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Influence of openings of infill wall on seismic vulnerability of existing RC structures

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Abstract. The contribution of infill wall is generally not considered in the structural analysis of reinforced concrete (RC) structures due to the lack of knowledge of the complex behavior of the infilled frame of RC structures. However, one of the significant factors affecting structural behavior and earthquake performance of RC structures is the infill wall. Considering structural and architectural features of RC structures, any infill wall may have openings with different amounts and aspect ratios. In the present study, the influence of infill walls with different opening rates on the structural behaviors and earthquake performance of existing RC structures were evaluated. Therefore, the change in the opening ratio in the infill wall has been investigated for monitoring the change in structural behavior and performance of the RC structures. The earthquake performance levels of existing RC structures with different structural properties were determined by detecting the damage levels of load-carrying components. The results of the analyzes indicate that the infill wall can completely change the distribution of column and beam damage level. It was observed that the openings in the walls had serious impact on the parameters affecting the behavior and earthquake performance of the RC structures. The infill walls have a beneficial effect on the earthquake performance of RC structures, provided they are placed regularly and there are appropriate openings rate throughout the RC structures and they do not cause structural irregularities.

Keywords: infill wall openings; seismic vulnerability; earthquake performance; RC structures

1. Introduction

It is realized by considering the earthquakes in recent years and their places of occurrence that a large part of the settlements in the world are located on the active earthquake zones. Most residential structures in settlements are RC structures with infill walls, which are a common structural system in many parts of the world (Fardis 2006, Cavaleri *et al*. 2017). If the infill walls are appropriately distributed throughout the RC structures and properly maintained, they usually have a beneficial effect on the earthquake performance and response of the RC structures (Shariq *et al*. 2008, Asteris *et al*. 2012, Ricci *et al*. 2008, Asteris *et al*. 2016, 2017a, b, Pasca *et al*. 2017, Behnam and Shojaei 2018, Dilmaç *et al*. 2018, Kostinakis and Athanatopoulou 2019). However, the contribution of the infill wall is usually not considered due to a lack of knowledge of the behavior of the surrounding frame and the infill wall (Asteris *et al*. 2012).

In recent years, a large number of experimental and numerical analyzes have been occurred by researchers, particularly on the effect and contribution of the infill wall on the seismic behavior and performance. In some of the studies, the effect of the modeling of the infill wall materials and components elements with the infill wall on the seismic behavior of RC structures were examined (Uva *et al*. 2012, Muho *et al*. 2019). In addition, the simplified mathematical methods were presented to predict the in-plane/out-of-plane behaviors and modes of infill walls in RC structures (Crowley and Pinho 2006, Asteris *et al*. 2011, Chrysostomou and Asteris 2012). Similarly, some studies have been carried out to determine the seismic behaviors of RC structures with infill walls using experimental evaluation, energy-based assessment, probabilistic approach or shaking-table test to improve strengthening methods and earthquake performance (Penna *et al*. 2014, Sattar and Liel 2016, Khoshnoud and Marsono 2016, Furtado *et al*. 2016, Merter *et al*. 2017, Benavent-Climent *et al*. 2018, Peng and Guner 2018).

In the modeling of RC structures, infill wall is generally considered as equivalent compressive diagonal struts. The diagonal strut approach was developed for the nonlinear analysis of structures with infill walls subjected to seismic forces, and its effect on structural behavior was examined (Saneinejad and Hobbs 1995). This approach was developed for the openings in the infill wall, and the effect on seismic behavior was investigated by considering a reduction factor. Considering the limited ductility of the fillers, the approach regards the nonlinear behavior of the infill wall. This approach to stimulate the behavior of infill walls has been found to be accurately sufficient to assess the seismic response of infilled RC frame structures (Perera 2005, Samoil'a 2012).

When considering the architectural properties of RC structures, infill walls usually have openings in certain proportions for different purpose. Therefore, the effect of the infill wall with openings on the reduction of rigidity and fundamental periods of filled RC structures is determined

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by analysis and experimental studies (Asteris 2003, Asteris *et al*. 2015a, b, 2016). One of the important parameters is the fundamental period of vibration, which is critical for the seismic design of structures according to the modal superposition method. Although the presence of infill walls in structures significantly increase the structure weight and seismic design loads, it has a positive contribution to stiffness and earthquake safety (Asteris *et al*. 2017). In addition, the location and size of the infill wall with openings are also considered as parameters. However, the contribution of the infill wall on the seismic behavior an performance is not exactly determined, as it would be taken from the expression “In spite of the general success of modeling infilled frames with solid panels, major difficulties still remain unresolved regarding the modeling approach for infilled frames with opening” in FEMA 306 (1999).

Although infill walls are not accepted as load-carrying system elements per se, their interaction with RC frames significantly affect the dynamic and static behavior of an RC structure in terms of ductility, rigidity, strength and earthquake performance. The main aim of this study was to investigate the effect of window and door openings in infill walls on the earthquake performance and dynamic parameters of RC structures. In this paper, a three-dimensional modeling of existing RC structures with different structural properties was made according to project information, plans and architectural properties. The nonlinear analysis of existing RC structures was performed using the SAP2000 software (2002). The effect of likely opening rates in the walls on damage levels of load-carrying components and their impact on earthquake performance were examined. Therefore, the change in the opening ratio in the infill wall has been investigated for monitoring the change in structural behavior and performance of the RC structures. The results of the analyzes indicate that the infill wall can completely change the distribution of column and beam damage level. It is observed that the openings in the walls have a serious impact on the parameters affecting the behavior and earthquake performance of RC structures. The infill walls have a beneficial effect on earthquake performance of RC structure, provided they are placed regularly and there are appropriate openings rate throughout the RC structures and they do not cause structural irregularities. The earthquake performance analyzes of the RC structures were carried out by considering the requirements of the Turkish Earthquake Code (TEC) (2007).

2. Earthquake performance of existing RC structures

The first step in the earthquake performance analysis of existing RC structures is to collect information about the construction year, structural features and the material strengths. According to the collected the information for existing RC structures that classified with scope of the structural data and the load-carrying system of structures. These levels are “limited”, “moderate” and “comprehensive”. The information factors are applied to the calculated member capacities, which are 0.75 for the limited, 0.90 for the moderate, and 1.0 for the comprehensive knowledge levels, respectively (TEC 2007).

The pushover analysis with single mode method is used in the numerical analyses that lateral loads are increased until the seismic displacement demand is reached in this paper. The base shear force against the roof displacement curves is obtained by using plastic hinges at the both ends of the columns and beams. the steel tensile strain and concrete compressive strain demands are determined by considering the moment-curvature diagrams. The determined moment-curvature diagrams of column and beams are obtained using the confined and unconfined concrete models developed (Mander 1988). The calculated strain demands are compared with the damage limits to determine the damage level in concrete section. The base shear force against the roof displacement curves is obtained by using plastic hinges at the midpoint of the equivalent compressive diagonal struts for modeling of the infill wall. The infill wall compressive force demands at the plastic regions are calculated with the help of the force-displacement diagram. The inelastic behavior of the infill wall and level of damage according to the level of seismic load are investigated by using adoption of the plastic hinge method (Panagiotakos and Fardis 1996). The tensile strength values of the infill wall are used in the calculation of the axial load hinge to be assigned on the equivalent diagonal strut. However, the damages occurring in the walls under the influence of earthquake loads are not considered in the RC structure performance evaluation. Their damage levels are often not taken into account due to the lack of the information of the composite behavior of the surrounding frame and the infill wall. Therefore, the earthquake performance of RC structures is determined according to the damage levels of beams and column.

The TEC (2007) defines three damage limits that concrete and steel strain limits at the fibers of a cross section for minimum damage limit (MN), safety limit (SL), and collapse limit (CL). The earthquake performance levels of structures are defined after determining the damage levels of load-carrying components members. The earthquake performance of RC structures is expected as life safety performance level under the design spectrum obtained for %10 probability of exceeding in 50 years. The rules for determining structure performance are given below for each performance level (TEC 2007):

Four performance levels are defined for the structure according to TEC (2007) that has similarities with FEMA-356 (2000) guidelines. The earthquake performance level defined as Immediate Occupancy (IO), in any story, in the direction of the applied earthquake loads, not more than 10% of beams are in the significant damage state whereas all other structural members are in the minimum damage state. Earthquake performance level defined as Life Safety (LS), in any story, in the direction of the applied earthquake loads, not more than 20% of beams and some columns are in the extreme damage state whereas all other structural members are in the minimum or significant damage states. However, shear carried by those columns in the extreme damage state should be less than 20% of the story shear at each story. The performance level defined as Collapse Prevention (CP), in any story, in the direction of the applied

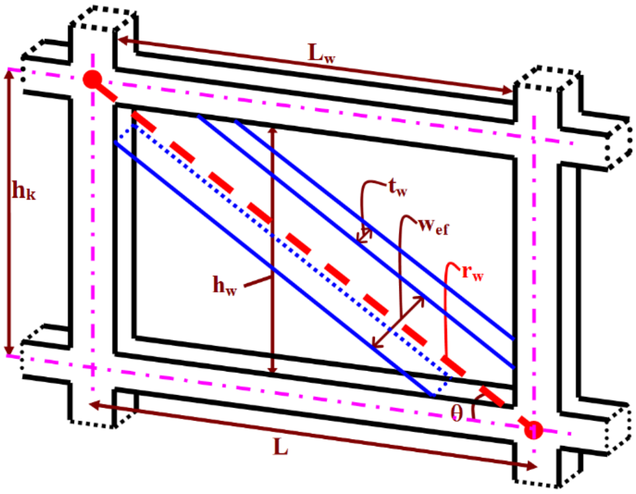


Fig. 1 The modeling diagonal strut of infill wall (Dilmaç *et al*. 2018)

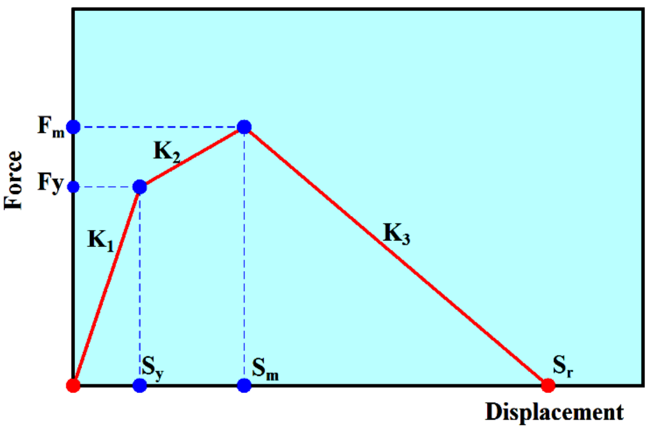


Fig. 2 The force-displacement relationships of the compressive diagonal struts

earthquake loads, not more than 20% of beams and some columns were in the collapse state whereas all other structural members are in the minimum, significant or extreme damage states. However, shear carried by those columns in the collapse state should be less than 20% of the story shear at each story. Furthermore, such columns should not lead to a stability loss. Occupancy of the structure should not be permitted. Performance level defined as Collapse (C), if the structure fails to satisfy any of the above performance levels, it is accepted as in the collapse state.

3. Modelling of the infill wall

The infill walls can be modelled using the equivalent compressive diagonal struts model as given in Fig. 1(Dilmaç *et al*. 2018). For attempting to model the behavior of RC structures with infill walls, experimental and conceptual observations have shown that a diagonal strut with appropriate geometric and mechanical properties can likely provide a solution to the problem (Asteris *et al*. 2012).

In the adoption of diagonal struts is supported with experimental and analytical study by considering the effect of the infilling in each wall as equivalent to diagonal bracing (Polyakov 1960, Holmes 1961, Smith1967, Asteris *et al*. 2012). The proportional relationship between the width (w_{ef}) and the length of (r_w) of the diagonal strut is indicated by using experimental data related the w_{ef} to the infill/frame contact r_w using the analytical equations. In this study, the structural and mechanical properties of the infill wall are determined by the equations mentioned in FEMA 356 (2000). The wef is taken into account by Eq. (1).

$$w_{ef} = 0.175.(\lambda_w.h_k)^{-0.4} r_w \tag{1}$$

$$\lambda_w = \left[\frac{E_m t_w \sin 2\theta}{4 E_c I_c h_w}\right]^{0.25} \tag{2}$$

where h_k is height of story and stiffness factor (λ_w) is taken into account by Eq. (2). The thickness (t_w) is considered as constant; 200 mm, θ is angle of diagonal to horizontal in degrees is given in Eq. (3), h_w is height of wall, L is length of span of equivalent diagonal strut and E_c and E_m are the elastic modulus of concrete and the infill wall, respectively. E_c and E_m are given by Eq. (4) and Eq. (5), respectively.

$$\theta = \tan^{-1}\left(\frac{h_w}{L_w}\right) \tag{3}$$

$$E_c = 5000\sqrt{f_{co}} \tag{4}$$

$$E_m = 550.f_m \tag{5}$$

where f_{co} is the compressive strength of concrete in MPa. The f_m is the compressive strength of infill wall that shall be taken as 2.1 MPa, 4.1 MPa and 6.2 MPa by a factor as specified as poor, fair, good of wall condition, respectively (FEMA-273 1997).

The model of nonlinear behavior of the infill wall is described by assigned axial load hinges on diagonal strut that features are defined (Panagiotakos and Fardis 1996). The model is consist of three stages. The first state (K_1) is defined the initial sliding behavior and the second stage (K_2) shows the behavior of the infill wall after it has left the frame. The attenuation behavior of the infill wall is modelled at the last stage (K_3). The force-displacement relation for the diagonal strut representing the infill wall is illustrated in Fig. 2.

The initial rigidity (K_1) is calculated in Eq.6 using the simple method defined in ECOEST-PREC 8 Report (Fardis 1996).

$$K_1 = \frac{G_w L_w t_w}{h_w} \tag{6}$$

where G_w is the shear modulus of the infill wall and is considered as equal to 0.4 times the elastic modulus of the infill wall (Kakaletsis *et al*. 2011, Celarec *et al*. 2012, Uva *et al*. 2012). The axial rigidity (K_2) and the attenuation rigidity (K_3) of the infill wall is calculated using the Eq. (7) and (8).

$$K_2 = \frac{E_m a_w t_w}{r_w} \tag{7}$$

$$0.005K_1 \leq K_3 \leq 0.1K_1 \tag{8}$$

The yield load (F_y) of the infill wall, the yield shortening (S_y) of the infill wall, the maximum compression strength of the infill wall (F_m) and the shortening (S_m) at the F_m point and the axial shortening (S_r) in case of mechanism are calculated by equations given below:

$$F_y = f_{tp} t_w L_w \tag{9}$$

$$S_y = \frac{F_y}{K_1} \tag{10}$$

$$F_m = 1.3F_y \qquad 0 \leq F_r \leq 0.1F_y \tag{11}$$

$$S_m = S_y + \frac{F_m - F_y}{K_2} \qquad S_r = S_m + \frac{F_m - F_r}{K_3} \tag{12}$$

The cracking strength of the infill wall (f_{tp}) is taken as 0.54 MPa (Jinya and Patel 2014) in the analyzes. The term F_r in Eq. (11) is defined as the permanent load of the infill wall and an appropriate value is taken in the given range.

3.1 Influence of openings in the infill wall

Infill walls have openings at certain rates originating from doors and windows when considering the architectural properties of the RC structures according to the purpose of use. However, most researches have focused on the effect of simple infill walls without openings on structural behavior. In addition, research on the openings of infill walls are often analytical, limited to particular cases. Therefore, this case cannot exactly represent the actual structural behavior. It is a known fact that the contribution of the infill wall to the lateral stiffness of the frame is reduced when the structure is exposed to a reverse cycle loading under the effect of the earthquake, as in the case of the actual structures.

In this paper, a finite element method proposed by Asteris (Asteris 2003, 2014) was used to investigate the influence of the openings of walls on the seismic behavior and performance of RC structures. The main feature of the method is that the fill/frame contact lengths and contact stresses are predicted as an integral part of the solution (Asteris *et al*. 2012). The effect of reducing the stiffness of the openings rate in the infill wall is taken into account in Eq. (13).

$$\lambda = 1 - 2a_w^{0.54} + a_w^{1.14} \tag{9}$$

where a_w is area of opening to the area of the infill wall. The stiffness reduction factor (λ) coefficient can be used to find the equivalent w_{ef} of a diagonal strut using the reduction of the stiffness factor (λ_w) given in Eq. (2).

To examine the influence of the infill wall and openings rates on earthquake performance and behavior, the analyses of existing RC structures with different numbers of stories were carried out in this study. The openings rates of infill walls in existing RC structures were analyzed by considering six different cases. The openings rates in infill walls that were taken into account in the analyses are indicated in Fig 3.

The opening case-1 (OpC-1) is when the structural system is a fully infilled frame. The openings areas are 1.2 m^2, 1.8 m^2, 2.4 m^2 and 3.4 m^2 in OpC-2, 3, 4 and 5, respectively. The bare-frame is displayed in OpC -6 in Fig.3. In this paper, the analyzes are carried out for each case. However, all the frames of the RC structures are not considered as infilled. Therefore, some frames are modelled as bare-frame by considering the architectural properties of the RC structures.

4. Determination of earthquake performance of existing RC structures

The major portion of structure stock in many countries consists of low and mid-rise RC structures (Ozmen *et al*. 2012, 2017). In this section, the earthquake performance level of existing mid-rise RC structures with different opening rates in their infill walls was investigated using pushover analysis method. These structures are located in high-hazard zones in Turkey. In the analyzes, the locations and openings of the infill walls were determined according to the RC structure architectural plan. Therefore, the thickness of the infill wall (t_w) is considered as a constant 200 mm. The plan views of the some selected RC structures with infill walls are given in Fig. 4.

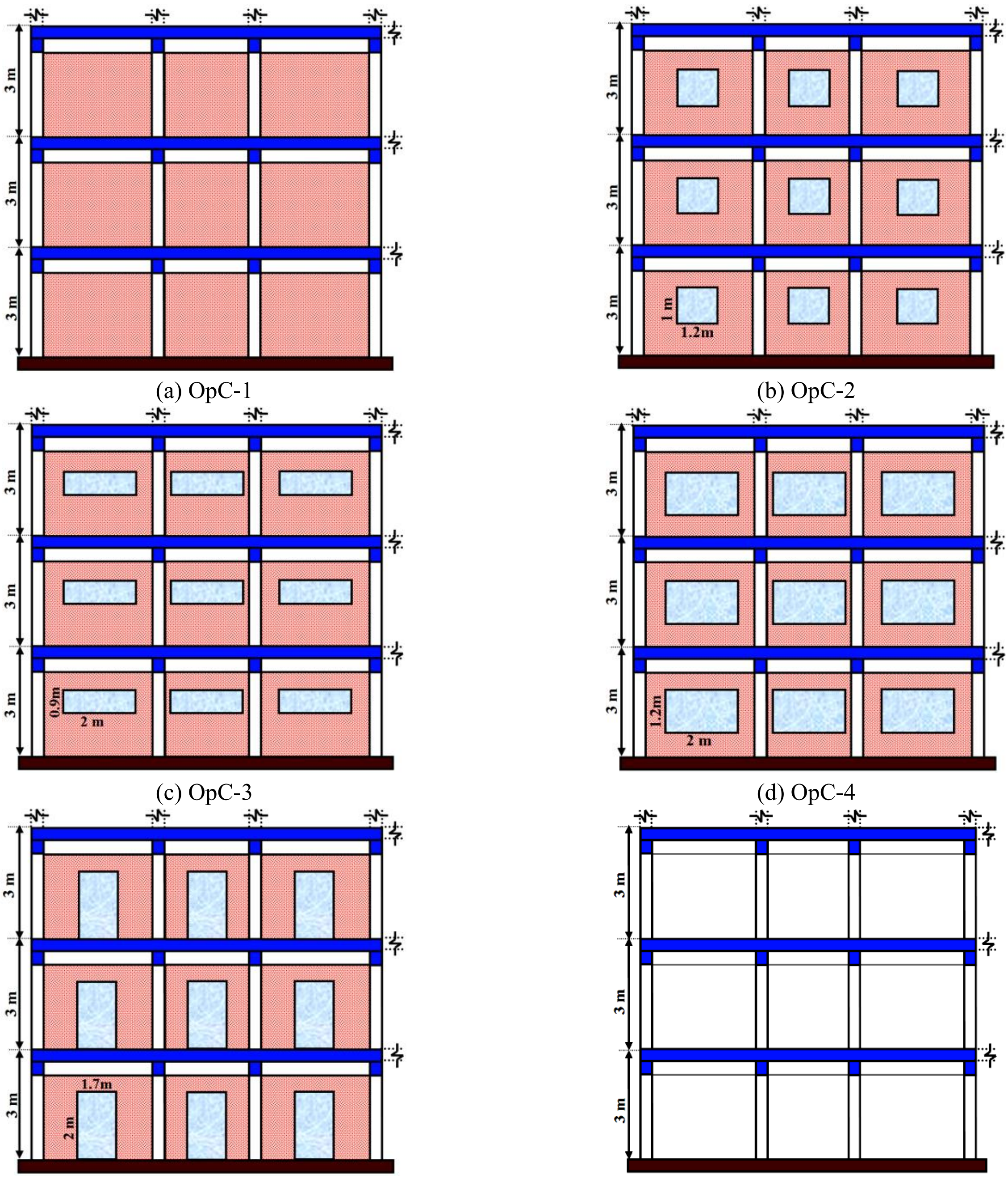
Nonlinear analyzes were performed in both directions of existing RC structures to investigate the effect of the openings on structural behavior and earthquake performance. However, in the analyzes, all infill walls in the plans of RC structures were modelled for six different cases as indicated in Fig.3. In other words, all the infill walls in the plans of the RC structures were modelled and analyzed either infilled, as in OpC-1 or different opening rate, as OpC -2, 3, 4, 5 and 6. Three-dimensional modelling and nonlinear analysis of the selected existing RC structures were carried out using the SAP 2000 software (2002).

Three types of plastic hinges were modelled by taking into account PM2M3, M2M3 and P in the nonlinear modelling of the columns, beams and walls, respectively. Gravity and seismic loads were considered by assuming a design ground acceleration of 0.4g and a soil class of C according to FEMA 356 (2000). To better examine the effect of openings on earthquake performance, the material strengths were chosen as 10 MPa for concrete and 220 MPa for steel in the analyses.

5. Influence of openings on structural behavior and seismic vulnerability

5.1 Influence of openings on fundamental period

The RC structure fundamental period is an important



(a) OpC-1 (b) OpC-2

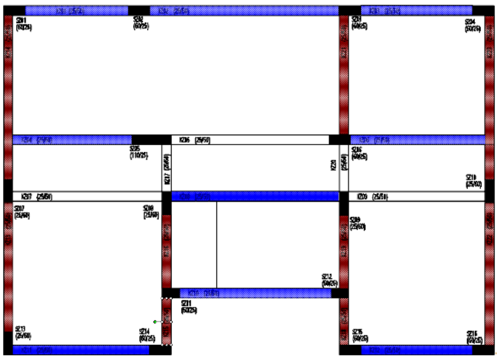
(c) OpC-3 (d) OpC-4

(e) OpC-5 (f) OpC-6

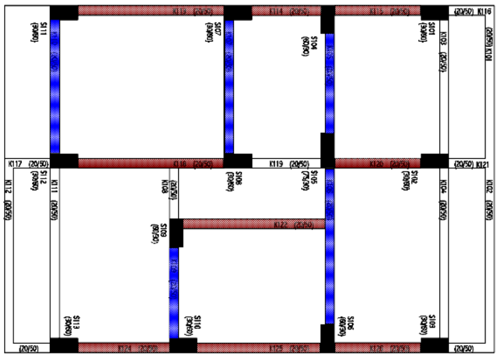
Fig. 3 Positions of openings for different cases

parameter that contains many structural information about the RC structure and is directly related to the rigidity of RC structures (Asteris 2015b). Therefore, the infill wall increases the lateral rigidity of the structures. However, it decreases the lateral rigidity in proportion to percentage of the openings in the infill wall. The influence of the opening rate (a_w) on the fundamental periods according to the number of stories of the some selected RC structures are displayed in Fig. 5.

Since the opening rate in the wall decreases the rigidity of the wall, the structure fundamental periods change in direct proportion to the percentage of the openings, as expected. Although there is no clear relationship between the structure fundamental period and the opening rate, it is certain that the infill wall affects the structural behavior and earthquake performance of the RC structures. When the period-opening rate relationship of an existing RC structure, given in Fig.5. (a), is examined, the period difference between OpC-1 and opening OpC -6 varies by about 50 per cent. Likewise, considering the decreased opening rates in the infill walls of existing RC structures, there is an increase between 10 and 13 per cent between OpC-1, 2, 3, 4 and OpC-5, respectively. The reason for this increase is the decrease in wall stiffness. However, it may not always be possible to clearly state the amount of change in fundamental period according to the opening rate.



(a)



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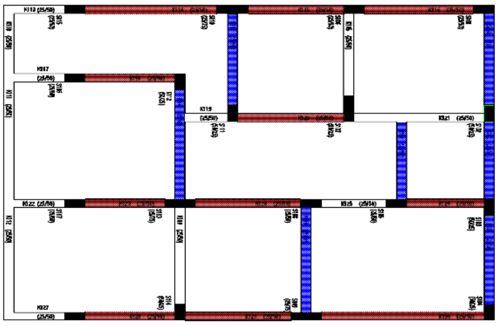

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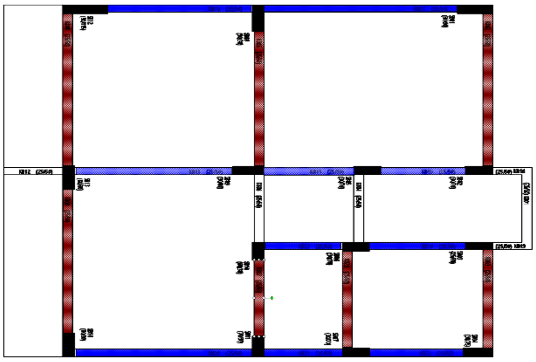
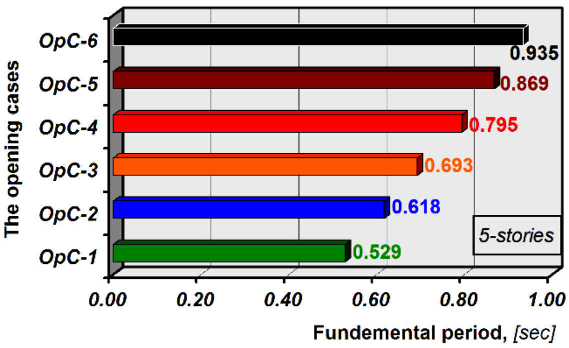
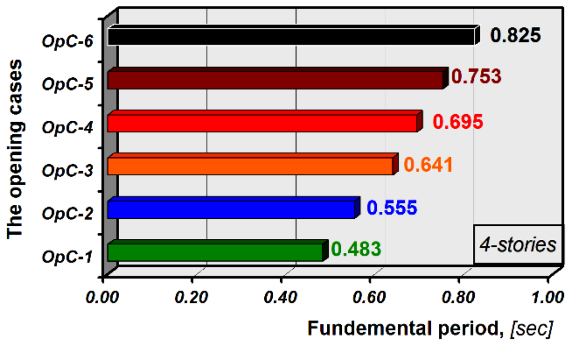


(d)

Fig. 4 The plans of selected some existing RC structures



(a)



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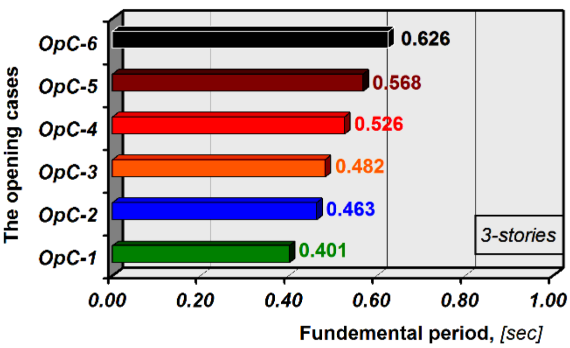

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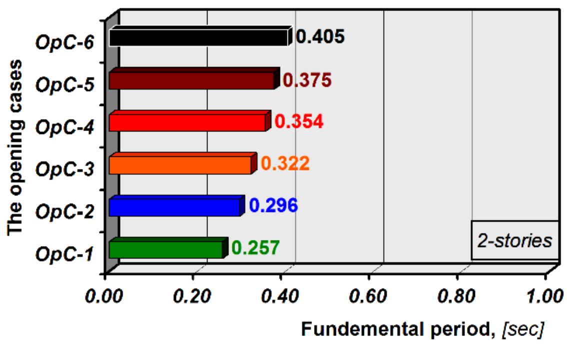

(d)

Fig. 5 The variation of structure fundamental period with openings rate

The main reason for this may be the differences in the structural properties such as different number of span and width of bays. In addition, it is possible that changes in the fundamental period occur since vertical and horizontal structural irregularities can change the form of infill walls. It is possible to obtain the results that this rate increases with the reduction of the number of stories. Considering the demand spectrum of the RC structures, this clearly

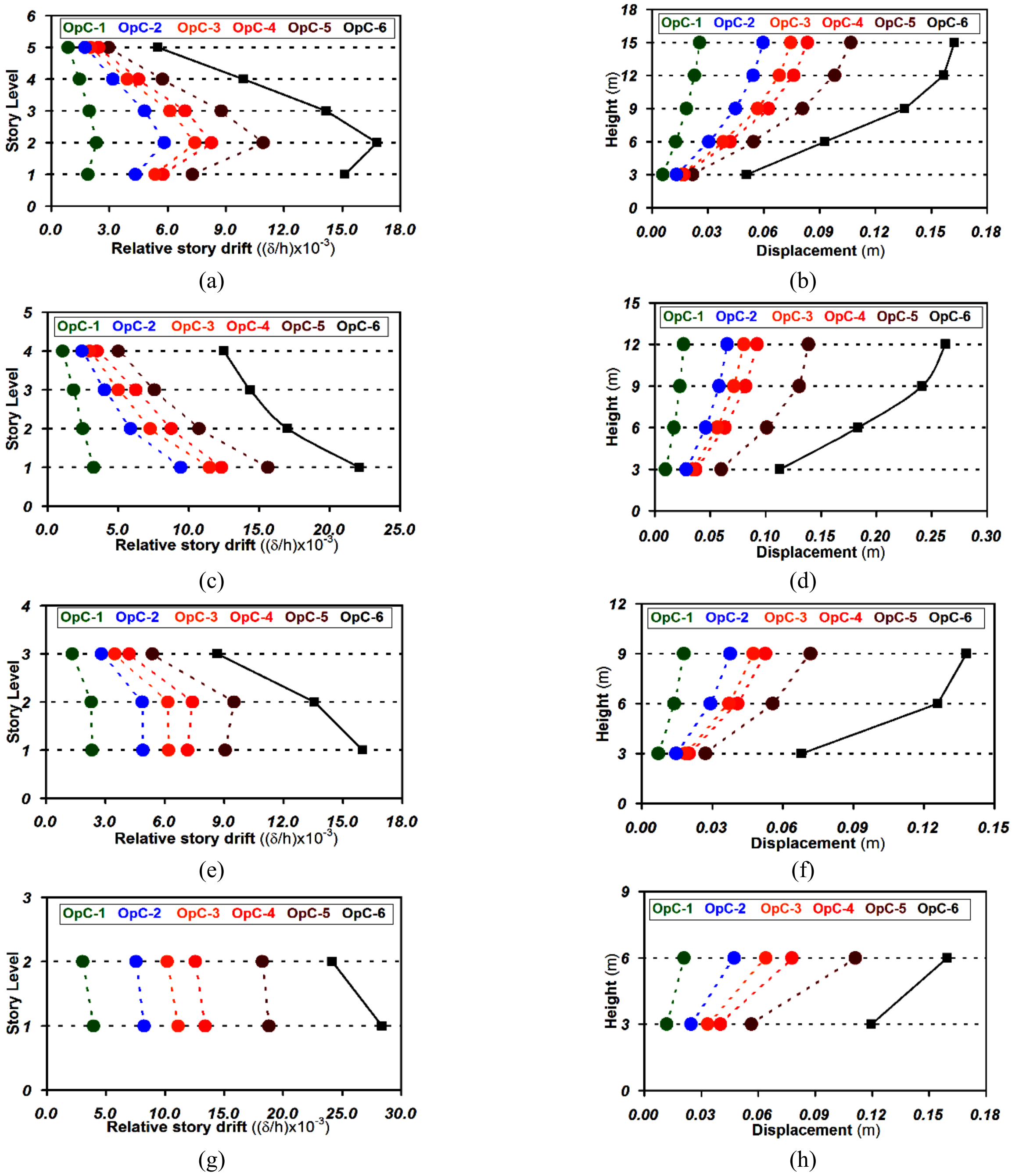

Fig. 6 The relative story drift and displacement at each story level

demonstrates that it contributes positively to limiting the damage levels of the load-carrying components of the RC structures under the earthquake load.

5.2 Influence of openings on relative story drift ratio and story displacement

The relative story drift ratio or total story displacement occurring at the story levels of the structures under earthquake loads are the most effective factor determining the damage levels of the structural load-carrying components of RC structures. Therefore, the relative story drift and displacement changes along the height of the RC structure are an important way of demonstrating the behavior of the load-carrying components in each story. It is important to determine the effect on the relative story drift or total story displacement in the analysis by considering the nonlinear behavior of infill walls with and without openings. The influence of the opening rate (a_w) on the story drift ratio and the total displacement according to the height and story level of the some selected RC structure is displayed in Fig. 6.

The differences in the peak relative story drift rates and total story displacement can be observed in the pushover analysis by evaluating Fig. 6. The displacement differences between the story levels, especially between the first and second stories, are caused by rigidity changes. However, since the existing RC structures are evaluated in the analyzes, it is usual that story displacement does not show a

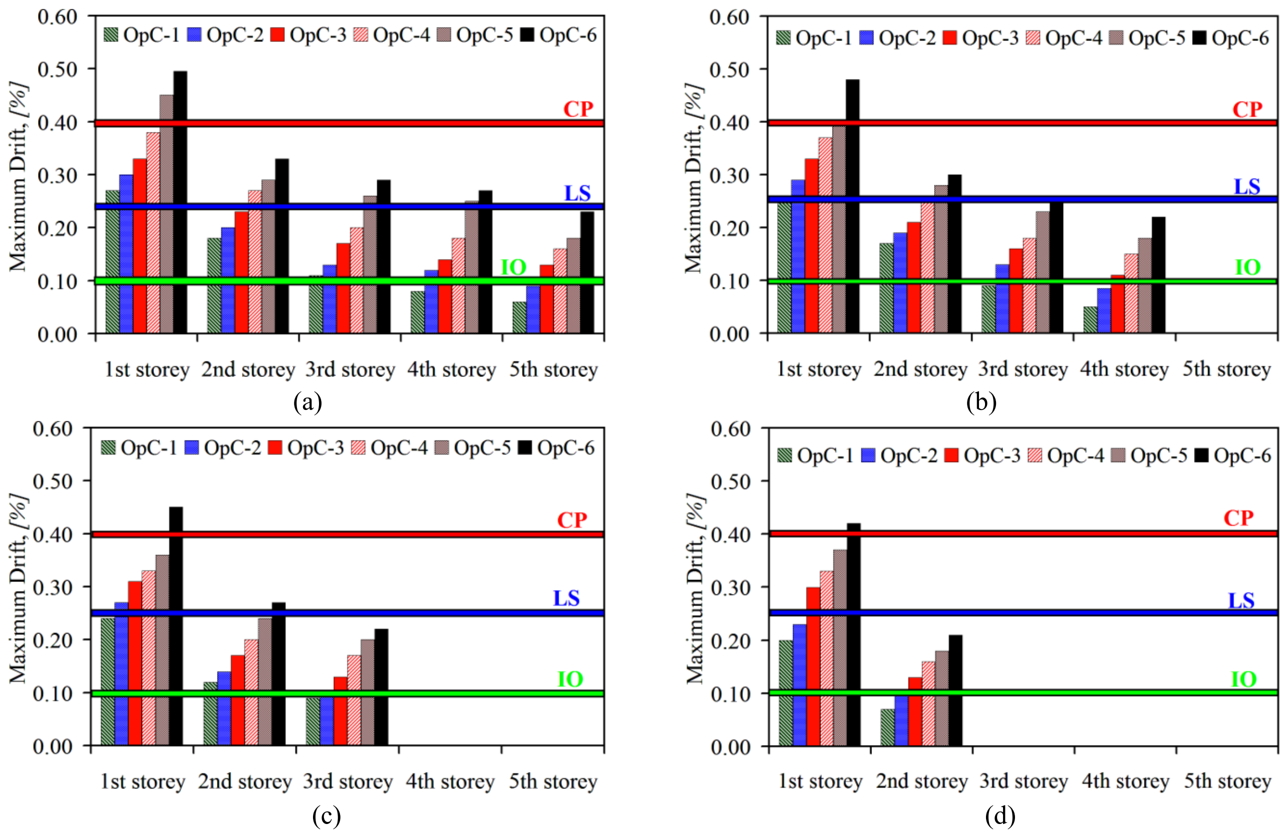

Fig. 7 The comparison with drift values corresponding to the performance level

steady regular difference between the first and second stories, considering the presence of possible weak ant soft story irregularities in these structures. The presence of the infill wall leads to a different performance level, as it causes different story drifts between the story levels. The comparison of drift values and their corresponding performance levels for each case are displayed in Fig. 7 according to story levels.

When comparing limit performance levels and story drift, the recommended limit conditions in the ASCE/SEI (2007) according to the maximum drift rate at each story level are taken into account. In the analyzes made according to design earthquake loads, it was seen that the damage to the column and beam components occurred at the first story. It was observed that these damages were gradually decreasing. However, significant differences were observed in the drift values and performance levels between OpC-1 and OpC-6. As the infill walls can cause increased shear stress at the column ends, its damages can be expected to increase. However, despite this shear effect, it is clear that the infill walls have a greater contribution to the overall rigidity and earthquake performance of RC structures.

The damage levels of the load-carrying components of the RC structural system under the earthquake effect were determined according to the damage limit values defined in the stress-strain relationship of the composite reinforced concrete components. To explain it more accurately, the earthquake performance of the existing RC structure was determined according to the moment-curvature and moment-rotation values of the reinforced concrete section. The changes in the hinge rotations according to the opening rates in the infill wall of some selected existing RC structures are given in Fig. 8.

5.3 Influence of openings on capacity of existing RC structures

The pushover analysis is a nonlinear static analysis under dead and live loads of the structures and under incremental lateral loads. Pushover analysis was carried out to obtain the lateral capacity curves and the values of ductility of displacement of the existing RC structures. The pushover curves of the some selected existing RC structures with infill walls with different opening rates were obtained from the static nonlinear analysis, as given in Fig. 9.
The lateral loads for pushover analyzes were defined based on the shape of first mode, for which the lateral load or seismic load were approximately equal to the total mass of the existing RC structure. The distribution of the lateral load effects was practically the same for OpC-1 and OpC-6. However, it can be seen that the presence of the infill wall greatly increased the lateral rigidity and lateral load-bearing capacity of the RC structures by considering the P-Δ effects indicated in Fig. 9. The ratio of total base shear to seismic weight of the OpC -6 was smaller than that of the OpC-1,2, 3, 4 and 5. In addition, while the earthquake performance of the existing RC structures with the OpC-6 did not provide the LS performance level, it can be seen that provide LS performance levels of structures with the OpC-1 and OpC-2, 3, 4 and 5.

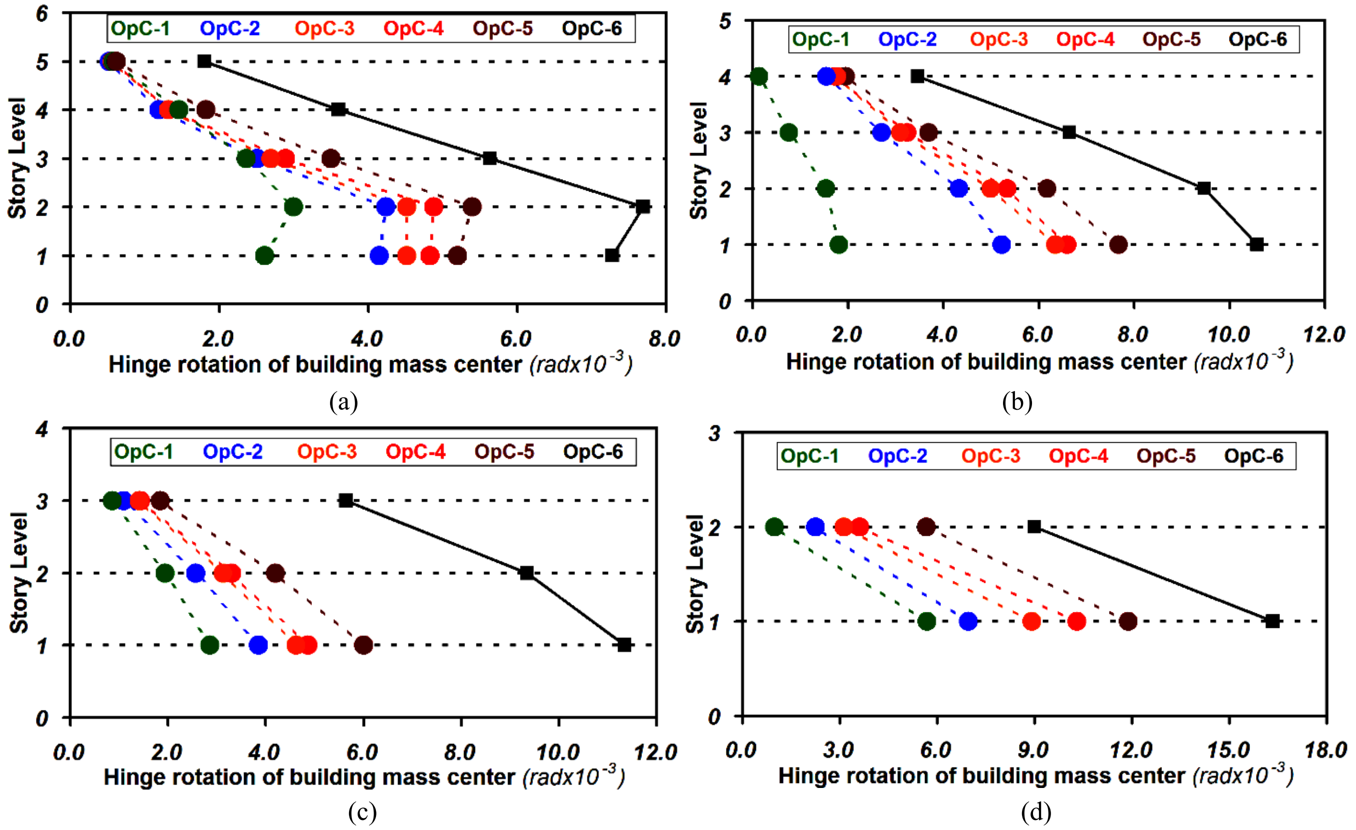

Fig. 8 The hinge rotation of at each story level

The damage levels of the load-carrying components of the RC structures were taken into account in the determination of the earthquake performance under the effect of seismic force. It is understood from the figures given above that the OpC-1,2, 3, 4 and 5 restrict the displacement of the load-carrying components of the RC structures. Therefore, the changes occur in the damage levels of the carrying components for different opening rates. The damage level changes in the load-carrying components and the infill wall on merely one axis of a three-story RC structure is given in Fig. 10.

Although most of the infill wall in the existing RC structures under the effect of earthquake load was severely damaged, the infill wall had a significant effect on limiting damage to the frame components. However, the different opening rate caused changes in the damage levels of the columns and beams. As can be seen from the analysis results, the damage levels of all the columns and beams in the first story were detected as CL in Fig. 10(a). Therefore, the RC structure earthquake performance provided the CP performance level. However, the percentage of the opening rates in the infill wall in Fig. 10(b) was analyzed as 48%, which restricted the damage to the columns and beams according to OpC-6. Due to the insufficiency of the shear capacity of the RC structures, it was not obtained as LS. The RC structures displayed in Fig. 10(c) and Fig. 10(d) provided the target earthquake performance level by considering the percentage of the opening rate as 11% and 23%, respectively.

5.4 Influence of openings on earthquake performance of existing RC structures

Nonlinear static analyzes are carried out for six different OpC of all selected existing RC structures in two direction. The analysis results of the eight existing RC structures are given in Table 1, Table 2, Table 3 and Table 4 according to 2, 3, 4, and 5 story structures, respectively. The architectural properties of these structures were taken into account. Therefore, in the pushover analyzes, the diagonal struts were placed between the appropriate axes to contribute to the seismic behavior of the existing RC structures that were chosen as smooth and symmetrical as possible. Where T is the fundamental period of the RC structure, d_{ep} is the target elasto-plastic displacement of the structure, R_{y1} is the earthquake load reduction coefficient, μ is the ductility of structures, a_y is the equivalent yield acceleration of the first mode of the RC structures, $S_{d(ay)}$ is the nonlinear spectral displacement of the first mode of the structure and V_t is the inelastic earthquake load acting on the structure. The necessary procedures for calculating these structural parameters are available in TEC and are not given in this paper. It is clearly seen that the infill wall provided a beneficial contribution to almost all parameters affecting the structural behavior and earthquake performance of the RC structures. It was observed that it provided target earthquake performance in almost all selected existing RC structures except in OpC-6. This is displayed in Fig. 11.

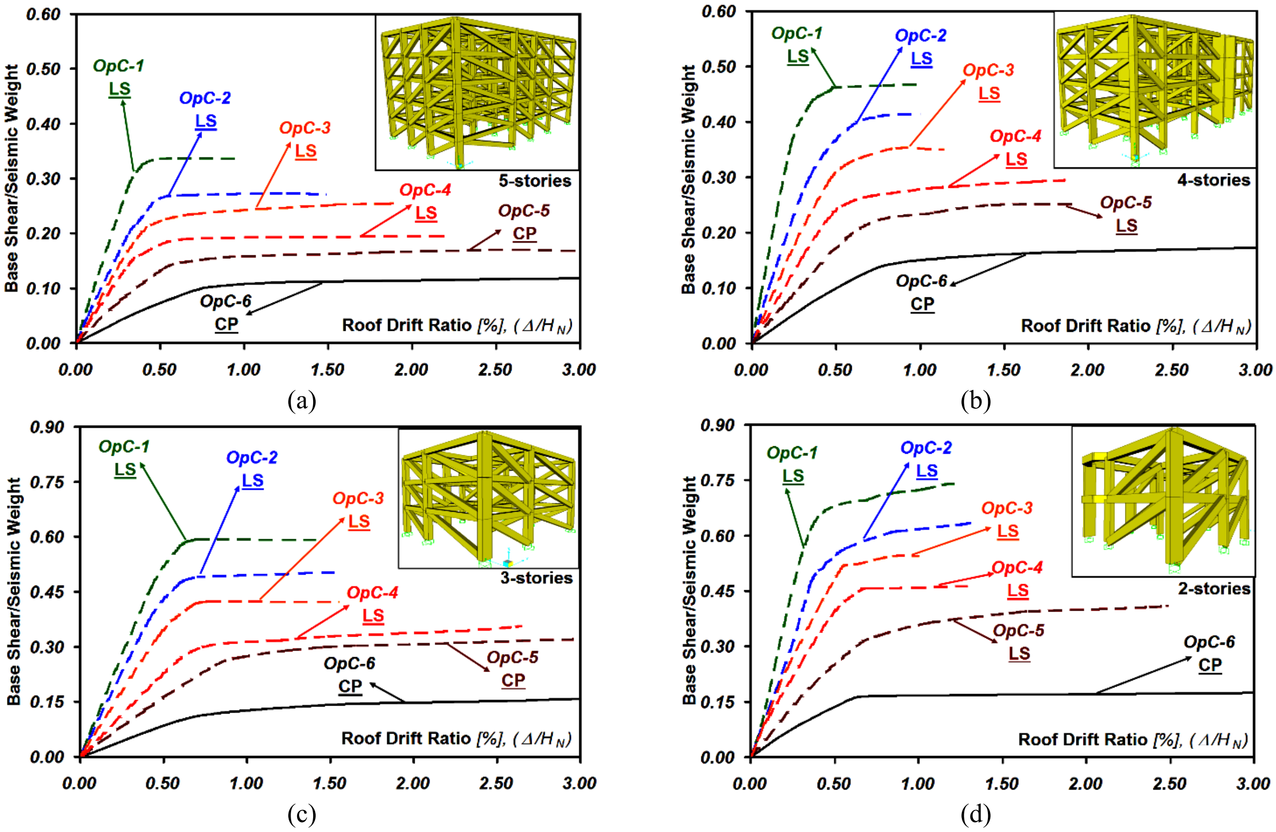

Fig. 9 The normalized pushover curves of selected some RC structures

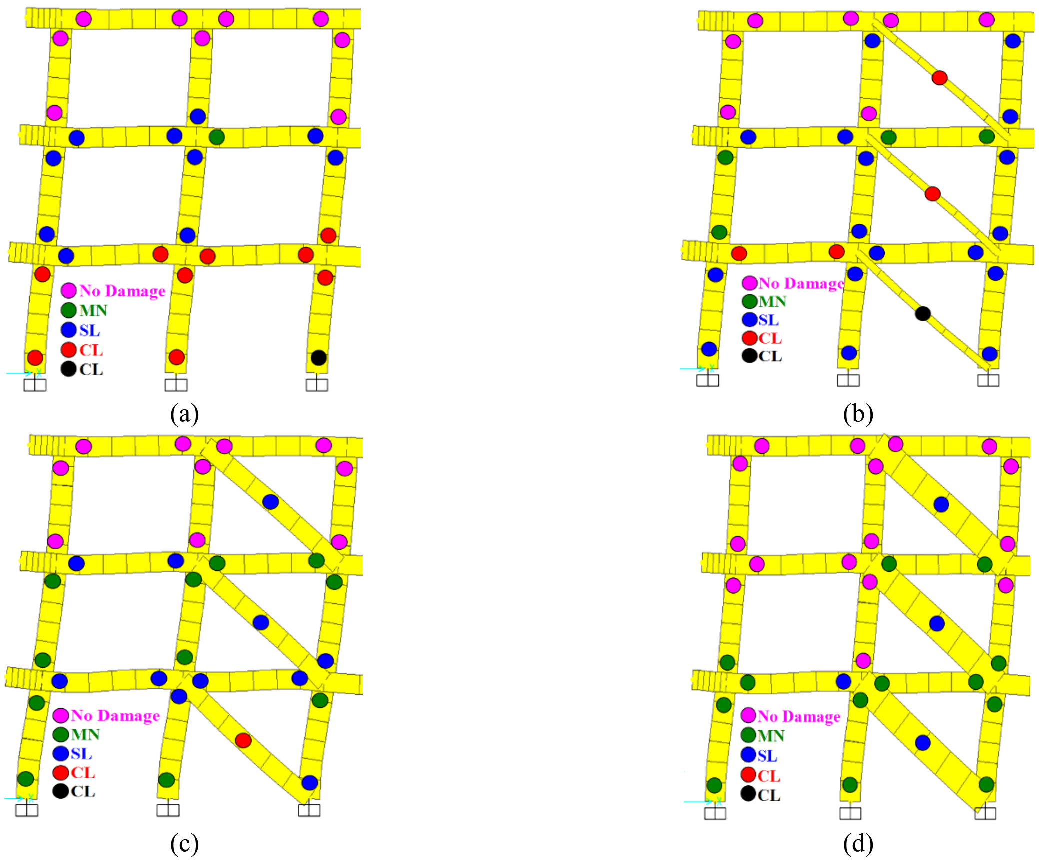

Fig. 10 The damage levels of load-carrying components of RC structures

Table 1 The analysis results of two-story structures

ID: 2A	Opening Case					
Number of Story :2	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.136	0.205	0.278	0.380	1.000
λ_w	2.614	2.614	2.614	2.614	2.614	0.000
λ	1.000	0.425	0.319	0.240	0.146	0.000
r_w *(m)*	4.330	4.330	4.330	4.330	4.330	0.000
w_{ef}/r_w	0.119	0.051	0.038	0.029	0.017	-
$T^{(x)}$ *(s)*	0.214	0.237	0.253	0.274	0.316	0.389
$d^{ep}_{(X)}$ *(m)*	0.047	0.062	0.065	0.069	0.074	0.080
$R^{(X)}_{y1}$	1.763	2.015	2.122	2.276	2.457	2.898
$\mu^{(X)}$	2.978	2.570	2.616	2.764	2.930	3.808
$a^{(X)}_y$ *(m/s²)*	5561	4868	4623	4309	3991	3384
$S^{(X)}_{d(ay)}$ *(m)*	0.012	0.019	0.019	0.020	0.019	0.016
$V_t^{(X)}$ *(kN)*	1817	1407	1283	1189	1053	705
$T^{(Y)}$ *(s)*	0.257	0.296	0.322	0.354	0.375	0.405
$d^{ep}_{(Y)}$ *(m)*	0.054	0.077	0.082	0.089	0.094	0.105
$R^{(Y)}_{y1}$	1.842	1.949	2.019	2.060	2.133	2.331
$\mu^{(Y)}$	3.223	2.602	2.665	2.691	2.747	3.559
$a^{(Y)}_y$ *(m/s²)*	5323	5031	4857	4759	4598	4207
$S^{(Y)}_{d(ay)}$ *(m)*	0.012	0.017	0.018	0.018	0.018	0.015
$V_t^{(Y)}$ *(kN)*	1763	1379	1284	1213	1132	947

ID: 2B	Opening Case					
Number of Story :2	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.163	0.212	0.287	0.383	1.000
λ_w	2.590	2.594	2.594	2.594	2.590	0.000
λ	1.000	0.481	0.382	0.304	0.208	0.000
r_w *(m)*	4.520	4.520	4.520	4.520	4.520	0.000
w_{ef}/r_w	0.120	0.057	0.046	0.036	0.025	-
$T^{(x)}$ *(s)*	0.343	0.410	0.426	0.440	0.460	0.499
$d^{ep}_{(X)}$ *(m)*	0.048	0.076	0.084	0.090	0.099	0.118
$R^{(X)}_{y1}$	1.291	1.756	1.966	2.150	2.481	3.659
$\mu^{(X)}$	1.622	1.987	2.258	2.327	2.746	4.322
$a^{(X)}_y$ *(m/s²)*	7596	5583	4988	4554	3954	2681
$S^{(X)}_{d(ay)}$ *(m)*	0.024	0.031	0.031	0.032	0.030	0.022
$V_t^{(X)}$ *(kN)*	2739	2541	2385	2189	1977	990
$T^{(Y)}$ *(s)*	0.264	0.284	0.287	0.290	0.295	0.321
$d^{ep}_{(Y)}$ *(m)*	0.037	0.039	0.041	0.042	0.044	0.048
$R^{(Y)}_{y1}$	1.473	1.416	1.456	1.482	1.517	1.623
$\mu^{(Y)}$	2.343	1.586	1.612	1.624	1.583	1.774
$a^{(Y)}_y$ *(m/s²)*	6655	6925	6738	6619	6465	6042
$S^{(Y)}_{d(ay)}$ *(m)*	0.013	0.021	0.021	0.021	0.023	0.023
$V_t^{(Y)}$ *(kN)*	2955	2412	2335	2179	3562	1886

Table 2 The analysis results of three-story structures

ID: 3C	Opening Case						ID: 3D	Opening Case					
Number of Story :3	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6	Number of Story :3	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.118	0.173	0.361	0.432	1.000	a_w *(%)*	0.000	0.106	0.159	0.212	0.321	1.000
λ_w	1.960	1.960	1.960	1.960	1.960	0.000	λ_w	2.204	2.204	2.204	2.204	2.204	0.000
λ	1.000	0.462	0.359	0.281	0.186	0.000	λ	1.000	0.482	0.382	0.304	0.209	0.000
r_w *(m)*	4.360	4.360	4.360	4.360	4.360	0.000	r_w *(m)*	4.360	4.360	4.360	4.360	4.360	0.000
w_{ef} / r_w	0.134	0.062	0.048	0.038	0.025	-	w_{ef} / r_w	0.128	0.061	0.049	0.039	0.027	-
$T^{(x)}$ *(s)*	0.470	0.533	0.549	0.563	0.582	0.636	$T^{(x)}$ *(s)*	0.398	0.451	0.461	0.471	0.486	0.513
$d^{ep}{}_{(X)}$ *(m)*	0.113	0.135	0.143	0.147	0.154	0.173	$d^{ep}{}_{(X)}$ *(m)*	0.087	0.100	0.104	0.109	0.114	0.127
$R^{(X)}{}_{y1}$	3.013	3.509	4.393	4.390	4.582	4.355	$R^{(X)}{}_{y1}$	2.550	2.393	2.478	2.592	2.779	3.390
$\mu^{(X)}$	4.202	3.885	5.291	5.198	5.212	3.327	$\mu^{(X)}$	3.704	2.383	2.477	2.412	.2.565	2.670
$a^{(X)}{}_y$ *(m/s^2)*	3255	2795	233	2234	2140	2252	$a^{(X)}{}_y$ *(m/s^2)*	3840	4099	3970	3783	3529	2891
$S^{(X)}{}_{d(ay)}$ *(m)*	0.021	0.027	0.021	0.022	0.023	0.039	$S^{(X)}{}_{d(ay)}$ *(m)*	0.018	0.033	0.033	0.035	0.035	0.038
$V_t^{(X)}$ *(kN)*	3257	2517	2395	2200	2045	2057	$V_t^{(X)}$ *(kN)*	1707	1299	1218	1155	1038	700
$T^{(Y)}$ *(s)*	0.493	0.566	0.585	0.602	0.624	0.674	$T^{(Y)}$ *(s)*	0.401	0.463	0.482	0.526	0.468	0.626
$d^{ep}{}_{(Y)}$ *(m)*	0.118	0.145	0.153	0.159	0.166	0.179	$d^{ep}{}_{(Y)}$ *(m)*	0.101	0.113	0.116	0.119	0.125	0.137
$R^{(Y)}{}_{y1}$	2.743	3.520	3.935	4.278	4.450	5.152	$R^{(Y)}{}_{y1}$	3.381	3.021	3.072	3.137	3.288	3.950
$\mu^{(Y)}$	3.301	3.464	4.130	4.307	4.210	4.455	$\mu^{(Y)}$	4.941	3.304	3.322	3.084	3.110	3.848
$a^{(Y)}{}_y$ *(m/s^2)*	3579	2787	2492	2294	2204	1903	$a^{(Y)}{}_y$ *(m/s^2)*	2900	3247	3192	3127	2984	2481
$S^{(Y)}{}_{d(av)}$ *(m)*	0.027	0.032	0.028	0.028	0.030	0.027	$S^{(Y)}{}_{d(av)}$ *(m)*	0.016	0.027	0.027	0.030	0.031	0.029
$V_t^{(Y)}$ *(kN)*	3522	2787	2558	2245	2135	1703	$V_t^{(Y)}$ *(kN)*	1646	1227	1129	1045	956	612

Table 3 The analysis results of four-story structures

ID: 4E	Opening Case						ID: 4F	Opening Case					
Number of Story :4	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6	Number of Story :4	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.153	0.205	0.294	0.391	1.000	a_w *(%)*	0.000	0.117	0.176	0.235	0.335	1.000
λ_w	2.200	2.200	2.200	2.200	2.200	0.000	λ_w	2.494	2.494	2.495	2.494	2.494	0.000
λ	1.000	0.473	0.371	0.294	0.198	0.000	λ	1.000	0.458	0.356	0.278	0.182	0.000
r_w *(m)*	4.590	4.590	4.590	4.590	4.590	0.000	r_w *(m)*	0.000	4.460	4.460	4.460	4.460	0.000
w_{ef}/r_w	0.128	0.060	0.047	0.038	0.025	-	w_{ef}/r_w	0.121	0.056	0.043	0.034	0.022	-
$T^{(X)}$ *(s)*	0.721	0.793	0.812	0.828	0.846	0.888	$T^{(X)}$ *(s)*	0.601	0.671	0.695	0.715	0.730	0.798
$d^{ep}_{(X)}$ *(m)*	0.200	0.226	0.232	0.237	0.242	0.257	$d^{ep}_{(X)}$ *(m)*	0.156	0.194	0.200	0.207	0.213	0.233
$R^{(X)}_{y1}$	5.260	9.090	7.020	9.120	7.260	7.410	$R^{(X)}_{y1}$	3.550	4.040	4.432	4.645	4.880	5.730
$\mu^{(X)}$	5.553	8.930	9.090	8.530	5.760	3.930	$\mu^{(X)}$	3.769	2.860	2.340	2.754	6.103	3.600
$a^{(X)}_y$ *(m/s²)*	1864	1078	1086	1075	1350	1322	$a^{(X)}_y$ *(m/s²)*	2759	2423	2213	2109	2007	1710
$S^{(X)}_{d(av)}$ *(m)*	0.027	0.019	0.019	0.021	0.032	0.044	$S^{(X)}_{d(av)}$ *(m)*	0.032	0.049	0.062	0.055	0.021	0.043
$V_t^{(X)}$ *(kN)*	1307	1038	517	1001	973	1071	$V_t^{(X)}$ *(kN)*	3121	2382	2277	2166	1973	1930
$T^{(Y)}$ *(s)*	0.721	0.835	0.864	0.888	0.917	0.942	$T^{(Y)}$ *(s)*	0.483	0.555	0.641	0.695	0.753	0.825
$d^{ep}_{(Y)}$ *(m)*	0.202	0.239	0.248	0.256	0.265	0.275	$d^{ep}_{(Y)}$ *(m)*	0.146	0.170	0.172	0.175	0.177	0.185
$R^{(Y)}_{y1}$	6.550	7.710	8.268	8.290	8.750	7.497	$R^{(Y)}_{y1}$	3.848	5.600	5.508	5.797	6.208	5.350
$\mu^{(Y)}$	4.748	4.660	5.071	4.680	5.040	4.095	$\mu^{(Y)}$	3.212	5.304	5.300	5.402	5.550	4.310
$a^{(Y)}_y$ *(m/s²)*	1496	170	1186	1182	1104	1262	$a^{(Y)}_y$ *(m/s²)*	2549	1750	1780	1692	1579	1831
$S^{(Y)}_{d(av)}$ *(m)*	0.033	0.037	0.038	0.042	0.040	0.051	$S^{(Y)}_{d(av)}$ *(m)*	0.035	0.024	0.024	0.024	0.024	0.029
$V_t^{(Y)}$ *(kN)*	1178	971	952	869	897	983	$V_t^{(Y)}$ *(kN)*	2853	2070	2010	1895	1863	2505

Table 4 The analysis results of five-story structures

ID: 5G	Opening Case					
Number of Story :5	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.164	0.242	0.319	0.467	1.000
λ_w	2.093	2.093	2.093	2.093	2.093	0.000
λ	1.000	0.367	0.257	0.178	0.089	0.000
r_w *(m)*	3.397	3.397	3.398	3.397	3.397	0.000
w_{ef} / r_w	0.130	0.048	0.033	0.023	0.012	-
$T^{(x)}$ *(s)*	0.893	0.971	0.982	0.990	0.997	1.094
$d^{ep}_{(X)}$ *(m)*	0.269	0.299	0.303	0.306	0.308	0.324
$R^{(X)}_{y1}$	7.060	9.890	7.150	10.120	10.320	4.697
$\mu^{(X)}$	6.130	8.665	5.336	8.110	9.025	3.911
$a^{(X)}_y$ *(m/s²)*	1387	932	1278	897	883	2088
$S^{(X)}_{d(av)}$ *(m)*	0.033	0.025	0.042	0.028	0.025	0.044
$V_t^{(X)}$ *(kN)*	2778	2406	2361	2346	2325	5700
$T^{(Y)}$ *(s)*	0.529	0.618	0.693	0.808	0.869	0.935
$d^{ep}_{(Y)}$ *(m)*	0.307	0.328	0.331	0.334	0.336	0.353
$R^{(Y)}_{y1}$	6.859	10.720	11.098	11.096	11.260	4.969
$\mu^{(Y)}$	5.290	9.220	9.330	9.108	9.430	3.456
$a^{(Y)}_y$ *(m/s²)*	1320	808	776	772	758	1974
$S^{(Y)}_{d(av)}$ *(m)*	0.043	0.026	0.026	0.027	0.026	0.054
$V_t^{(Y)}$ *(kN)*	2768	2346	2228	2289	2216	6275

ID: 5H	Opening Case					
Number of Story :5	OpC-1	OpC-2	OpC-3	OpC-4	OpC-5	OpC-6
a_w *(%)*	0.000	0.160	0.240	0.320	0.453	1.000
λ_w	2.250	2.250	2.250	2.250	2.250	0.000
λ	1.000	0.380	0.271	0.192	0.101	0.000
r_w *(m)*	3.530	3.500	3.530	3.520	3.530	0.000
w_{ef} / r_w	0.127	0.048	0.034	0.024	0.013	-
$T^{(x)}$ *(s)*	0.650	0.773	0.794	0.808	0.817	0.842
$d^{ep}_{(X)}$ *(m)*	0.171	0.217	0.224	0.229	0.232	0.245
$R^{(X)}_{y1}$	3.280	5.050	5.310	5.640	5.950	5.850
$\mu^{(X)}$	2.950	4.310	4.440	4.670	4.650	4.150
$a^{(X)}_y$ *(m/s²)*	2984	1942	1844	1736	1648	1675
$S^{(X)}_{d(av)}$ *(m)*	0.045	0.039	0.039	0.038	0.039	0.042
$V_t^{(X)}$ *(kN)*	1327	1551	1436	1394	1250	2610
$T^{(Y)}$ *(s)*	0.747	0.864	0.886	0.899	0.909	0.921
$d^{ep}_{(Y)}$ *(m)*	0.207	0.248	0.255	0.260	0.264	0.286
$R^{(Y)}_{y1}$	4.470	5.710	6.310	6.730	6.690	7.120
$\mu^{(Y)}$	4.130	4.690	4.980	5.090	5.060	5.790
$a^{(Y)}_y$ *(m/s²)*	2194	1717	1552	1455	1463	1376
$S^{(Y)}_{d(av)}$ *(m)*	0.039	0.041	0.037	0.039	0.040	0.034
$V_t^{(Y)}$ *(kN)*	1207	1296	1235	1148	1065	1712

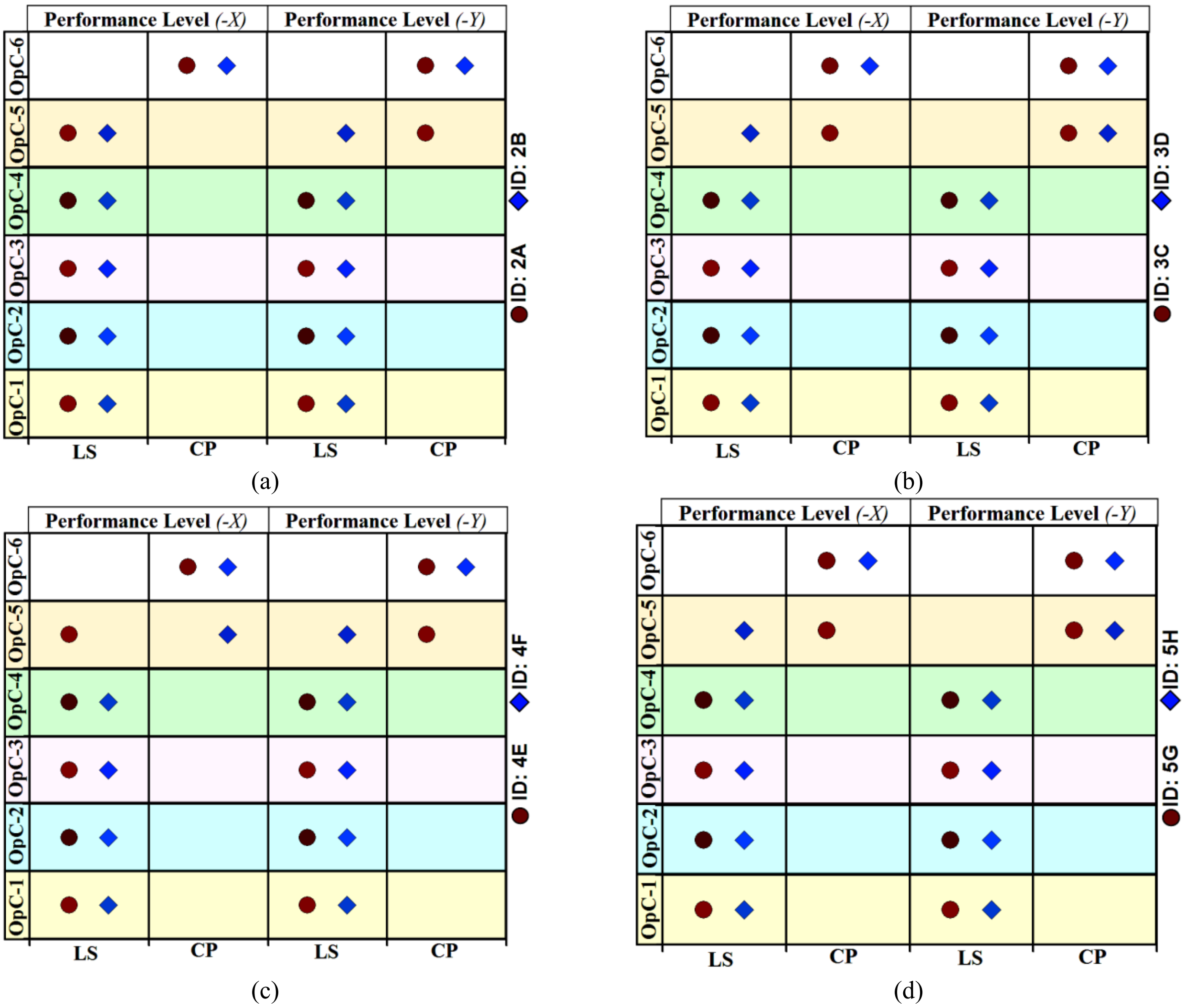

Fig. 11 The performance level of existing RC structures

5. Conclusions

Most RC structures are defined by the presence of infill walls as a traditional construction application in many countries with high seismicity.

Infill walls are not considered in the analyzes as infill walls are generally not accepted among the structural system elements.

Failure to consider this assumption in analyzes can have a negative effect on the determination of seismic fragility or damage of load-carrying elements, since the presence of infill walls and change of structural properties can cause significant differences in all parameters of RC structures related to earthquake safety. Therefore, their interaction with the RC frames should be understood to examine the ductility, rigidity, strength and earthquake performance of RC structures.

The results of the study indicate that the infill walls increased the rigidity and strength of the RC structures as long as seismic demand did not exceed the load-carrying capacity of the infill walls.

Infill walls with or without openings have a beneficial effect on many parameters such as the fundamental period, r elative story drift rate, shear capacity and seismic vulnerability of RC structures and are taken into account when determining their earthquake performance.

In the determination of the earthquake performance of RC structures under earthquake loads, only the damage levels of the columns and beams are considered by codes. However, the effect of the infill walls on the seismic vulnerability of investigated RC structures is useful both in collapse limit cases and damage limitation. This result applies to many frame

structures with infill, provided that the distribution of the walls does not cause structural irregularities in the plan. In addition, bending and shear failures due to the bending and shear impact can be prevented in columns and beams, respectively.

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