-eccentric masonry infill”, *Earthq. Eng. Struct. D.,* **28**, 173-191.
Guevara, L.T. and Garcia, L.E. (2005), “The captive and short column effects”, *Earthq. Spectra,* **21**(1), 141-160.
Gülkan, P. and Wasti, T. (1993), “Interaction between frame and infill: non-linear investigation”, *Turkish Civil Engineers XII, Book for Bulletins of Technical Congresses*, Ankara, 39-52.
Guney, D. and Boduroglu, M.H. (2006), “Effect of infill walls on the nonlinear tensile behavior of symmetric and asymmetric structures under earthquake effect”, *ITU J.,* **5**, 165-174.
Hendry, A.W. (1990), *Structural Masonry*, MacMillan Education Ltd., London.
International Conference of Building Officials (ICBO) (1973), *Uniform Building Code*, Whittier.
Kakaletsis, D. and Karayannis, C. (2007), “Experimental investigation of infilled R/C frames with eccentric openings”, *Struct. Eng. Mech*., **26**(3), 231-250.
Klingner, R.E. and Bertero, V.V. (1976), “Infilled frames in earthquake-resistant construction”, EERC Report No. 76-32, University of California, Berkeley.
Paulay, T. and Priestley, M.J.N. (1992), *Seismic Design of Reinforced Concrete and Masonry Buildings*, Wiley, New York.
Polyakov, S.V. (1956), *On the Interaction Between Masonry Filler Walls and Enclosing Frame When Loaded in the Plane of the Wall*, Translations in Earthquake Engineering Research Institute, Ed. Cairns, G.L., Trans., Moscow.
SAP2000 (2004), *Integrated Software for Structural Analysis & Design*, Computers and Structures Inc., California, USA.
Sezen, H., Elwood, K.J., Whittaker, A.S., Mosalam, K.M., Wallace J.W. and Stanton, J.F. (2000), *Structural Engineering Reconnaissance of the August 17, 1999 Earthquake: Kocaeli (Izmit) Turkey*, *PEER 2000/09*, University of California, Berkeley.
Stafford, S.B. (1966), “Behavior of square infilled frames”, *J. Struct. Div.*, **92**(1), 381-403.
Stafford, S.B. (1967), “Methods for predicting the lateral stiffness and strength of multi-storey infilled frames”, *Build. Sci.,* **2**, 247-257.
TEC-2007, Turkish Earthquake Code (2007), *Specifications for Structures to be Built in Seismic Areas*, Ministry of Public Works and Settlement, Ankara, Turkey.
Umehara, H. and Jirsa, J. (1984), “Short Rectangular Reinforced Concrete Columns Under Bidirectional Loading”, *J. Struct. Eng.,* **110**(3), 605-618.
Uzsoy, S. and Citipitioglu, E. (1972), “Influence of infill walls on building frames: an example from the may 12, 1971 earthquake in turkey”, *B. Seismol. Soc. Am.,* **62**(5), 1113-1117.
Wood, S., Stark, R. and Creer, S. (1991), “Collapse of eight story R/C building during 1985 Chile earth-quake”, *J. Struct. Eng.,* **117**, 600-619.

Notations

A_w : Cross sectional area of column section
ω : Band window width
W : Frame clear width
f_{cd} : Design compressive strength of the concrete
K : Number of storeys
ℓ : Free length of the column (clear storey height or the height of the band window)
L : Clear frame height
Mr_t : Ultimate moment resistances calculated at the top of the column clear height
Mr_b : Ultimate moment resistances calculated at the bottom of the column clear height
N : Number of bays
V_e : Shear force taken into account for the calculation of the transverse reinforcement of the column
V_r : Shear strength of the column cross section