Comparing Effects of Openings in Concrete Shear Walls under Near-Fault Ground Motions

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SUMMARY:
The results of a time history study for tall concrete buildings are presented, addressing the effects of openings in concrete shear walls under near fault earthquake ground motions. For this challenge, two near-fault earthquakes were selected from different records of past earthquakes: Loma Prieta and Taiwan. A ten-story building was modeled with three different types of lateral resisting systems: complete shear walls, shear walls with square opening in the centre and shear wall with opening at right end side. Studied models were analyzed with nonlinear software under the two mentioned records. The results evaluated were time history of displacements and basal shears of the investigated models. Results of the analyses showed a substantial decrease in terms of strength of the wall for shear walls with openings. In the model with opening at centre of the wall, maximum lateral displacement was up to 8% less than maximum lateral displacement of the model with opening at the right end side; while for the complete shear wall that decrease was up to 17% less. The investigated building shows a specific behaviour of the openings, when compared with the complete wall case, which causes an increase in the time history of displacements. Finite element analyses of a panel with opening, showed a dramatic decline in ultimate force up to 54%. This study verified large lateral displacements and ductility for shear walls with openings in comparison with complete shear wall.

Keywords: Concrete shear wall, Openings, Displacement time history and basal shear, Earthquake records

1. INTRODUCTION

The shear wall is a structural element designed to resist lateral forces. For slender walls where the bending deformation is higher, shear wall resists the loads due to cantilever action; and for short walls where the shear deformation is higher, it resists the loads due to truss action. These walls are more important in seismically active zones because during earthquakes shear forces on the structures increase. When a building has a story without shear walls, or with poorly placed shear walls, it is known as a soft story building. This structural element can provide adequate strength and stiffness to control lateral displacements. Shear walls are usually located regularly in plan and in elevation, to minimize torsion effects in each floor due to possible offset between centre of mass and shear centre. Wall strength depends on: strength of the sheathing; the type, size, and spacing of the fasteners; the panel aspect ratio (ratio of length to width of shear panel); and the strength of the studs. Shear walls that are perforated with openings are called coupled walls. These walls act as isolated cantilevered walls connected by coupling beams (also called spandrel beams or lintels) designed for bending and shear effects. Openings are used as architectural needs to have window or doors; besides, engineers want to design buildings without shear lag under negative shear.

Many researchers have investigated the effect of opening in concrete shear wall. Elnashahi and Pinho (1998) tested a coupled shear wall at real scale. In their work, the load capacity and stress distribution around the openings were analyzed by conducting three-dimensional (3D) nonlinear pushover analyses on typical shear wall dominant building structures.

They investigated the pattern of cracks, and the connection between wall and slab; the research showed significant contribution for increasing the global lateral resistance, by the interaction between wall-to-wall and wall-to-slab.

Saheb and Desayi (1990) considered U shaped shear wall with rectangular opening in the web, under shaking table tests. To investigate the behavior of the shear walls, and to assess the validity of the numerical tool, a 3-D refined non-linear analysis was conducted. In that investigation, it was shown that the refined model is able to describe the global behavior of the structure and qualitatively the distribution of damage at the base of the specimen.

The resistant structural skeletons of tall buildings subjected to horizontal forces due to wind (or earthquake) often have double symmetry but are open sections and should therefore be analyzed including the effects of torsion-bending theory of Vlasov (1961). Two computer programs have been developed in Fortran language by Barros (1999) for the consideration of torsion-bending in the analysis of tall buildings, using the continuous medium technique in which the discretized system of horizontal links (bracing slabs and beams) at the various floors are replaced by a continuous media of equivalent stiffness along the height. The programs determine the generalized displacements and the generalized stress resultants in the structural members, in tall buildings of tubular skeleton (tube within a tube) with peripheral resisting elements and inner core, under torsion-bending.

Hui and Bing (2003) have modelled a coupled shear wall under lateral load. Experimental analysis has shown a considerable increase in lateral strength with diagonal tensile tie and compressive strut. In another research, two concrete shear walls with opening have been assessed by Doh and Fragomeni (2004). This coupled shear walls were 120*120*10 cm, with an opening with dimensions 30*30 cm. This study has been carried out to find a better behaviour for shear walls; FRP was also used to increase the strength of the shear wall.

Kheyroddin and Naderpour (2008) retrofitted the link beam in coupled shear walls using CFRP; they indicated a statistical method to increase the strength and ductility of the shear wall. Khatami (2010) studied coupled shear walls under cyclic loading and recommended optimization side for openings on concrete shear walls. Barjari (2012) investigated coupled shear walls that have been retrofitted; on these, the effect of steel reinforcing plates was seen to significantly increase the ultimate strength of coupled shear walls.

In this study, two different types of openings have been investigated. Results of three buildings with coupled shear wall, rectangular shear wall and square shear wall are compared in this investigation. All the models have been analyzed under lateral time history; their lateral displacements, energy absorption capacity and hysteretic behaviours have also been determined. An example of a coupled shear wall is shown in Figure 1.

Figure 1: Concrete shear wall with opening (Iran; Semnan 2011)

2. BUILDING MODEL AND EARTHQAUKE ACTIONS

For this study, nonlinear behavior of coupled concrete shear walls is investigated. A 10-story building with a 3-meters height for each story, regular in plan and with a coupled shear wall, is modeled. This building consists of five spans of 5-meter in X direction and three 4-meter spans in Y direction. Gravity loads on the floors of the building are considered, consisting in 6 kPa dead load and 2 kPa live load. Concrete compressive strength is 25 MPa, and yielding strength of steel is 400 MPa. Shear walls are placed in the middle of the 3rd span along the X direction. The modelled building is shown in Figure 2.

The objective of the analysis is to compare the numerical results of the effect of openings in shear walls, occurring during the seismic response of the considered reinforced concrete buildings under near-fault earthquakes. Shear walls were modelled using three different shapes. The first model considers complete shear walls, which is called 10-C-SH. Number 10 denotes the number of stories of the investigated tall building; C is short for complete and SH the abbreviation for shear wall. The other two models have openings in order to weaken the structure. Square openings were modelled in centre and right hand side, respectively, of the shear walls.

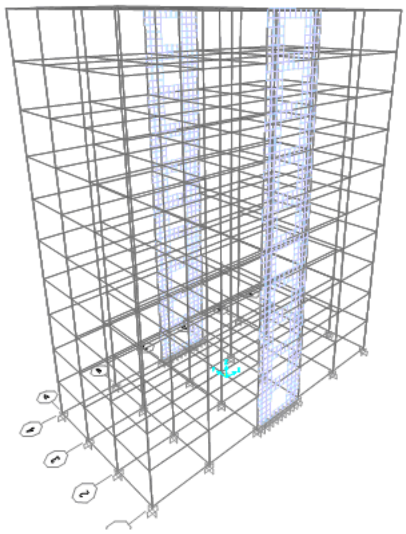


Figure 2: The analyzed building model

One of the models is denoted by 10-SH-RO, which shows square opening in right hand side of the shear wall; and the other model is denoted by 10-SH-CR, which represents the presence of the square opening in the centre of the wall. Results for the three types of shear wall are compared with each other. Quantities in this investigation that were evaluated for comparison are: lateral time history displacement and amount of energy absorption under near fault ground motion. The three models for the shear walls are represented in Figure 3.

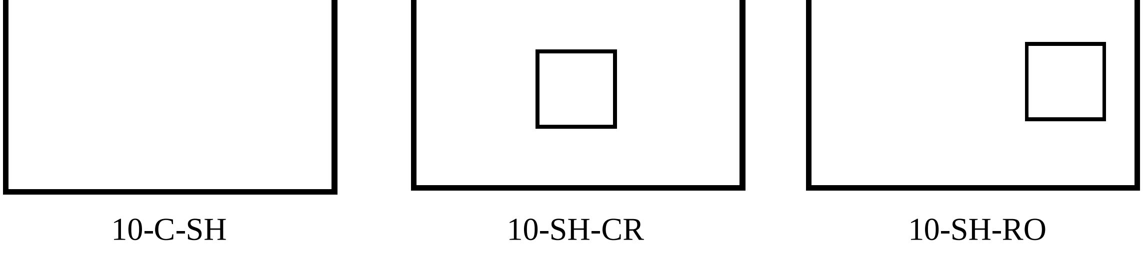
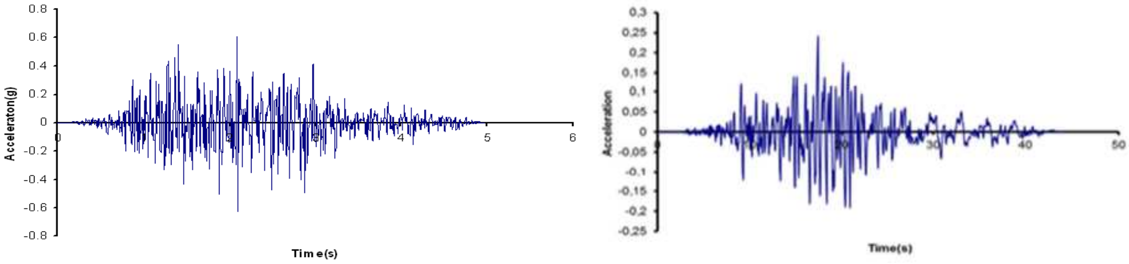


Figure 3: Three different shapes of opening

In this investigation, two earthquake records are used: Taiwan and Loma Prieta. The Taiwan earthquake occurred on 14 October 1986. Seismic excitation was strong with a magnitude of 7.30; in this record PGA was 0.207g, which occurred at a epicentre distance of 77 km. The other record used for the analysis is Loma Prieta, which occurred on 18 November 1989. With a magnitude of 6.9, this earthquake had a maximum PGA of about 0.638g. These two earthquake records (shown in Figure 4) have been selected for a comparative analysis of the results of the three different types of shear walls used in the 3D building considered.



A) Loma Prieta Record B) Taiwan Record

Figure 4: Two Near-Fault Earthquakes

3. RESULTS OF THE ANALYSIS OF THE NUMERICAL MODELS

3.1. Lateral Displacements

Numerical modelling of the buildings is performed using SAP 2000. Three different systems were considered in order to analyse the proposed modelled building. In this part of the study, the models are called complete shear wall (10CSH), shear wall with square opening in the centre of the wall (10SHCO) and shear wall with square opening at the right hand side of the wall (10SHRO). The two mentioned earthquake records were used to analyse the time history responses.

Firstly, all the models were analysed under Loma Prieta record. The nonlinear time history of displacements, shown in Figure 5, indicates a general fluctuation of top lateral displacement responses in all of the investigated models.

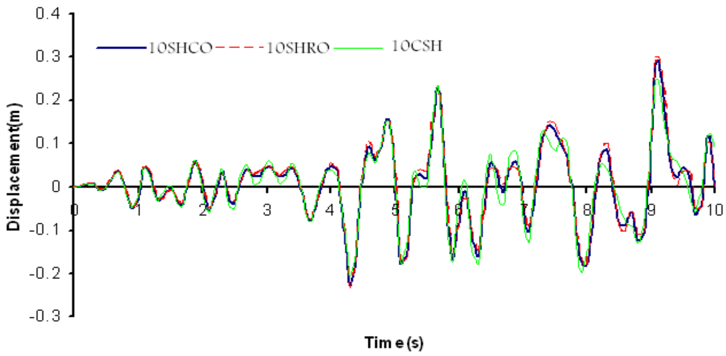


Figure 5: Time history of displacements under Loma Prieta earthquake

Maximum lateral displacement occurred in 10SHRO model, from the three studied models, at the instant of 9.2 seconds. These maxima of top lateral displacements under Loma Prieta were: 29 cm for 10SHRO model; a value of 27 cm for 10SHCO model (8% less than the maximum lateral displacement of 10SHRO model); and 25 cm for 10CSH model (17% less than for 10SHRO model).
Furthermore for the models investigated under Taiwan earthquake record (with a PGA about one third of the Loma Prieta's PGA), the obtained time history of displacements shows a more regular pattern. The maximum top lateral displacements were: 17 cm, which occurred for 10SHRO model; 15 cm, for 10SHCO model; and finally, 14 cm for the 10CSH model.

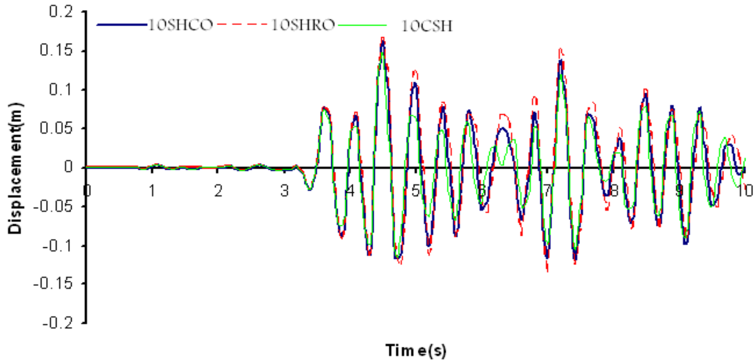


Figure 6: Time history of displacements under Taiwan earthquake

For all the models and earthquake records, the shear walls confer a considerable stiffness to the building, contributing to reductions in the lateral displacements and to increases in the lateral strength.

3.2. Energy absorption

Shear walls energy absorption at the basement first story is higher than in the other stories, and on the order of 75% of the earthquake energy (Khatami and Kheyroddin, 2010). Considering the three shear wall models of the building under Loma Prieta earthquake, the basal shear for different models has been compared with each other (Figure 7). The lowest basal shear found is 175 ton, which occurred in 10SHRO model. The basal shear rises to 850 ton for 10SHCO model. The basal shear maximum value is 1200 ton, in 10CSH model.

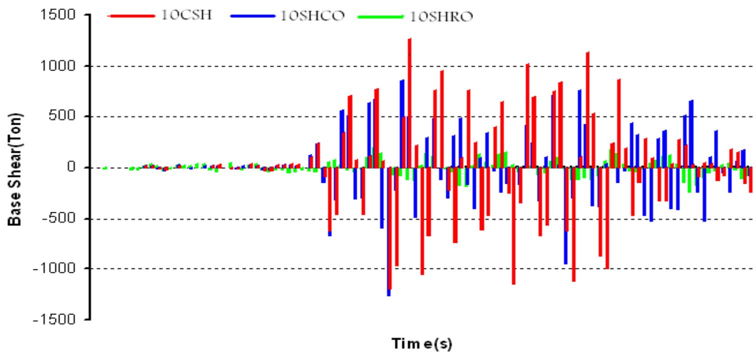


Figure 7: Energy Absorption under Loma Prieta record

For the Taiwan earthquake comparisons (Figure 8), the basal shear maximum values were evaluated as: about 800 ton in the 10CSH model; 475 ton in the 10SHCO model (about 60% of the value supported by the 10CSH model); and just 90 ton, for the 10SHRO model.

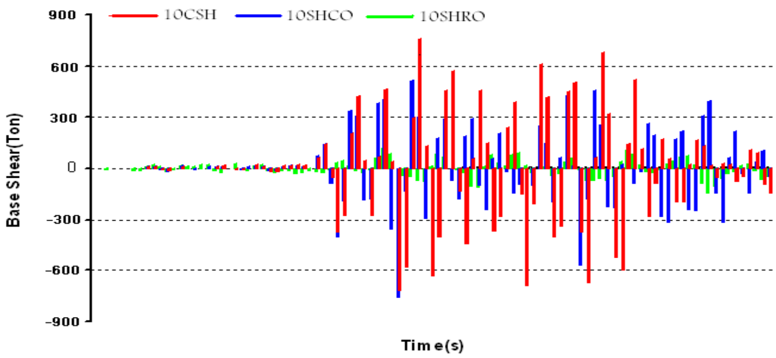


Figure 8: Energy Absorption under Taiwan record

These results indicate that with respect to the energy absorption the complete shear wall model absorbs most of the energy, in comparison with other models under near fault ground motions. The results of the analyses are summarized in Tables 3.1 and 3.2.

Table 3.1: The results of the analysis under Loma Prieta earthquake

Shear Wall Type	Maximum Lateral Displacement (cm)	Maximum Basal Shear (ton)
10 C SH	25	1200
10 SH CO	27	850
10 SH RO	29	180

Table 3.2: The results of the analysis under Taiwan earthquake

Shear Wall Type	Maximum Lateral Displacement (cm)	Maximum Basal Shear (ton)
10 C SH	14	800
10 SH CO	15	475
10 SH RO	17	90

4. COMPLEMENTARY FINITE ELEMENT ANALYSIS OF A SHEAR WALL PANEL

Three different shear wall panels are selected for investigating the influence of openings on a shear wall. The shear walls are modelled by ANSYS software (1992), using the 3D SOLID 65 element represented in Figure 9. This element is capable of cracking in tension and crushing in compression. In concrete applications, for instance, the solid capability of the element may be used to model the concrete while the rebar capability is available for modelling reinforcement behaviour. Other cases for which the element is also applicable would be reinforced composites and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions. Up to three different rebar specifications may be defined. Nonlinear behaviour, initial deflections and imperfections, and creep are other capabilities available for this element.

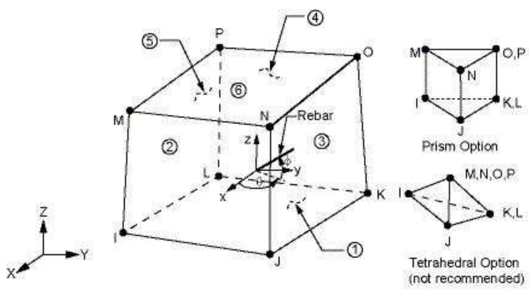


Figure 9. Solid element (SOLID 65) in ANSYS

Shear wall panels are analysed by the mentioned finite element program to assess the effect of openings on the wall. The reference model is a complete shear wall, so-called CSH. Dimensions of the wall and its thickness were selected in order that the cross-section is equal with that from the SAP 2000 model: this means that the concrete shear wall is 400*300*10 cm. Two other shear walls are also modelled with an opening in centre and at the right hand side of the wall. They are called SHCO and SHRO for centre opening and right side opening, respectively. Shape of opening is a square with size of 100*100cm. Walls have been meshed by square elements (10*10 cm). The results of past studies have shown that square meshes are able to analyse finite element model of shear walls better than other shapes (Khatami and Kheyroddin, 2011). Two input strength parameters – ultimate uni-axial tensile and compressive strength – were needed to define a failure surface for the concrete. The Poisson ratio for the concrete was assumed to be 0.2. The shear wall transfer coefficient of closed crack is 0.9 and of open crack is 0.25.

4.1. Calibration of the Used Software

To control the accuracy of the mentioned finite element program and to calibrate the meshing realised using eight-node solid elements, Doh and Fragomeni (2004) experimental work and results were herein used. Also, Hallinan and Guan (2005) examined numerically the behaviour of concrete square shear wall – tested in laboratory – with a 30 cm square opening in the middle. The wall dimensions were 120*120*10 cm (length, width and thickness, respectively) as represented in Figure 10.

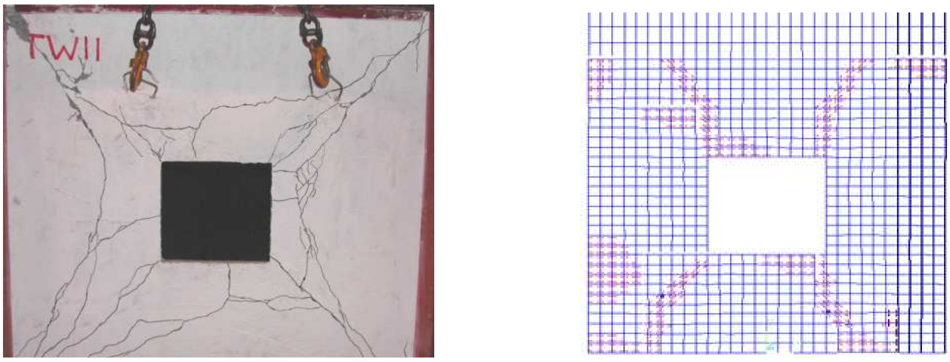


Figure 10. Experimental shear wall and ANSYS results

The shear wall is reinforced with #14 bars, positioned every 10 cm. A lateral load of 1000 kN was applied at top of the shear wall in order to push it. When the lateral load reaches to 220 kN, the wall started cracking and at this stage the lateral displacement due to this load is equal to 0.25 mm. The lateral load bearing capacity of the wall increases until reaching 1.9 mm of lateral displacement and finally it yields when the applied load is 840 kN.

It has been seen in this experiment that the cracking of the opening's corners extended and spread to the corner of the wall by increasing the amount of lateral load, until finally the shear wall was completely destroyed and collapsed at 1010 kN lateral loading force; at this collapse load the panel reached an 8 mm lateral displacement. In order to investigate the accuracy of the nonlinear analysis with the finite element program, results of mentioned experimental test were compared with the finite element program results. This comparison has been carried out to verify key aspects of the numerical model. The load-displacement curve shown in Figure 11 indicates that the results of the finite element program are very similar to the experimental results.

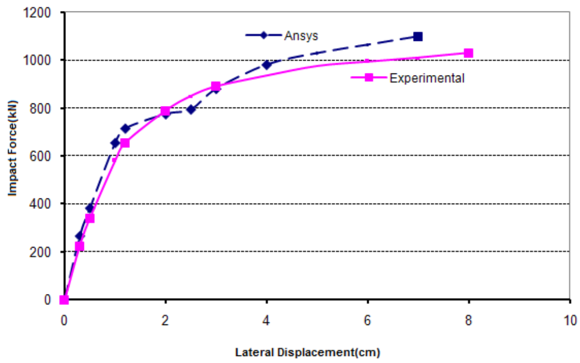


Figure 11. Comparison of results obtained with ANSYS and with the experimental analysis

The ultimate lateral strength in the finite element analysis is 1090 kN, which is 8% more than the value from the experimental investigation. Final top lateral displacement of the panel, determined by ANSYS, was 7.2 mm. Consequently, the used finite element software has shown good response.

4.2. Results for Different Panel Models

Three different types of shear wall panels (CSH, SHCO and SHRO), coherent with the shear wall typologies used earlier in the 10-floor 3D building, have been analyzed using the software ANSYS calibrated in the previous paragraph with a rational calibration case. Results of the analysis showed different responses for each panel typology. The crack patterns of the panel models are shown in Figure 12.

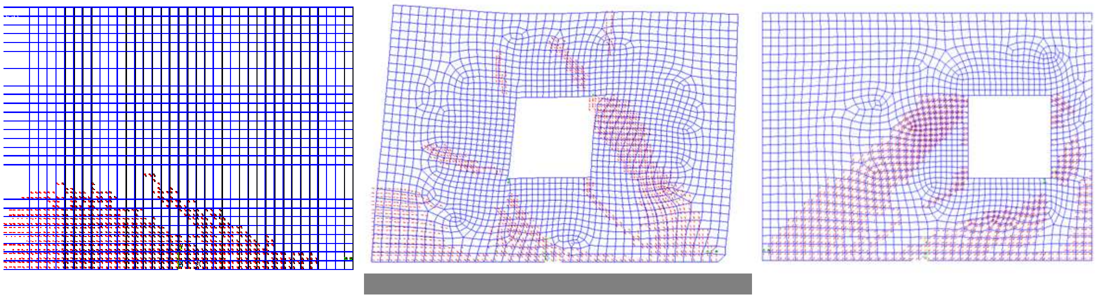


Figure 12. Crack patterns of the three analysed panel models

The results for each panel model are represented by the load-deflection paths in Figure 13, but are detailed separately below. For the CSH model (complete shear wall) the analytical value of the first crack load is 220 kN, which occurred at a displacement of 0.25 mm. Also, the failure load for this panel is 1220 kN, which obviously was the highest value of the failure load among the three analysed panel models.

For the SHCO panel model (square opening in the centre) the first crack occurs at a lateral load of 210 kN; afterwards, model still stiffens and resists load until yielding at around 685 kN. Load-displacement curve shows that the final load is about 890 kN with a 12 mm displacement at the onset of failure. In this model the ultimate load is 37% lower than the CSH panel model.

The last panel model CHRO (opening in the right hand side of the panel) the first crack load and the ultimate load were 198 kN and 790 kN, respectively; yielding occurs around 450 kN.

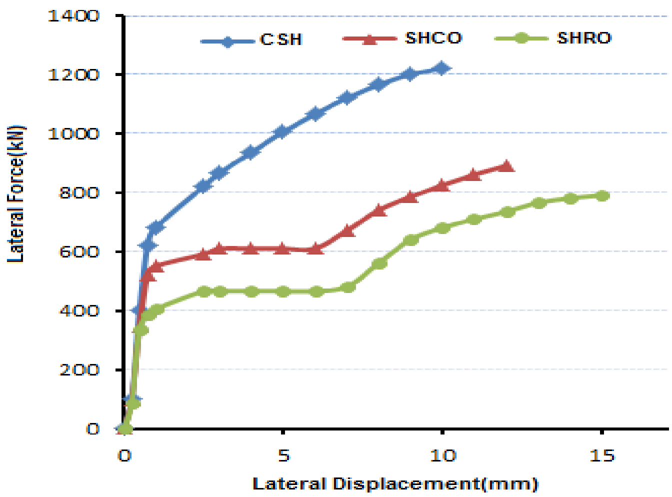


Figure 14. Comparison the Load Paths of the three panel models under lateral loads

Overall it seems that the existence of openings causes a delay in the carrying capacity of the panel to resist lateral forces. For the SHCO panel model the yielding plateau occurs between lateral displacements of 3 to 6 mm; while for the SHRO panel model, the yielding plateau is wider and occurs between 2.5 to 7.5 mm.

With increase in the loading, cracks appear in concrete and it undergoes nonlinear deformations with a slight increase in lateral load carrying capacity nevertheless causing significant deformability in the wall.

These results indicate that openings can decrease the final lateral load capacity of the shear wall up to 54% (in relation to the complete shear wall case). It is also recommended that openings be situated at the center of the corresponding shear walls, minimizing decrease of strength and the increase of deformations for lower loads.

Table 4.1: The results of panel model analysis under Loma Prieta earthquake

	Maximum Lateral Force (kN)	Yielding Displacement (mm)	Maximum Lateral Displacement (mm)	Ductility
CSH	1220	1.2	10	8.33
SHCO	890	1.3	12	9.23
SHRO	790	1.3	15.5	11.93

5. CONCLUSIONS

Three different structural systems of a 3D building with shear wall, under two near-fault ground motions, were analyzed. Lateral displacements and basal shears were selected as the comparative quantities in a first study of the buildings by using SAP 2000. The final ultimate resisting lateral force and the top lateral displacement were selected in a second study of almost square panel models (without and with opening) by using ANSYS. In the first study, the complete shear wall of the 3D building was able to absorb more energy than other investigated models of shear wall with openings. As opening decreases lateral carrying capacities of shear walls and panels, the second study also indicated a deformation delay – of the panel with opening as compared with the complete panel – occurring at the yielding load level. These facts are characteristic of the behavior and performance of shear walls and panel with openings, decreasing their role in lateral load carrying capacity.

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