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Assessing 3D Earthquake Behaviour of Nonstructural Components Under Eurocode 8 Standard

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ABSTRACT

This study presents the earthquake performance of nonstructural components (NCs) anchored to a reinforced concrete (RC) building. For this purpose, 5 multi-storey RC building is modelled as three dimensional (3D) using SAP2000 software based on finite element approach. Brick, bookcase, bedroom, armchair, washing machine, dish washer, refrigerator is considered as non-structural components in 3D numerical analyses. These NSCs are modelled in the RC building taking into account Eurocode 8 seismic design standard. For this standard, it is assumed that NSCs were anchored to building. One component of 1989 Loma-Prieta earthquake (epicenter distance: 23 km) is used in the 3D numerical analyses. Earthquake analysis is examined as with/without NCs. According to numerical analysis results, it is clearly seen that NCs obviously effect earthquake behaviour of RC building and different displacements, shear forces, seismic accelerations on selected columns are obtained for this standard. It is strongly recommended that while modelling a RC building, nonstructural elements should not be ignored.

Introduction

Nonstructural components (NSCs) are crucial for the service life of buildings and include most of the structure costs (Giuseppe et al. 2018, Taghavi and Miranda 2003). In recent years, the destruction or damage of nonstructural systems during strong ground motions has caused considerably rising of repair costs and construction time (Fierro et al. 2011, Dhakal 2010, Miranda et al. 2012). Therefore, interest on NSCs has recently increased visibly. In order to achieve a very perfect seismic performance, it is necessary to provide good coordination of structural and non-structural performance. NSCs, generally referred to as secondary systems in the literature, include elements fixed to the floors, bearing elements and roof of a building and do not contribute to the dead, live or seismic load capacity of the structures (Pürgstaller et al. 2020). These important components are generally classified in three different groups; (a) architectural components, (b) mechanical and electrical equipment, and (c) building

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contents (Villaverde 1997). The importance of non-structural components has just begun to be understood and has been begun to be explored by researchers in recent years. Firstly, Pantelides et al. have pioneered to perform studies on non-structural elements (Pantelies 1996). In that study, by using ABAQUS and SAP 90 programs, the nonlinear earthquake behavior of a single story commercial building consisting of masonry walls, glass and aluminum workshop, and a steel bar joist metal deck roof system was examined. It was emphasized that testing architectural glass the in plane drifts are more important than other non-structural components. Sucuoğlu and Vallabhan examined earthquake behaviour of window glass panels (Sucuoğlu and Vallabhan 1997). An analytical procedure has been developed to calculate the in-plane deformation capacity and out-of-plane resistance of window panes exposed to seismic loading. Xue et al. applied direct displacement design techniques to the structures by considering the performance-based seismic design code. In this technique, nonstructural components are designed taking into account either acceleration or displacement and the non-structural damage is limited by the structural drift limit (Xue et al. 2008). Then, in a study, the seismic effects of non-structural component parameters i.e. building height, number of bays, ratio of area of shear walls to area of floor, ratio of infilled panels to total number of panels and type of frame on the earthquake periods of reinforced concrete structures were examined. A new procedure, which was a function of considered parameters, was proposed for predicting of earthquake period of buildings. It was clearly seen that this proposed procedure provides a better estimate of seismic periods when compared with other standards (Kose 2009). Hou et al. focused on developing recommendations for obtaining the horizontal earthquake forces on the nonstructural components anchored to a structure. It was clearly seen that the existing analysis methods is not inadequate to observe the horizontal seismic forces on the nonstructural components. Moreover, according to test results, a practical model which can well capture the central tendency of the test results and can be integrated into the existing design method was developed (Hou et al. 2018). An important method was proposed for examining the nonlinear earthquake response of nonstructural components attached to building structures. For this method obtained for seismic behaviour of the nonstructural components, the geometric characteristics, weights, and target ductility of the nonstructural component requires (Villaverde 2006). As seen from these studies, there are very few studies on seismic performance of nonstructural components in the literature. Besides, according to EUROCODE seismic design standard, seismic effects of nonstructural components on 3D middle fault (23 km) earthquake performance of reinforced concrete buildings collapsed during middle fault earthquake have been rarely examined in the past. In this study, seismic displacement, shear force and seismic acceleration behaviors of a RC building are examined considering nonstructural components and middle fault earthquakes. This RC building was constructed in 1956 in Sakarya-Turkey and this structure was subjected to a strong earthquake (Mw: 7.4). The building was completely destroyed during the earthquake and many lives were lost in this structure. Therefore, it is very important to examine this structure and to investigate why it was destroyed. For this purpose, this RC building is modelled as three dimensional (3D) and SAP2000 software is used for modelling. All bearing elements (beams, columns and foundation) are modelled according to original project and original concrete grade of bearing elements is defined to software. Middle fault components (x-y-z) of 1989 Loma-Prieta earthquakes are used in the 3D numerical analyses. Firstly, RC structure was analyzed only by considering the structural elements (without NSCs). Then, nonstructural elements are modelled in the structure considering EUROCODE standard. Brick, bookcase, bedroom, armchair, washing machine, dish washer, refrigerator is considered as non-structural components in the numerical analyses. Seismic forces for all non-structural elements were calculated separately for each floor according to EUROCODE standard and all computed nonstructural forces for this standard are implemented to 3D model considering main places of the nonstructural components in the building. Secondly, building is analyzed considering nonstructural components. According to 3D numerical analysis results, seismic displacements, shear forces and seismic accelerations on the different columns for with/without NSCs are compared in detail. As a result of all analyses, it has been understood that non-structural elements have a great importance on the seismic behavior of RC structures and it is strongly recommended that nonstructural elements should be included in the structural analyzing.

EUROCODE Provision for non-structural component force

Earthquake accelerations to which non-structural components (NSCs) are exposed are higher than those in the building due to the amplification of ground motion along the height of the building. Therefore, examination of seismic effects of NSCs on earthquake behaviour of RC buildings is very important for safety and future of these structures. Eurocode 8 (Design of structures for earthquake resistance) have been created in 2004. According to Eurocode 8 standard, non-structural elements should be modeled taking into account ground motion, structural amplification, soil factor, and self-weight, flexibility and importance of the non-structural element. The effects of the seismic loads on nonstructural components are determined by applying to the nonstructural element force (Fig. 1) which is defined as follows.

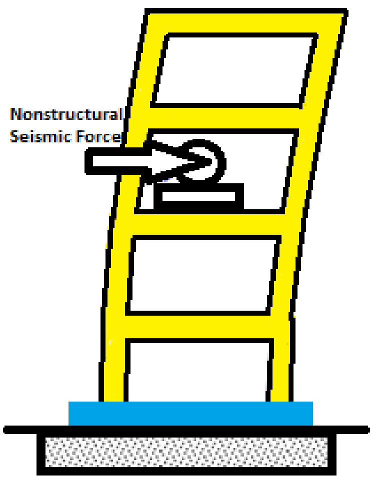


Fig. 1 Non-structural component force in the structure.

$$F_{pg} = \frac{S_a W_a \gamma_a}{q_a} \qquad (1)$$

and Sa is computed as Eq.

$$S_a = \frac{a_g}{g} S \left[\frac{3 \times \left(1 + \frac{z}{H}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - 0.5 \right] \tag{2}$$

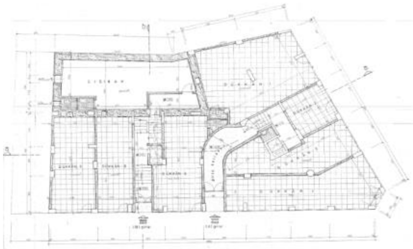
where
F= Non-structural component force.
Wp= Weight of non-structural component.
γa= importance factor which ranges from 1.5 for important and/or hazardous elements to 1.0 for all other elements.
qa= behaviour factor for non-structural elements equal to either 1.0 or 2.0 depending on their behavior during earthquake shaking. For example, behaviour factor for cantilever parapets or ornamentation, signs and billboards, chimneys, and tanks are assigned as 1.0 while that for exterior and interior walls, partitions and facades, anchorage elements for false ceilings and light fixtures is assigned as 2.0.
ag= Design ground acceleration.
g= acceleration of gravity.
S= Soil factor.
z= height of the non-structural element above the base of the building.
H= Total height of the building.
Ta= Fundamental period of the non-structural element.
T1= Fundamental period of the building in the relevant direction.

General Information about RC Building

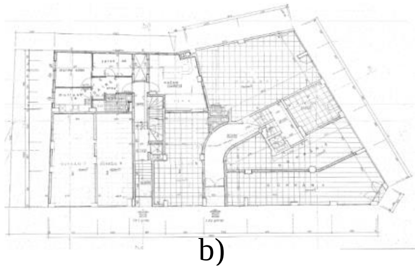
In this study, middle fault seismic effects of nonstructural components (NSCs) on the earthquake behaviour of reinforced concrete (RC) buildings are aimed to examine by using SAP2000 software based on the finite element method. For this purpose, a RC building, collapsed in a strong earthquake, is selected for three dimensional (3D) numerical analyses (Fig. 2a). This structure was built in 1956 in Sakarya-Turkey and it has 5 multi floors. This building is located very close to the sea and this building was actively used by people for 44 years. The lowest floor is intended for people sitting in the building to store excess goods. The other floors are actively used by people. The most critical sections of these floors are shown in Fig. 3. Each floor has polygonal geometry and has two balconies. Foundation class of the structure is a B. This building was destroyed in a severe earthquake in 1999 and the appearance of the demolished structure is presented in Figure 2b. As a result of the examinations made after the building was destroyed, the most fragile and damaged columns of the building were identified. The building was first broken from 3 different sections during the earthquake, and after these three different areas were damaged, the building collapsed suddenly. In this study, A-A cross-section, B-B cross-section and C-C cross-section, which are the different regions detected, were examined. The location of these sections in the structure is presented in detail in the next section.


a) b)

Fig. 2 Before and b) after views of collapsed RC structure.



a)



b)

c)

d)

e)

Fig. 3 Sections of structure floors a) first floor b) second floor c) third floor d) fourth floor e) fifth floor.

3D Modelling Structural and Nonstructural Components of RC Building and Ground Motions

In this study, it is aimed to examine the seismic displacement, shear force and seismic acceleration performance of nonstructural components. For this purpose, five multi-storey RC building collapsed in a strong earthquake is selected for three dimensional modelling and SAP2000 software based on finite element method is utilized while modelling of this structure.

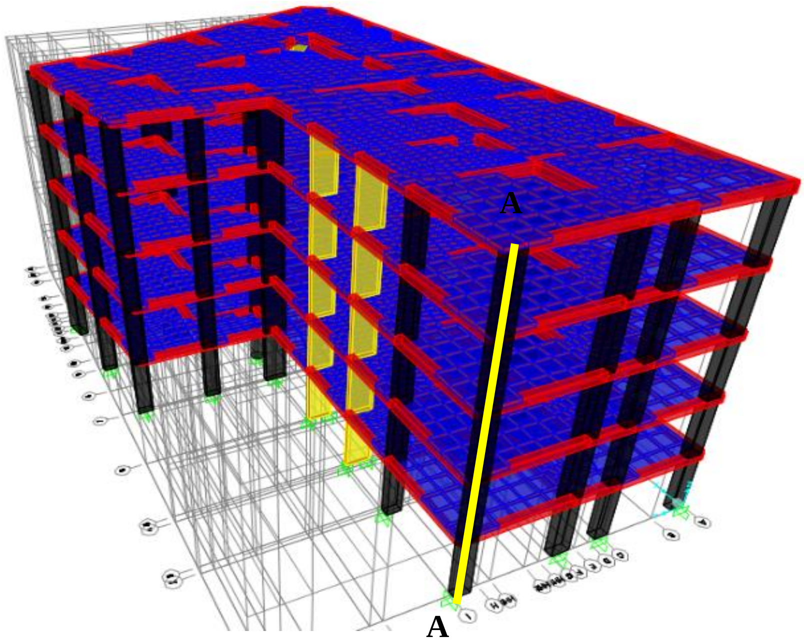


Fig. 4 3D model of RC structure.

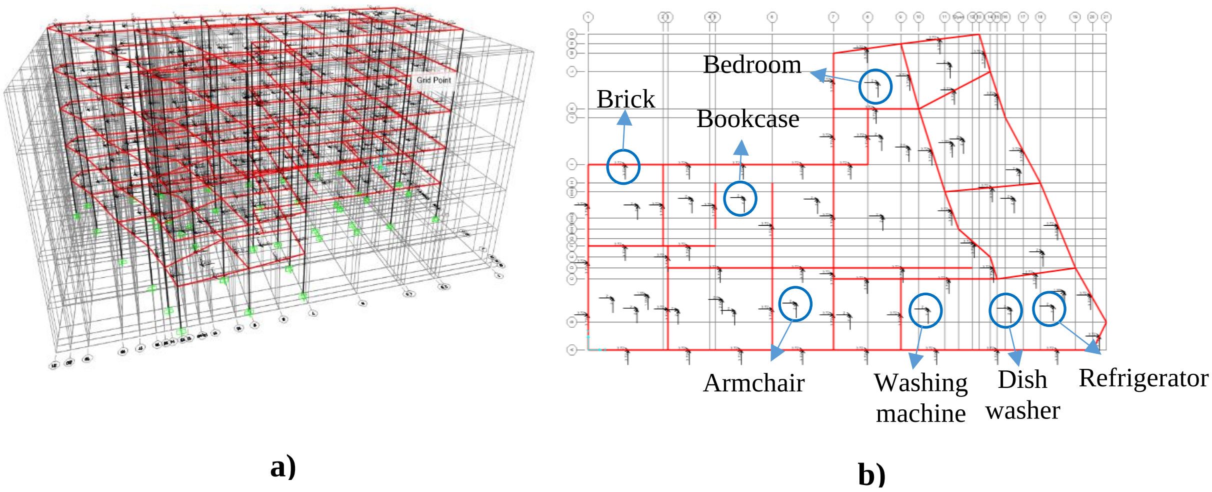
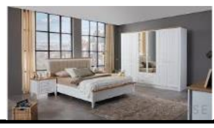


Fig. 5 Nonstructural component loads in the structure a) general view of nonstructural components b) nonstructural component loads of fifth floor .

Table 1 Seismic Forces of Nonstructural Components for Different Standards.

Non-structural components (NSCs)	Figure of NSCs	Floor	EUROCODE
Brick		*First*	165
		Second	217
		Third	271
		Fourth	324
		Fifth	382
Washing Machine		*First*	48
		Second	67
		Third	87
		Fourth	108
		Fifth	119
Dish Washer		*First*	47
		Second	64
		Third	77
		Fourth	89
		Fifth	102
Refrigator		*First*	54
		Second	71
		Third	89
		Fourth	107
		Fifth	118
Armchair		*First*	34
		Second	46
		Third	59
		Fourth	70
		Fifth	82
Bedroom		*First*	130
		Second	206
		Third	261
		Fourth	307
		Fifth	361
Bookcase		*First*	51
		Second	69
		Third	88
		Fourth	103
		Fifth	121

While modelling this RC structure, 6 different columns are defined to the software and width-height of these columns are 30x75 cm, 30x95 cm, 35x60 cm, 35x75 cm, 35x90 cm and 35x115 cm, respectively. Moreover, there is a circular column in the structure and its diameter is 65 cm. Then, width-height of beams that were used in the 3D model are 25x40 cm, 30x40 cm and 30x45 cm, respectively. Class of concrete of columns and beams are C20 and this value is obtained from original structure project. In the structure, there are totally 2 different shear walls and their widths are 20 cm and 25 cm. In addition, thickness of floor covering is 20 cm for all floors. Height of each floor is 3 m and there are totally 5 floors in the structure. Firstly, structural components are created according to original structure project and then, nonstructural components are defined to the structure. While modelling structural components, mass source is defined to software using dead and live loads. Rigid diaphragms are created in the structure considering constraint z axis. Nonlinear time history analyses are performed according to direct integration solution type. Hilber-Hughes-Taylor method is taken into account in the 3D analyses and its gamma and beta value is 0.5 and 0.25, respectively. G+Q+E combination is used in the time history analyses. 3D model of structure is shown in Fig. 4. Secondly, nonstructural elements (brick, bookcase, bedroom, armchair, washing machine, dish washer, refrigerator) are created according to original place of nonstructural building elements. Nonstructural component loads are calculated according to 5 different seismic design standards. After calculated these loads, nonstructural loads are defined to software considering original places of nonstructural components in the structure (Fig. 5). Calculated loads according to these design standards are presented in Table 1. Moreover, earthquake accelerations for far, middle and middle fault ground motions were used in 3D earthquake analyses are shown in Fig. 6. According to Fig. 6, maximum acceleration for middle fault earthquake is 3.97 m/s^2.

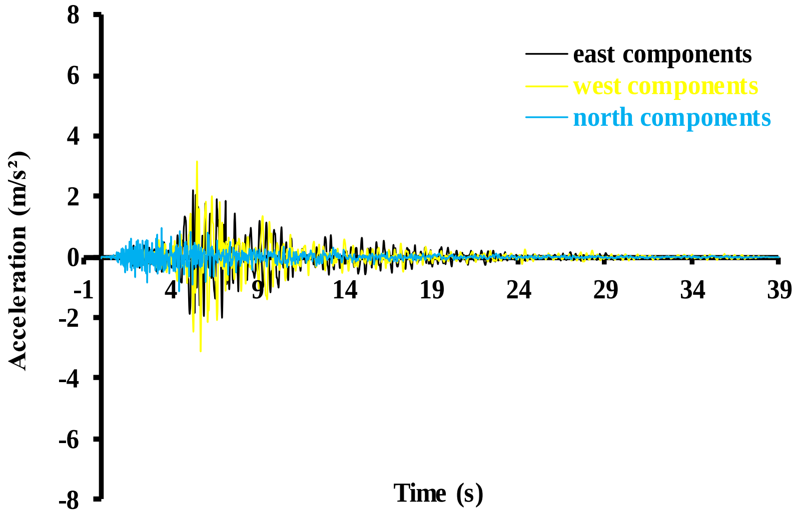


Fig. 6 Time History Graphics for Middle Fault Ground Motions.

Three Dimensional Nonlinear Seismic Analysis Results

Many researchers around the world ignore the nonstructural components when performed seismic modeling of structures. However, although the nonstructural elements cannot bear any load, they can clearly change the seismic behavior of the structures during an earthquake. Therefore, in this study, the importance of non-structural components on the earthquake behavior of the structures has been revealed in detail. In this section, the earthquake behavior of an RC building modelled as three dimensions is presented by considering the nonstructural elements. This building was destroyed in a severe earthquake in 1999. The most critical section of structure (section A-A) that caused the building to be demolished is selected for investigation and earthquake displacement, shear force and acceleration behaviors for selected sections are presented in this section. Nonstructural components have been examined considering EUROCODE seismic design standards. For the most critical section selected from the structure, 3D numerical seismic analysis results are shown in detail below.

3D Seismic displacement, shear force and acceleration results along A-A axis of structure

One of the most critical sections that cause the building to be destroyed during the earthquake is A-A section. View of this section is presented in Figure 7 in detail. Section A-A is dealt with for different nodal points at the floor level and seismic analysis results are shown for these different nodal points. Besides, maximum seismic displacement results for middle fault earthquake are summarized in Table 2. For Point A1, 1.39 mm maximum displacements are acquired for structure without NSC in near fault earthquake. When nonstructural components are placed in the structure, significant displacement differences are observed on nodal Point A1. 1.81 mm maximum displacements are gained in the middle fault earthquake for EUROCODE standard. In addition, nonstructural components significantly increase maximum seismic displacements of the structure. When Point A2 is examined, the importance of nonstructural elements on nonlinear seismic displacement behaviour of RC structures is understood seriously. According to Table 2, 3.74 mm maximum displacement is observed in the middle fault earthquake for structure without NSC. After modelled the nonstructural components in the structure, 4.53 mm maximum seismic displacements are observed in the middle fault earthquake for EUROCODE, standard. For Point A3, more displacements are acquired than Points A1 and A2. In spite of the maximum displacement for structure without NSC is 6.01 mm, it has been observed that the maximum displacements in the structure with nonstructural elements are much larger than 8.21 mm.

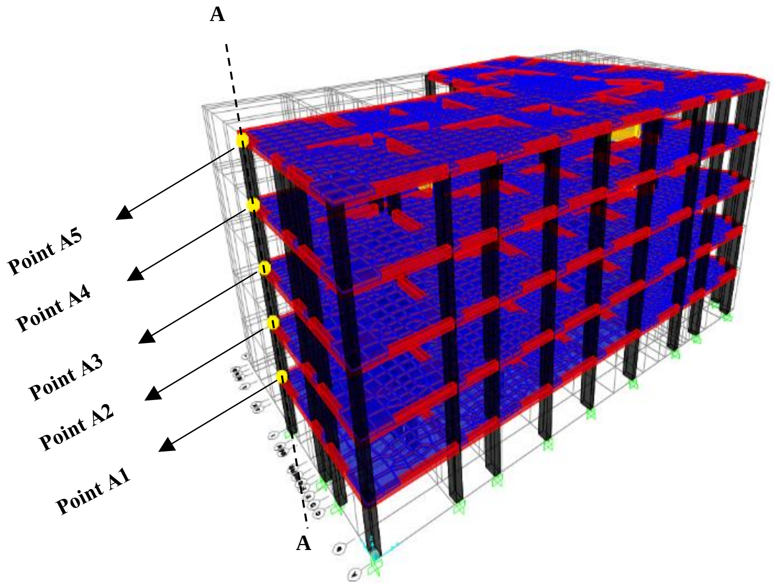


Fig. 7 View of A-A section of Structure.

For A4 and A5 points, larger displacements are obtained than other points. Moreover, for Points A4 and A5, it is clearly seen that nonstructural components increase the seismic displacement behaviour of RC structure. In case of compared to Point A1, approximately 11 mm more displacement is obtained for Point A5. Although 9.54 mm maximum displacement occurred for structure without NSC in the middle fault earthquake at 15 m of structure height, it is obviously observed that the maximum displacement acquired by considering the EUROCODE standard on same nodal point is 13.52 mm for structure with NSC.

Table 2. Displacement results for A-A section.

	Point	*Situation of Structure*	*Middle-Fault (mm)*
X Displacements along A	**Point A1 (3 m)**	Empty Structure	1.39
		Eurocode 8 Standard	1.81
	Point A2 (6 m)	Empty Structure	3.74
		Eurocode 8 Standard	4.53
	Point A3 (9 m)	Empty Structure	6.01
		Eurocode 8 Standard	8.21
	Point A4 (12 m)	Empty Structure	7.85
		Eurocode 8 Standard	11.54
	Point A5 (15 m)	Empty Structure	9.54
		Eurocode 8 Standard	13.52

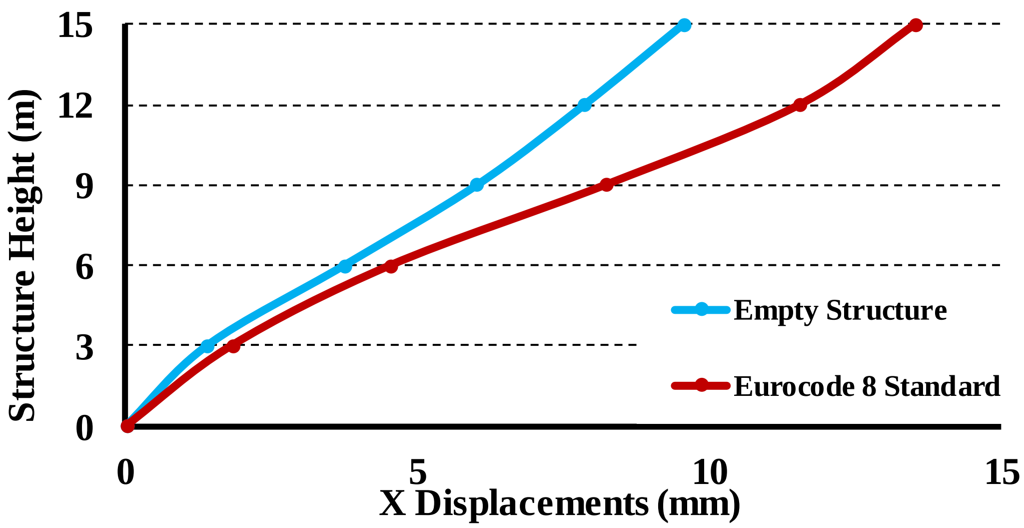
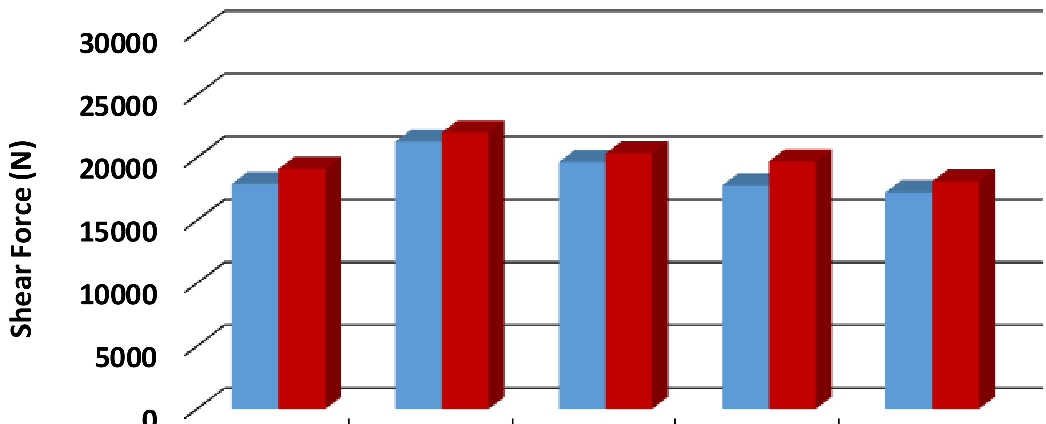


Fig. 8 Displacements along Axis A-A for Middle-Fault earthquake.

Seismic displacement results observed along height of structure are graphically shown in Fig. 8. For Fig. 8, vertical column in the figure represents the building height and the horizontal column in the figure shows the seismic displacements obtained throughout building height. Besides, 3m, 6m, 9m, 12m and 15m of the height of the building represent Points A1, A2, A3, A4 and A5, respectively. According to Figure 8, the seismic effects of nonstructural elements on RC structures clearly appear. In Figure 8, seismic displacement results are presented graphically for the middle fault earthquake. For middle fault earthquake, it is clearly understood how nonstructural elements change the seismic displacement behavior of the structure (Fig. 8). According to Figures 9, the maximum shear force results took place on 5 different nodal points along the A-A section are presented graphically. Shear forces occurred in middle fault earthquake on section A-A are presented in Figure 9. According to Fig. 9, maximum shear force is obtained for EUROCODE standard and minimum shear force is observed for structure without nonstructural elements. According to these results, the effects of nonstructural elements on the seismic shear force behavior of RC structures are clearly seen.



	Point A1 (N)	Point A2 (N)	Point A3 (N)	Point A4 (N)	Point A5 (N)
Empty Structure	17903	21263	19657	17779	17236
Eurocode 8 Standard	19112	22013	20326	19703	18103

Fig. 9 Shear Forces along Axis A-A for middle-fault earthquake.

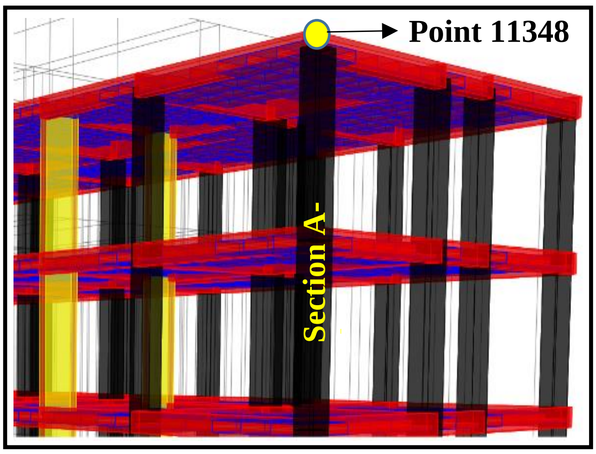


Fig. 10 View of the highest nodal point on section A-A.

According to 3D numerical results gained above, maximum displacements are observed on the highest point of the A-A section (Point 11348). For this reason, by taking this nodal point as reference, the acceleration values on this point are examined in detail. Seismic accelerations occurred along middle fault earthquake on Point 11348, which is the highest nodal point selected on the A-A section (Fig. 10), are presented in Figs. 11-12. Accelerations occurred on Point 11348 are shown in Figure 11 for structure without nonstructural component. According to Figure 10, maximum acceleration (1815 mm/sec^2) is acquired for middle fault earthquake and this value is observed in the 28.17th second of the earthquake. In case of nonstructural components are added to the structure, it is observed that the seismic acceleration values that occurred during the earthquake increased on the same nodal point. The acceleration values obtained by considering EUROCODE standard for structure with nonstructural element are presented in Figure 12. According to Figure 12, it is understood that the maximum acceleration values on Point 11348 consisted in the middle fault earthquake and this maximum acceleration value is 6781 mm/sec^2. If Figs. 11 and 12 are compared with each other, it is obviously seen how nonstructural elements change the seismic acceleration behavior of RC structures.

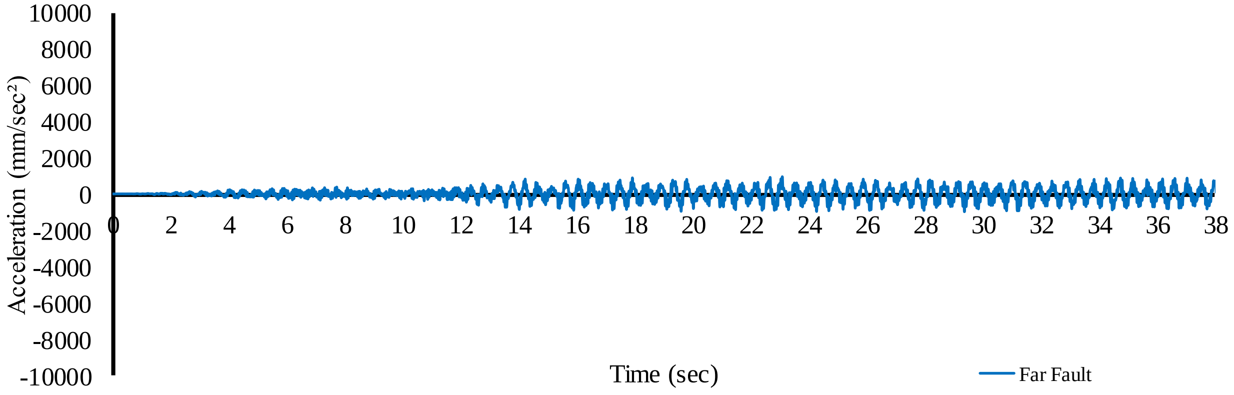


Fig. 11 Seismic accelerations on Point 11348 during middle fault earthquake for structure without NSC.

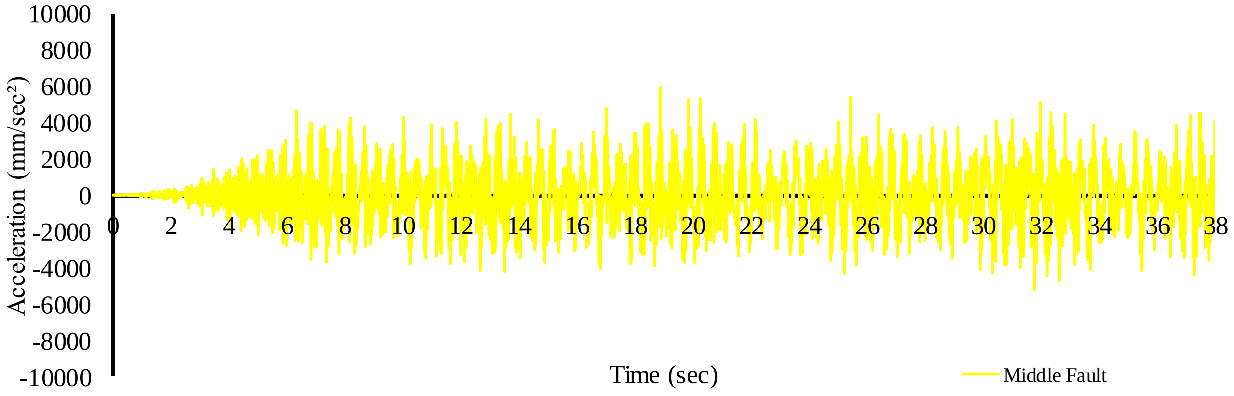


Fig. 12 Seismic accelerations on Point 11348 during middle fault earthquake for structure with NSC (according to EUROCODE standard).

Conclusions

In this study, three dimensional (3D) nonlinear seismic hazard performance of nonstructural components (NSCs) is evaluated considering EUROCODE structural design code. Structure is modelled both with NSCs and without NSCs and 3D seismic performance analyses are performed under middle fault components of 1989 Loma-Prieta earthquake (fault distances to structure: 23 km). Total 7 various furniture are taken into account as NSCs in the numerical analyses and these NSCs are brick, bookcase, bedroom, armchair, washing machine, dish washer, refrigerator. Seismic loads of NSCs are calculated according to EUROCODE structural design code and these loads are applied to 3D model of RC structure. As a result of this study, the following important results have been obtained.

- NSCs are vital for evaluating of seismic damage performances of RC structures. In this paper, it is clearly observed that these components obviously affect displacement, shear force, acceleration behaviors of RC structures. When compared seismic performance of structure with/without NSCs, more displacements, shear forces and seismic accelerations are observed on selected structural columns for structure with NSCs. This result clearly shows importance of NSCs for RC structures.
- The largest shear forces occurred at 6 m level (on Point 2) of structure height.
- It has been observed that nonstructural elements clearly increase the seismic acceleration values occurred on structural elements in RC structures.
- Nonstructural elements are of great importance for the seismic behavior and structure safety of RC structures. It is highly recommended to never neglect nonstructural elements when modeling an RC structure.

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