Effects of Coupled Shear Wall Openings on Nonlinear Behavior of RC Building Structures

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ABSTRACT: Despite the common acceptance of high stress concentration around the wall openings and their significant effects on the general system behavior, current building codes and design provisions comprise no specific or broadly described information concerning the detailing of coupled shear-walls openings and shear core systems. To address this deficiency, the load capacity and stress distribution around the wall openings were studied in representative 2D and 3D finite element models. Diaphragm flexibility, behavior of transverse walls and slab-wall interaction during 3D action were investigated. An effort was spent to illuminate the impacts and significance of different size and location of openings within the coupled shear-walls having variable reinforcement ratios. The analyses results showed that stress flow and crack patterns around the openings of 3D cases were drastically different than those computed for 2D cases. The tension-compression (T/C) coupling effects caused by the wall-to-wall and wall-to-slab interactions provided a significant contribution for increasing the global lateral resistance. Based on the obtained results, the amount and location of the main reinforcement needed around the openings of pierced shear walls were recommended.

1 INTRODUCTION

The critical evaluation of shear-wall openings might be most effectively accomplished on tunnel form buildings (i.e., box systems or half-tunnel systems). Since there is no columns and beams in their structural system, and all slab and wall elements are utilized as primary load carrying and transferring members (Figure 1). The simultaneous casting of slabs and walls at story levels result in monolithic structures that provides high seismic performance by minimizing the cold-joint formations in the most probable plastic hinge locations such as around wall-openings and base of shear walls (Balkaya and Kalkan 2003a). In addition to their considerable resistance against lateral loads, the speed and ease of construction make them preferable as the multi-unit construction of residential buildings particularly in the countries exposed to substantial seismic risk such as: Turkey, Italy, Japan and Chile.

Figure 1. Tunnel form construction technique and its formwork system

However, in spite of the significant potential of tunnel form buildings against earthquake loads, cutouts to provide the functional use in their shear-walls may alter the force distribution significantly. In the literature, no analytical or experimental study utilizing the 3D models either in a linear or a nonlinear fashion has been directed to the investigation of the effects of such openings within the pierced shear walls. The current approaches given in the design provisions for detailing of the reinforcement around the openings are generally based on the results derived from 2D analyses. The available studies were only considered the 2D effects of openings. In 1958, Benjamin and Williams observed high stress concentrations around the openings in their test specimens. Subsequent investigations have been concentrated on the inelastic behavior of the shear walls with openings subjected to monotonic (Seya and Matseri, 1979; Matsui and Ogawa, 1979) and cyclic loadings (Daniel et al. 1986, Aejaz and Wight 1991). Different locations of openings have been considered, including those centrally placed (Daniel et al. 1986), staggered openings (Aejaz and Wight 1991), and doors placed near the edges of the shear walls (Arvidsson 1974). In general, studies considering shear wall openings concentrated on coupling beam effects between adjacent shear walls. However, lack of such beams as it is the case in tunnel form buildings, may require a different approach for their accurate analysis and reinforcement detailing.

In the tunnel form construction technique, slabs are supported only along their three sides with shear walls while one side remained unsupported in order to take the formwork back after concrete casting (Figure 1). In common practice these three shear walls contain at least one opening for the functional use and access. In our study, the stress development and their distribution around such openings were investigated by focusing on the effects of transverse walls, their contribution to the general behavior and influences of slab-wall interaction. Towards this aim, 3D and 2D pushover analyses were conducted on 2 and 5-story tunnel form buildings. The analyses were employed considering the effects of variable size and location of openings, and their impacts to shear flow. To accurately predict the nonlinear behavior of the model structures with sufficient accuracy, due care has been given to create detailed and efficient models taking into account all necessary geometric and strength characteristics of shear walls, slabs and slab-wall connections. During the modeling, the reinforcement was simulated as discrete elements around the openings and as smeared layers within the shear walls and slabs. The nonlinear 2D and 3D finite element analyses results were compared to illuminate their differences, and highlight 3D effects. In the final part, discussion for the amount and location of the main reinforcement needed around the openings of the pierced shear walls were presented based on the results of the 3D analyses.

2 ANALYTICAL MODEL

By way of evaluating the 3D and 2D nonlinear capacities of the shear wall dominant systems, 2 and 5-story residential buildings were modeled in finite element domain. A detailed description of typical plan and section (for 5-storey) of these buildings are illustrated in Figure 2. Both buildings have identical plans and only their storey levels vary. Their structural systems are composed of solely shear walls and slabs having the same thickness (12 cm) as usual applications. All of the intended lateral strength and stiffness reside in the interior shear walls with the contribution of the slabs. In addition to their resistance to lateral loads, these distributed walls in the plan are also designed to carry the gravitational loads. Obtained capacity curves at the end of the pushover analyses are shown in Figure 3. For the sake brevity, only the results of analyses were presented herein, further details of the modeling and application of 3D pushover analyses were given in elsewhere (Balkaya and Kalkan, 2003b).

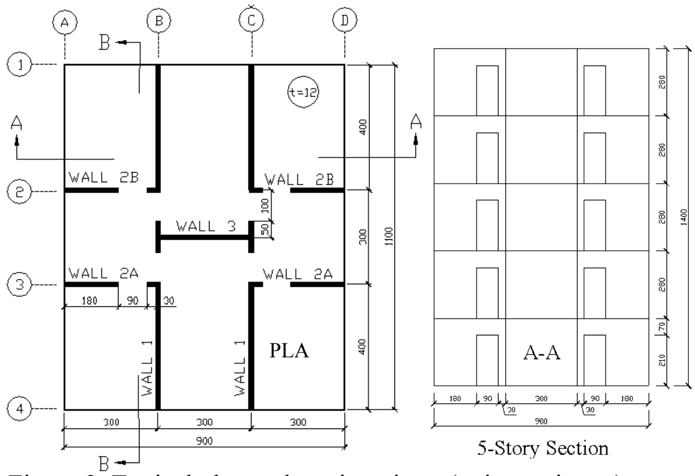
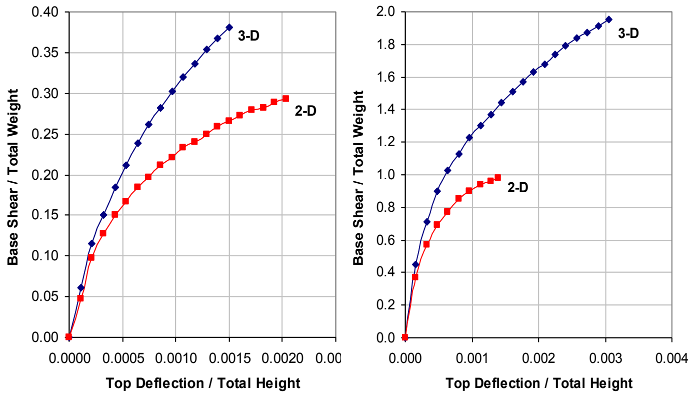


Figure 2. Typical plan and section views (units are in cm)

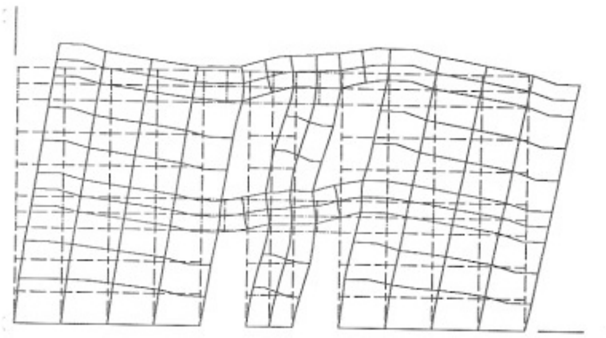


(a) 2-Story (b) 5-Story

Figure 3. Capacity curves (based on pushover analyses) for 3D and 2D models of 2 and 5 storey buildings

3 STRENGTH AND DEFORMATION AROUND OPENINGS

The effects of openings on the strength and deformation capacity of shear wall systems are different than those observed in the conventional frame-wall systems due to the coupling effects of beams connecting the adjacent shear walls. These differences are more evident when the 3D behavior is under consideration. In general, no contra flexure points occur above the openings as they do in the 2D coupled wall cases due to the restraint of motion caused by the existing transverse walls and slabs having a continuous edge support in the three dimensions. In this study, the part of the wall between the openings was deflected more in the 2D models than 3D models. These deflected shapes for the 2D and 3D models of 2-story building are shown in Figure 4. These deflected shapes correspond to the last step of pushover analysis before the occurrence of failure. That means excessive crack development at the base level of the shear walls did not yield any more inelastic deformation. The crack patterns observed from the 2D and 3D models of the 2-story building exhibited significant differentiation at the 2D case failure loading level. However, at the failure load level of the 3D model, the crack patterns turned out to be similar to those observed at the 2D model failure load level. The capacity of the main walls was reached at their respective load levels for each case. Similar observations were also obtained for the 5-story building, as well. For both case studies, the 2D models resulted in an earlier development and wider propagation of the cracks around the openings. The 2D models showed comparably more bending of the individual walls near the base level than the 3D model, which revealed smaller individual wall bending but mostly involved its major sections in the global bending behavior. The crack patterns for the 5-story building around the openings of the upper stories, located above the second story of the 2D model, exhibited similar patterns in the 3D model. This was basically due to the local stress flow around the openings, and the composite global behavior at the upper levels in the 3D model. In fact, these levels did not reach their maximum cracking moment capacities. The edge and special reinforcement, including the concrete cover, affected the excessive crack propagation around the openings significantly due to the additional strength they provided.



(a) 2D model deflected shape (Section B-B)

(b) 3D model deflected shape (Section B-B)

Figure 4. Deflected shapes for *Wall 1* in 2D and 3D models of 2-story building

4 SLAB-WALL INTERACTION

In order to investigate the details of slab-wall interaction, a basic model prescribed in Figure 5 was developed considering the different plans and shear wall configurations. The finite element model was analyzed by employing the 3D nonlinear pushover analyses. The analyses were repeated for seven different cases having variable opening dimensions as presented in Table 1. For the cases of *4a* and *4b*, *Wall 3* was considered as a 12/70 (cm) coupling beam between the *Wall 1* and *Wall 2*. Similarly, in the cases of *5a* and *5b*, *Wall 3* was totally removed from the model to eliminate the transverse wall effects while providing maximum width and height to the openings. The size and location of the openings, amount of wall reinforcement and discrete reinforcement around the openings were the focal points studied herein. In order to better illuminate the consequences of slab-wall interaction, the amount of smeared reinforcement incorporated in the walls was increased from 0.2% to 0.5% within the layers near the inner and outer faces of the walls and in both horizontal and vertical directions. The number of concrete layers used in the modeling of the walls was also increased to smooth out the nonlinear cracking effects and to better visualize the flexural behavior. In general, the cracks at the base of the shear walls developed due to the slab and wall bending moments as well as the moments created by the membrane forces. The lateral loads were applied in the weak direction (y-direction) as uniformly distributed forces along the first floor and roof levels. In the case of 4b, the presence of vertical loads was excluded while for 5b besides the slab weight, the wall weights were also considered during axial loading steps.

Table 1. Opening dimensions in the model structure

	Opening Size (cm)	
Case	Width, D	Height, H
1	100	210
2	200	210
3	300	210
4a	400	210
4b*	400	210
5a	400	280
5b*	400	280

* Loading condition is different

For the first three cases investigated the membrane action had the dominant effects on the behavior due to the out-of-plane bending moments of the slabs which were observed as much smaller than the moments created by the membrane forces. This membrane force couple developed between the forces originated from *Wall 1* with the combination of the closer part of *Wall 3* and those from *Wall 2* with its companion part of *Wall 3*. These combined parts acted as a T-beam, and local moments due to the membrane forces were calculated considering this T-beam components (Balkaya and Schnobrich, 1993). The graphical representations of the total moment capacities of the models are presented in Figure 6 with the contribution of the moments created by the slab-bending and membrane forces within the shear walls. For the first three cases, the moments created by the membrane forces within the walls were dominant. With the increase in the size of the opening, this moment contribution from the membrane forces was reduced significantly. In the extreme case (Case-5), the wall bending turned out to be a relativelv dominant force mechanism.

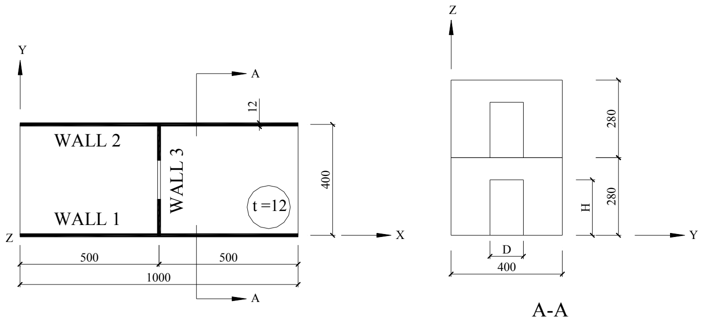


Figure 5. Typical plan and section view for slab-wall interaction model (units are in cm)

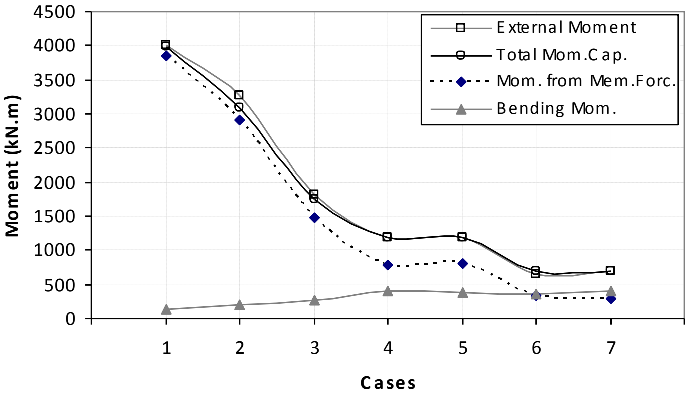


Figure 6. Distribution of external moment, total computed moment and its components for seven different cases

The whole picture of the obtained moment capacity results showed that the membrane moment came only from the T/C coupling forces acting in the *Wall 1* and *Wall 2*. The total moment capacity of the structure was reduced from 4,000 kN.m (400 ton.m) to 690 kN.m (69 ton.m) as a consequence of increasing the size of the openings within the interior walls. The load-deflection curves developed for the studied cases are presented in Figure 7. The total energy absorption was increased with the increase in the size of the openings (in *Wall-3*) with the exception of the extreme case 5. The structures showed more ductile behavior as the lateral deflection increased. Especially, the roof displacements increased after the formation of the plastic hinges at the base of the structures. The case 1 was observed to behave in a relatively brittle fashion. As no lateral confinement was assumed, once the *Wall 1* or *Wall 2* depends on the loading direction achieved a certain level of the compressive strain, 0.004, that the wall was assumed to be crushed out. For the cases of 4 and 5 the structure behaved in a more flexible manner than the first three cases.

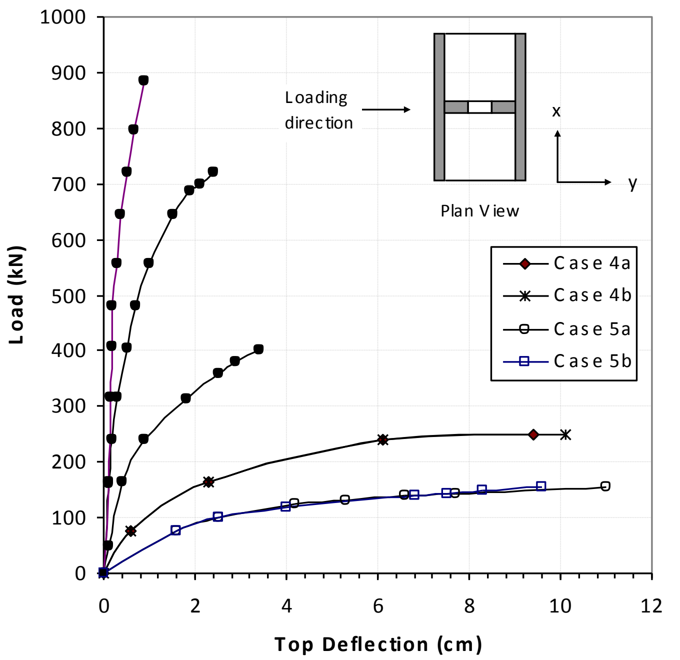


Figure 7. Load-deflection curves for the slab-wall interaction model

5 REINFORCEMENT DETAILING AROUND OPENINGS

In the current codes and design provisions, there are no specific or broadly described guidelines related to detailing of the reinforcement around the openings of pierced shear walls especially for the cases in which there are no connection beams between the adjacent shear walls. In 1990, Wood presented a reasonable estimate for the lower bound of the shear strength of low-rise walls with minimum web reinforcement. The UBC (ICBO, 1997) indicate that in addition to the minimum reinforcement in the walls, not less than 2 #5 bars shall be provided around the openings. The placement of diagonal shear reinforcements with an angle of 45 degrees at the sections above the openings is recommended by the Turkish Seismic Design Code (Ministry of Public Works and Settlement, 1998).

In fact, due to the formation of high stress concentration around the openings, use of the shear reinforcement as stirrups in the pierced part in addition to the edge reinforcement provides a significant confinement to the concrete covering the main longitudinal bars, and prevents the buckling of the bars and the premature shear failure. If diagonal bars are not provided, additional shear reinforcement shall be used to resist the diagonal tension. The minimum amount of reinforcement and its detailing shown in Figure 8 is recommended for pierced shear walls in the case of existence of shallow parts above the openings (using 2 #4 as top and bottom bars, and 2

#4 at each vertical edge). Paulay and Binney (1974) suggested the use of the diagonal reinforcement in deep coupling beams because of the relatively large shears that develop and the likelihood of shear failures under reversed seismic loadings. Since the deep connections between shear walls in the tunnel form buildings behave in a similar fashion, the reinforcement details given in Figure 8(b) and 8(c) can be suggested when the wall part above the openings of the pierced walls is deeper. These types of reinforcement details may also be addressed in the seismic codes and design provisions. If fact, the degrees of coupling between the wall parts considering the stiffness of the adjacent slabs and transverse walls in the three dimensions should be the bases for the reliable reinforcement detailing around the openings of the tunnel form buildings.

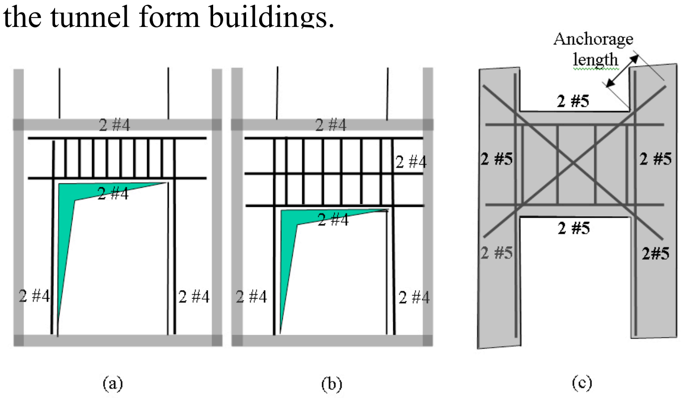


Figure 8. Reinforcement detailing around the openings of pierced shearwalls

6 CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that both analysis and experimental studies conducted on shear wall dominant buildings without considering the 3D effects of existing transverse walls as well as the diaphragm flexibilities may yield inaccurate results. In this study, the stress flow and crack patterns around the openings of pierced shear walls observed through the 3D models were found to be drastically different than those obtained for the 2D models. That was attributed to the nonexistence of contra-flexure points during the 3D behavior. The deflected shapes obtained for the sections above the openings in the 3D models demonstrated more rigid forms than those observed in the 2D models. In general, considering the interaction effects of the slabs and transverse walls during the analyses increased the overall capacity of pierced shear walls. It is further observed that despite the existence of openings introducing a strong disturbance of the shear flow within the transverse walls, these walls provided a significant contribution to the formation of the T/C coupling mechanism during the 3D behavior (Balkaya and Kalkan, 2003c). However, the magnitude of this contribution was highly affected with the opening dimensions and their locations within the transverse walls. Additionally, due to the nature of high stress concentrations around the openings, use of the diagonal shear reinforcement in addition to the edge reinforcement, may lead significant contribution for retarding and slowing down the crack propagation. For that reason, reinforcement details given in this study are recommended for various shear wall-opening configurations. The observations and experience gained from this study for the shear wall openings and their impacts on the 3D force mechanism and the general system behavior may help to accomplish more accurate design and analysis of shear wall dominant systems.

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