DOI: http://dx.doi.org/10.12989/cac.2010.7.6.523

Investigation of short column effect of RC buildings: failure and prevention

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(Received January 4, 2010, Accepted May 28, 2010)

Abstract. If an infill wall in a reinforced concrete frame is shorter than the column height and there is no initial gap between the column and the infill wall, the short column effect can occur during an earthquake shaking. This form of damage is frequently observed in many earthquake-damaged buildings all around the world and especially in Turkey. In this study, an effective method, which consists of placing additional infill wall segments surrounding the short column, to prevent this type of failure is examined. The influence of adding infill wall in the reduction of the shear force in the short column is also investigated. A parametric study is carried out for one-storey infilled frames with one to five bays using the percentage of the additional infill wall surrounding the short column and the number of spans as the parameters. Then the investigation is extended to a case of a multistorey building damaged due to short column effect during the 1998 Adana-Ceyhan earthquake in Turkey. The results show that the addition of the infill walls around the potential short columns is an effective way to significantly reduce the shear force.

Keywords: short column effect; dynamic analysis; earthquake damage; infill wall.

1. Introduction

Partial height infill walls are frequently used in many types of buildings where the incomplete height is generally attributed to window openings. If the infill walls in a reinforced concrete (RC) frame are constructed shorter than the column height and they are connected to the column, i.e. there is limited or no gap between the column and infill wall, the columns are unable to bend freely under the earthquake-induced lateral loads due to the high in-plane stiffness of the infill walls (Cagatay 2005). Hence, the columns are confined and can only bend between the top of the infill wall and the bottom of the beam of the bounding frame, inducing the so-called short column effect. In this case, excessive shear forces occur in the short column height, especially during earthquake-induced shaking. Therefore, if the partial height infill is not separated from the bounding frame in a building, the columns can be seriously damaged during an earthquake and this situation can cause severe damage and eventually collapse of the building. This short column effect is a form of damage observed frequently in earthquake-damaged buildings all around the world (Cagatay 2005, Guevara and Garcia 2005, Pineda 1994, Sezen *et al.* 2000, Caglar and Mutlu 2009) and especially

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Fig. 1 An example of short column failure in 1999 Kocaeli earthquake in Turkey

Fig. 2 Another example of short column failure in 1998 Adana-Ceyhan earthquake in Turkey

in Turkey (refer to Figs. 1 and 2). Cagatay (2005) examined the failure of a building due to short column effect during an earthquake and concluded that the shear force in the columns, in the case of an infill wall 40 cm shorter than the column, was about 5 times higher than the shear force without infill wall. With less difference between the infill wall and the column height, the shear force in the column increased, while the relationship being not linear.

The separation of the infill wall, with an adequate gap that would allow the column to bend, from the bounding RC frame is one of the best ways to eliminate the short column effect. However, in this case, the wall can easily fail in the out-of-plane direction due to inefficiency of its rigidity along the axis perpendicular to the wall plane (Hashemi and Mosalam 2007).

After the earthquakes, which took place recently in China 2008, Italy 2009, Haiti 2010, and Chile 2010, cost effective retrofit solutions are again becoming a very important task for structural engineers. This paper examines the failure of a building due to the short column effect during the

1998 Adana-Ceyhan earthquake. In addition, influence of adding infill walls in the reduction of the shear force in the short column is also investigated. Moreover, the paper suggests some cost-effective remedies to prevent the short column effect.

2. Short column behavior

Consider the partially infilled frame with connected infill walls to the columns shown in Fig. 3. The shear force, V, of the short column can be calculated from equilibrium as follows

$$V = \frac{M_t + M_b}{l_s} \tag{1}$$

where M_t and M_b are the bending moments at the top and bottom of the short column, respectively, and l_s is the length of the short column (refer to Fig. 4).

Theoretically, the smaller the short column length, the larger is the shear force obtained. Generally, the effect of infill walls on the design of RC structures is ignored where the weight of the infill wall is considered but it is not modeled in the analysis of the building. In that regard, the structural model contains only beams, columns, and slabs (refer to Fig. 5). On the other hand, the real behavior of the structure with infill walls during an earthquake is significantly different from the model without infill walls (Hashemi and Mosalam 2007). In cases where short columns, e.g. due to partial infill walls connected to the column, cannot be avoided, the shear forces in the columns can cause collapse of the building. Modern seismic codes, such as the Turkish Earthquake Code (Specification for Buildings to be Built in Seismic Zones 2007), state that the shear force used in the calculation of transverse reinforcement should be obtained by considering the short column height. However, there are many existing buildings, which were constructed without considering the presence of partial infill heights and the short columns. Therefore, it is very important to prevent or reduce possible shear failure in these types of buildings due to the short column effect during an

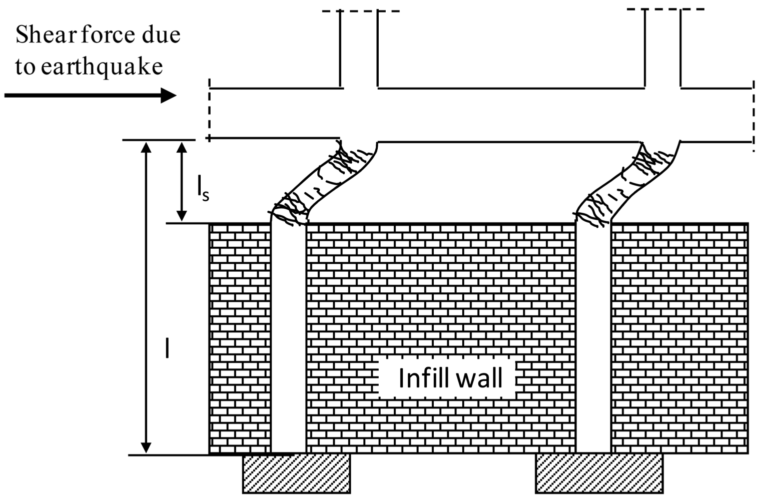


Fig. 3 Short column behavior

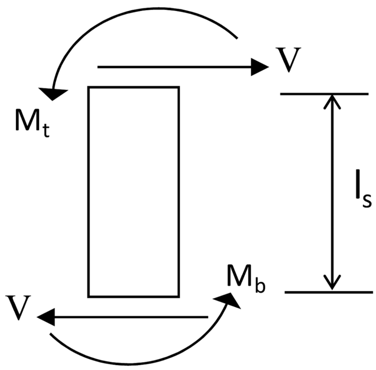


Fig. 4 Free-body diagram of a short column

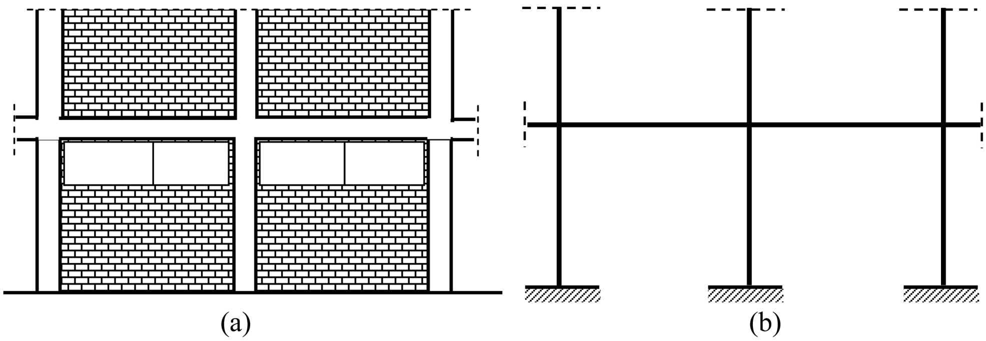


Fig. 5 (a) Building with partial infill walls, (b) computational model of the building without infill walls

earthquake by an effective way without costly measures.

3. Some practical recommendations to eliminate the short column effect

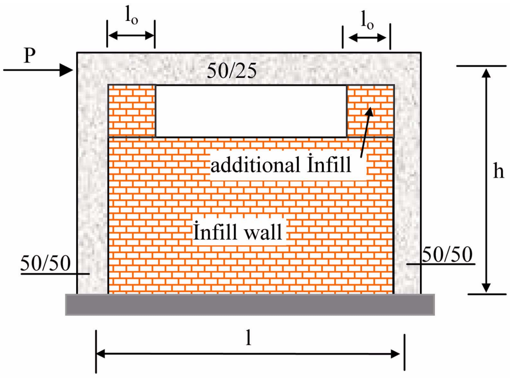
One of the best ways to eliminate the short column effect is to separate the infill wall from the bounding structural frame with an adequate gap that would allow the column to freely bend (Cagatay 2005). However, in this case, another problem occurs where the wall can easily fail in the out-of-plane direction due to inefficiency of its rigidity along the axis perpendicular to the wall plane (Kadsiewski and Mosalam 2008). Cagatay (2005) proposed a suitable method which consists of locating a steel beam with a U-shaped section between the infill wall and the RC frame. Hence, the RC column is free to bend along its entire height due to earthquake or lateral loads and the added steel beam with a U-shaped section prevents the infill wall from failing in the out-of-plane direction.

One of the other effective methods to eliminate the short column effect is to reduce the shear force acting on the short column. Pineda (1994) recommended a solution by adding infill wall segments that would slightly reduce the opening width next to the short column. He performed experimental tests on 1:3 scale models of two-dimensional (2D) frames. He recommended adding infill wall with a width of twice the required gap opening height.

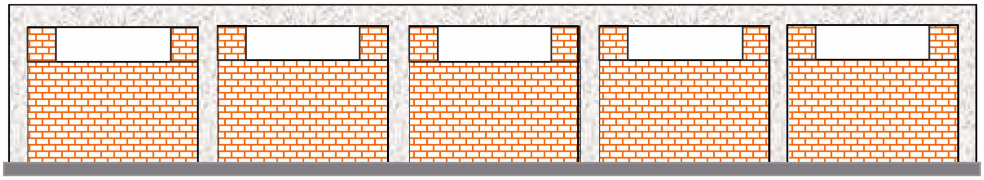
Alternatively, the requirements of the seismic-resistant codes, e.g. the Turkish Earthquake Code (Specification for Buildings to be Built in Seismic Zones 2007), must also be satisfied to completely prevent the short column effect. In the following sections, the effect of adding infill wall segments surrounding the short column on the shear force demand are examined in 2D and three-dimensional (3D) computational models.

4. Effect of adding infill wall segments on shear demand

In the study, the analyses of 2D RC infilled frames are carried out to investigate the effects of adding infill wall segments neighbouring the short column on reducing in shear force by using the structural analysis software, SAP2000 (SAP Series 1999). In the analysis, shell elements are used to model infill wall. The models are developed by using a single storey and different number of bays



(a)



(b)

Fig. 6 The general form of 2D RC frames: (a) one storey, one bay infilled frame, (b) one storey, five bays infilled frame

(one to five). The selected parameters consisted of the width of the added infill wall (l_o), and the number of spans of the frames as shown in Fig. 6.

The sections of the structural elements are rectangular and their dimensions are kept constant for all frames with different bays. Column and beam sections are 50 cm×50 cm, 50 cm×25 cm, respectively, infill wall thickness and height of additional infill are 20 cm and 30 cm, respectively, and storey height is 300 cm. Modulus of elasticity (Young's modulus) for concrete and masonry are taken as $E_c = 2.85\times10^4$ MPa and $E_m = 2.85\times10^3$ MPa (TS500 1984), respectively.

A concentrated load has been applied to the point at the top of the beam at the first floor level. In all the configurations, a horizontal force of 100 kN (P in Fig. 6) has been applied.

The length of the spans (l) is taken as 5 m. The length of the additional wall (l_o) is variable where its value is changed from 0.25 m to 1.50 m. Therefore, the (l_o/l) ratio is changed between the values of 0.05 to 0.30. The case of no additional infill wall, $l_o = 0$, is also considered in the study.

The results of the analysis given in Table 1 indicate that the addition of infill wall next to the shear wall significantly reduces the shear force in the short columns of the frames. The maximum shear force values are obtained in the case of no addition of infill wall (short column effect). In the table, the shear force values are given for both exterior columns (where the load P is acting on these columns) and interior columns. The more the additional infill wall or larger (l_o/l) ratio, the less the shear force is obtained. However, the relationship between the additional infill wall or (l_o/l) ratio and the shear force reduction (compared to the no additional infill wall case) is not linear as shown in Figs. 7 and 8. The addition of infill wall of 20% of the span for interior columns reduced the shear force in the short column by about 65%. This is very important for reducing the shear force

Table 1. The shear forces in short columns of the one-story frames

Additional infill (l_o) (m)	l_o/l	Shear Force, (kN) 1-bay	2-bays Exterior	2-bays Interior	3-bays Exterior	3-bays Interior	4-bays Exterior	4-bays Interior	5-bays Exterior	5-bays Interior
0	0.0	52.6	33.7	43.4	28.6	33.2	26.9	29.7	26.3	28.5
0.25	0.05	45.7	29.5	36.0	25.4	27.6	23.9	24.7	23.5	23.7
0.50	0.10	36.2	24.0	26.5	21.0	20.4	20.1	18.4	19.7	17.8
0.75	0.15	28.5	19.5	19.0	17.5	14.8	16.9	13.5	16.7	13.2
1.00	0.20	22.8	16.3	14.0	14.9	11.1	14.4	10.1	14.3	9.9
1.25	0.25	18.8	14.0	10.7	13.1	8.5	12.8	7.9	12.7	7.7
1.50	0.30	16.1	12.5	8.4	11.7	6.8	11.5	6.3	11.5	6.2

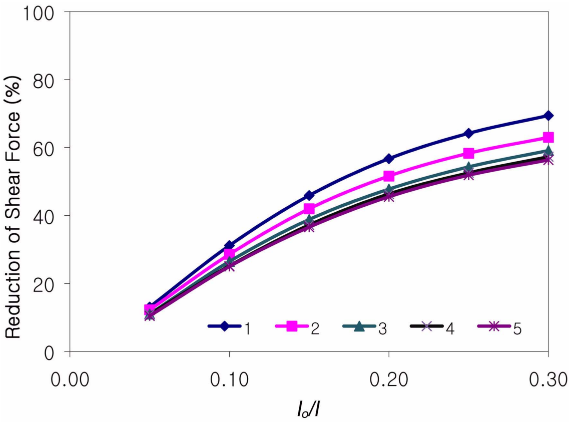


Fig. 7 Reduction of shear force for different l_o/l values for exterior columns for different number of bays (1 to 5)

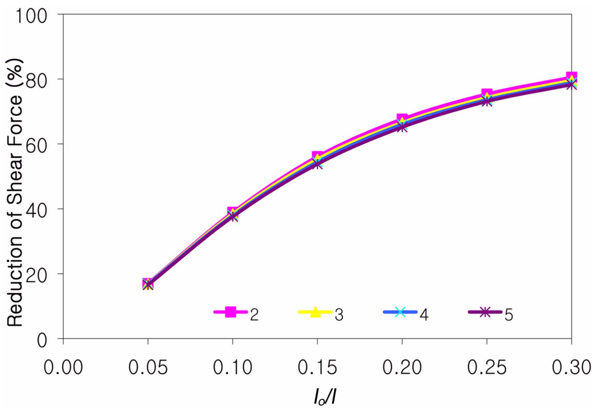


Fig. 8 Reduction of shear force for different l_o/l values for interior columns for different number of bays (2 to 5)

and eliminating the short column effect without costly measures.

5. Investigation of a case-study building

The selected building for this case-study was damaged during the 1988 Adana-Ceyhan earthquake due to short column effect (refer to Figs. 9 and 10).

The plan view of the layout of the two-storey case-study building is given in Fig. 11. The short column effect was observed at all the exterior columns of the first storey. On the other hand, no damage was observed on the second storey.

The columns do not have adequate transverse reinforcement as would be required by any modern seismic resistant code, as shown in Fig. 10. On the other hand, even if the concrete strength and the stirrups were satisfying the code requirements without considering the presence of a short column, there would still be shear failure because of the amplification of shear forces due to short column effect. Even though the infill walls caused the short column effect in all the exterior columns of the

Fig. 9 Overview of the case-study building

Fig. 10 Short column effect in the case-study building

building, there was no apparent damage, not even cracks in the infill walls. Hence, the infill walls acted as rigid shear wall.

6. Dynamic analysis of the case-study building

The computational model of the building is given in Fig. 12. It is to be noted that the model includes a water storage unit on the second floor. The storey heights are 4 m. The building was symmetrically separated with a seismic joint at the 6th axis into two parts. Therefore, only one part of the building is modeled and analyzed for the dynamic response in two stages:

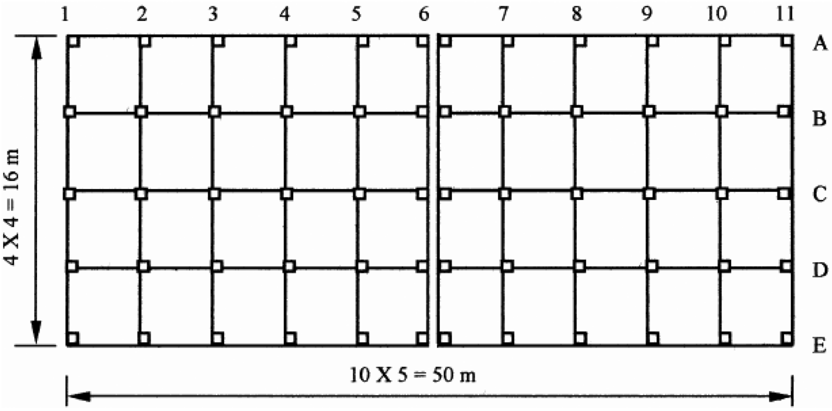


Fig. 11 Plan view of the layout of the case-study building

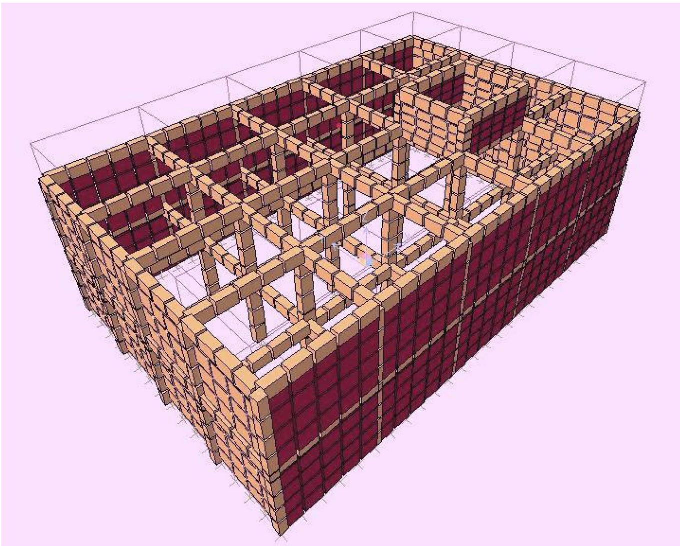


Fig. 12 Computational model of the case-study building

1. In the first stage, the dynamic analysis of the building is performed in accordance with the Turkish Earthquake (Specification for Buildings to be Built in Seismic Zones 2007) by using the equivalent static method.
2. In the second stage, the width of the additional infill is changed in the range l_o= 0.25 m to 2.0 m (5% to 40% of the span) and the results are compared with those without additional infill, i.e. l_o = 0, (refer to Fig. 13).

All the beams are 60×40 cm, and the thickness of the slabs and infill walls are 20 cm. All the columns along the A and E axes are 40×40 cm but those along B, C and D axes are 60×40 cm. Rigid diaphragm assumption is adopted for the slabs in the analyses. For further design and modeling details of this case-study building, the reader is referred to (Cagatay 2005).

The shear force-additional infill wall relationship for axis E, as an example, is given in Fig. 14.

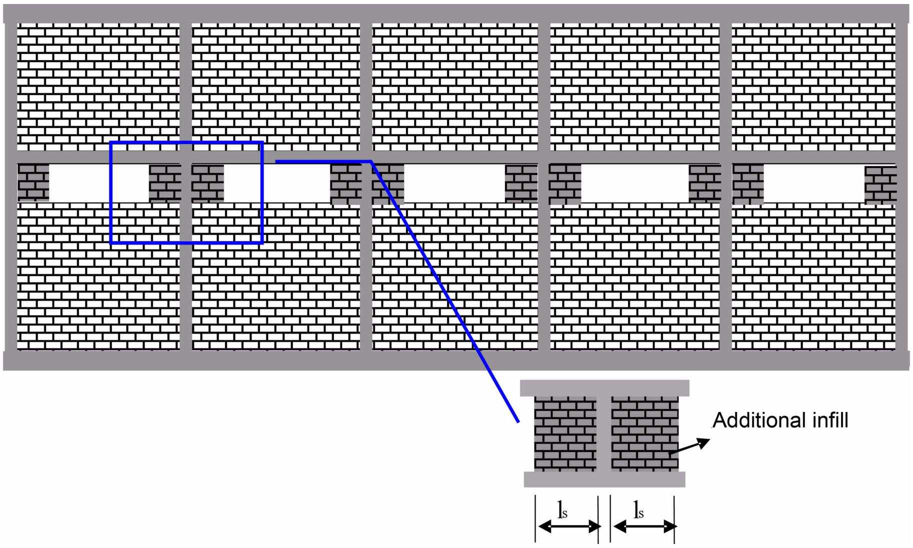


Fig. 13 Additional infill walls (with darker colour) surrounding the short columns

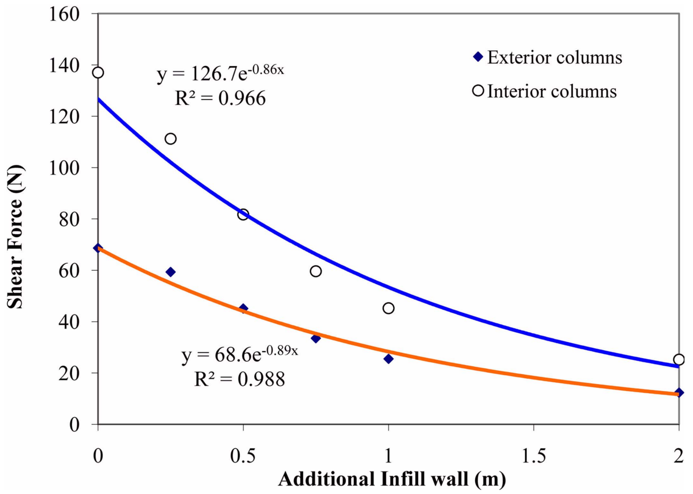


Fig. 14 Effect of additional infill wall on the shear force at the E axis of the case-study building

The addition of the infill wall reduces the shear force significantly. This addition of 0.25 m and 0.5 m (5% and 10% of the span) for the interior column at the E axis reduces the shear force by 19% and 40%, respectively. In the case where the addition of the infill wall for 1 m (20% of the span), the shear force is reduced by as much as 67%. Therefore, the addition of infill wall is recommended here as 20% of the span to significantly reduce the short column effect. As shown in the Fig. 14, the best fit of the data points is represented by a power relationship between the shear force and the additional infill wall length. The more the additional infill wall beyond 20%, the less is the reduction of the shear force obtained.

7. Conclusions

An effective method to prevent failure of structural frames due to short column effect is examined for 2D and 3D structural frames including a case-study building damaged due to short column effect during the 27th June 1998 Adana-Ceyhan earthquake. Whenever short columns, due to adjacent partial infill walls, cannot be prevented altogether during the initial design phase (which is the recommended approach), an effective method is recommended in this study by the addition of short infill walls surrounding the short columns.

The results of 2D and 3D frames show that the addition of the infill wall next to each short column is an effective way in order to reduce the shear force of the short column. There is a power relationship between the reduction in shear force and the additional infill wall width. The addition of infill wall of 20% of the span length is recommended to reduce the short column effect by about 67%.

Acknowledgements

The authors acknowledge the input of Dr. Selim Günay, Post-doc Researcher, University of California, Berkeley, for his valuable suggestions and comments during the final revision of this manuscript.

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