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Seismic vulnerability assessment of low-rise irregular reinforced concrete structures using cumulative damage index

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Abstract. Evaluating seismic performance of urban structures for future earthquakes is one of the key prerequisites of rehabilitation programs. Irregular structures, as a specific case, are more susceptible to sustain earthquake damage than regular structures. The study here is to identify damage states of vertically irregular structures using the well-recognized Park-Ang damage index. For doing this, a regular 3-story reinforced concrete (RC) structure is first designed based on ACI-318 code, and a peak ground acceleration (PGA) of 0.3 g. Some known vertical irregularities such as setback, short column and soft story are then applied to the regular structure. All the four structures are subjected to seven different earthquakes accelerations and different amplitudes which are then analyzed using nonlinear dynamic procedure. The damage indices of the structures are then accounted for using the pointed out damage index. The results show that the structure with soft story irregularity sustains more damage in all the earthquake records than the other structures. The least damage belongs the regular structure showing that different earthquake with different accelerations and amplitudes have no significant effect on the regular structures.

Keywords: damage index; nonlinear dynamic analysis; seismic vulnerability; setback; short column; soft story

1. Introduction

As one of the most catastrophic natural hazards, earthquakes have always imposed important losses to the human civilizations. It is thus of paramount importance to provide adequate readiness prior to earthquake events. In this respect, one of the most important steps is to assess the seismic vulnerability of urban buildings, which is often performed defining a damage index (DI). Using a DI, it is understood how a building structure is vulnerable under the design earthquake. In that case, the results of such understanding would allow for making proper decisions when a rehabilitation program shall be adopted (Behnam *et al.* 2006). Regarding seismic structural performance, a damage can be categorized into two groups: a damage resulted from increased seismic demand (e.g., soft story, strong beam-weak column, and vertical irregularities), and damage due to reduction in ductility and energy dissipation capacity (e.g., poor construction quality, deteriorations due to long service life, etc.) (Cosenza and Manfredi 2000). In this regard,

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demand elevation and strength reduction can be mentioned as inherent parameters to seismic behavior of a structure (Tesfamariam and Saatcioglu 2010). Among these parameters, vertical irregularities resulting from architectural limitations have been found to significantly affect the structural performance. Paying attention to previous earthquakes reveals that irregualr structures- particularly irregular structures- sustain more damage than that of regualr structures (Gursoy *et al.* 2015). Although there are several irregularities, here three most commoly observed irregulraties are investgated; 1) setback irregularity which is defined as a story having dimensions of more than 130% of its adjcent srory, 2) soft story irregularity which is defined as the lateral stiffness of a story becoming less than 70% of the upper story or less than 80% of the three lower stories, and 3) short column which is a common irregularity in urban structures and is considered when the ratio of the effective length of a column to the smaller lateral dimension becomes less than 12. In this study, a number of reinforced concrete (RC) structures with some vertical irregularities are analysed through a nonlinear dynamic process where different earthquakes with different peak ground accelerations (PGA) are taken into consideration. The structural analyses results are then used for computing damage indices of the structural components and different story levels. It is hoped that the results of the investigations planned here can provide some quantitative measures about how structural irregularities can influence the seismic performance of structures.

2. Previous studies

There are many studies have revealed higher seismic vulnerability of irregular structures compared to regular structures. Moretti and Tassios (2006) conducted an experimental study on the behavior of urban structures with short columns. The study showed that cyclic response of short columns does not meet the ductile design requirements due to their brittle fracture mechanism. Similarly, Zhou and Liu (2010) showed that short columns with a circular concrete-filled steel section fractured through a brittle shear mechanism when subjected to a cyclic incremental loading. Al-Ali and Krawinkler (1998) studied seismic performance of frames when the allocated masses were distributed over an irregular manner throughout buildings height; they reported changes in story drifts, ductility and natural period of structures compared to regular buildings. Soni and Mistry (2006) showed that story drift demands undergone by irregular structures are much more than those experienced by regular buildings. In a similar study, Behnam (2015) showed that irregualr structures sustain more story drift than those od regular structures under an identical earthquake. Chintapakdee and Chopra (2004) studied the effect of stiffness and strength irregularities on drift and displacement demands of structures. Using nonlinear dynamic analyses they showed that larger drifts occur at stories adjacent to a soft or weak story (including the soft story itself) while other stories experienced smaller drifts. Le-Trung *et al.* (2012) showed that formation of a soft story leaves more damage than other irregularities. Habibi and Asadi (2016) evaluated seismic performance of several structures proportioned to meet ductile design requirements. The structures were of different in height which had some vertical irregularities. The study revealed that elements adjacent to the irregular region experienced more damage than other regions.

Since investigating the irregularity effects on the structural performance requires more in-depth understanding of irregular structure, using a DI can be benefitial for representating buildings response. The selected DI should be a good representative of both linear and nonlinear building responses. While there are many equations proposed over the last decades, equations consist, generally, of two parts: the energy dissipated in an element during analysis, and the maximum

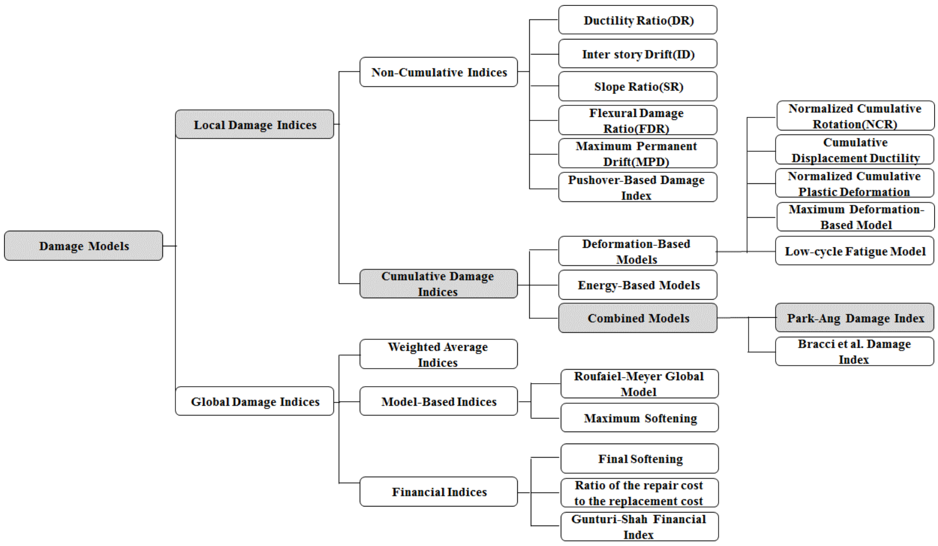


Fig. 1 The categorizations of damage indices (Williams *et al.* 1997)

deformation tolerated. Other parameters such as magnitude, duration and number of loading cycles have also been included in some proposed formulations. A DI often computes a value between of 0 and 1 that represents, respectively, no damage and a complete damge. From a different perspective, local (reflecting an element response) and global (reflecting response of entire structure) DIs are computed in either cumulative or non-cumulative forms. Most of the local DIs are cumulative formulae that correlate a damage to magnitude and number of loading cycles. A cumulative DI provides a mesure that reflects more aspects of the structural response that are not addressed by the maximum deformation measure. Local DIs are used for computing damage experienced by different elements and include, commonly, two features of the response: ductility and energy dissipation. The ductility measure is to normalize the maximum value of rotation, curvature or displacement response experienced by an element (ATC 2001). Among the methods based on the deformation measure, Banon method (Banon *et al.* 1981) can be mentioned in which the cumulative damage resulting from a cyclic loading is reflected by two complementary measures. These measures include the normalized dissipated energy and the normalized cumulative deformation with the latter being the summation of plastic rotations divided over the yield rotation. Another simple measure computed on the basis of maximum relative displacements is the “story drift ratio” being also known as the “maximum deformation” DI (Ghobarah 2001). Fig. 1 summarizes different damage indices as discussed above.

The dissipated energy, on the other hand, has been regarded in many studies for estimating the amount of damage experienced by a structure subjected to dynamic analysis. Sadeghi and Nouban (Sadeghi and Nouban 2010) developed an energy-based DI using of which the strength degradation was computed at different locations within a finite element model. Given that both inelastic and cumulative deformations under cyclic loading contribute in damage of RC structures, DIs have been developed in a way to employ both groups of response parameters. For doing this, the load value and the number of cycles should be combined using appropriate factors. The combined DIs developed in such manner include simultaneously the maximum deformation and the dissipated energy. The method used for computing the energy dissipation employed by a DI formula should be stated. Experimental studies have shown significance of three parameters used in the structural modelling based on nonlinear dynamic analysis. These parameters include stiffness deterioration (α), strength degradation (β), and the pinching of response (γ) resulting from slippage (Park *et al.* 1985). Park and Ang (1985) developed hysteresis models for representing behaviour of RC members with inclusion of these parameters. Williams *et al.* (1997) showed how other hysteresis models can be obtained using appropriate values for aforementioned parameters. For instance, they showed that using an α=0.2, β=0.1 and $\gamma=\infty$ can yield in the Takeda model which includes the commonly accepted stiffness degradation effects (Park *et al.* 1985). Therefore, the hysteresis curves resulting from analyses can be used for computing combined DIs. One of the well-employed cumulative DIs that concurrently employs maximum deformation and hysteretic energy is the Park-Ang's DI. The Park-Ang formulation has been utilized as the basis for evaluating DIs proposed by other researchers (Park and Ang 1985). The main feature of this index is its consistency with experimental observations as well as its simplicity to interpret the damage state. The Park-Ang DI also accounts for the overall structural damage by combining DI computed for different elements according to the ratio of total energy absorbed in each story. The Park-Ang DI is a linear combination of normalized values computed for the maximum deformation and hysteretic energy. Although the introduced DI has been originally developed for RC elements, it is also widely used for other types of structures such as steel structures. The Park-Ang DI was later modified by Stone and Taylor (Stone and Taylor 1993) as presented in Eq. (1) for computing DI of an element

$$D = \frac{\phi_m - \phi_y}{\phi_u - \phi_y} + \beta \frac{\int dE}{M_y \phi_u} \tag{1}$$

In this equation, ϕ_m and ϕ_y represent the maximum curvature and yield curvature, respectively, experienced by the element during the cyclic loading; ϕ_u is the ultimate curvature experienced by the element in a monotonic loading; M_y is the yield moment of the element, $\int dEh$ is the energy dissipated by the member throughout an excitation, and β is a calibration coefficient between of 0.1 and 0.15 recommended to be taken as 0.1. The DI determined using Eq. (1), is categorized into four groups: 1) DI<0.11means there is almost no damage or very minor cracking, 2) 0.11<DI<0.44 means the damage is considerable but the element is repairable, 3) 0.44<DI<0.77 means although the damage is extensive and the element is irreparable, it has not yet collapsed, 4) DI>0.77 means a complete destruction.

The modified Park-Ang DI is employed here for evaluating the effect of irregularities, as presented in the next sections. Eq. (1) was also used by Bertero and Bertero (Bertero and Bertero 1993) for reflecting rotational behavior of a plastic hinge. As previously stated, the Park-Ang DIs computed at element level are then combined over story and structure using in Eqs. (2) and (3), respectively.

$$DI_j^s = \sum_{k=1}^{mj} \lambda_{kj} . DI_{kj} \tag{2}$$

$$\boldsymbol{\lambda_{kj}} = \frac{\boldsymbol{E_{kj}}}{\boldsymbol{E_j}} \tag{3}$$

In these equations, DI_j^s is the DI computed for the jth story, DI_{kj} denotes the index computed for the k^{th} element of j^{th} story, $E_j = \sum_{i=1}^{m_j} E_{ij}$ denotes sum of energy dissipated at j^{th} story, and m_j is the number of elements in j^{th} story. The overall DI of structure, DI_G, is computed using Eqs. (4) and (5) in which $E_T = \sum_{s=1}^{N} E_s$ denotes sum of the energy absorbed in an N-story structure.

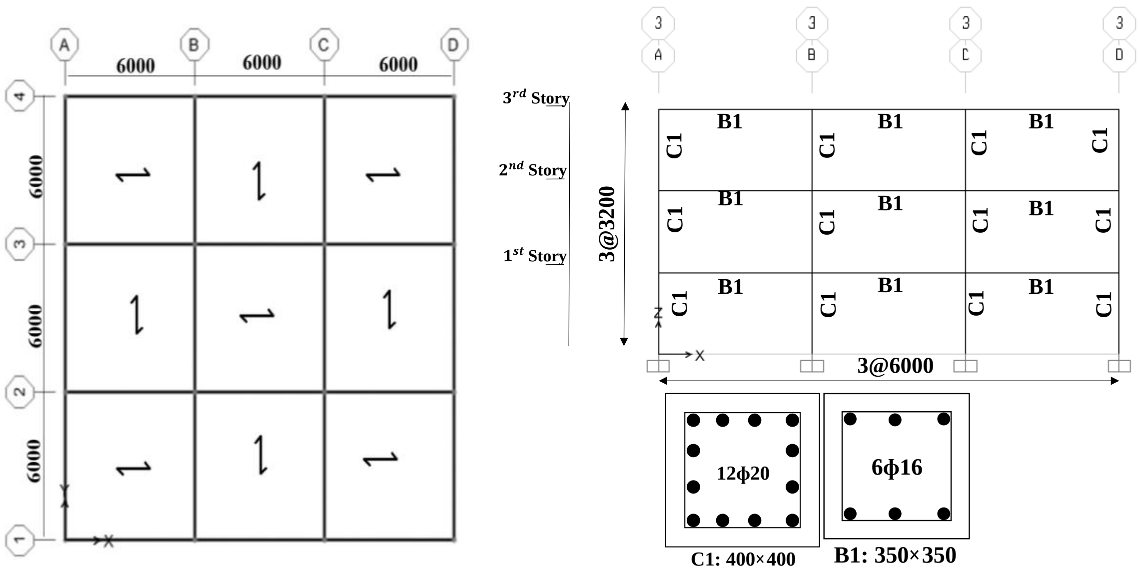
$$DI_G = \sum_{k=1}^{N} \lambda_i .DI_i^s \quad (4)$$

$$\lambda_i = \frac{E_i}{E_T} \quad (5)$$

Massumi and Moshtagh (2013) developed a new DI for tall RC structures using response at larger periods of a nonlinear model. Cao *et al.* (2013) also proposed a DI for RC structures based on their cyclic response and approved its acceptability by comparing against the values provided by the Park-Ang formulation. The advantage of this DI was the interpretations provided for its results addressing structural performance levels instead of damage states. Rodriguez *et al.* (2010) developed a new DI formulation that incorporated response parameters of a single degree of freedom (SDOF) system. These parameters included the maximum hysteresis absorbed at a unit mass of system under intense earthquakes. They emphasized that reducing structural displacements, especially those occurred at the roof level, are particularly important for decreasing structural damage. Carillo (2015) correlated the DI of RC shear walls to their stiffness degradation incorporating empirical observations and experimental shaking table tests. The presented review on proposed DI formulations demonstrates the importance of intuition regarding seismic behavior of structures. To improve the understanding of structures having degrees of vertical irregularity, the structural response can be represented by an appropriate DI. Here, a number of 3-story RC structures suffering from vertical irregularities are subjected to nonlinear dynamic analysis using seven different earthquake accelerations. The local and overall values of Park-Ang DI is, then, regarded for investigating the effect of irregularities in presence of different earthquakes.

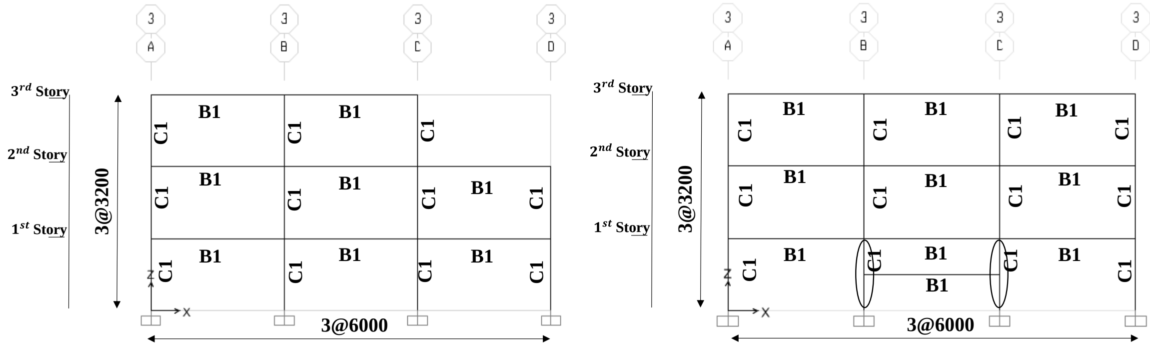
3. Case study

A 3-stoy RC structure is considered for evaluating the seismic effects of vertical irregularities. A regular form of this structure (shown in Fig. 2) having three 6m-wide bays in each direction is considered as the reference building. The lateral load resisting system used in both directions is an RC moment resisting frame with ordinary ductility. All stories are 3.2 m high and carry dead (D) and live (L) loads that equal, respectively, 4.0 kPa and 1.5 kPa. The structural seismic mass is computed using a D+0.2L combination. The effect of story slab in distributing story shear loads between resisting columns is modeled using rigid diaphragm constraints. The used concrete material has a density of 2500 N/m^3, compressive strength of 25MPa and a Poisson ratio of 0.2. The steel material used for longitudinal and transvers rebars have yield strengths of, respectively, 400 MPa and 300 MPa. The reference building is designed based on ACI code (ACI318 2008) and considering a peak ground acceleration (PGA) of 0.3 g. Geometrical properties of the plan and the

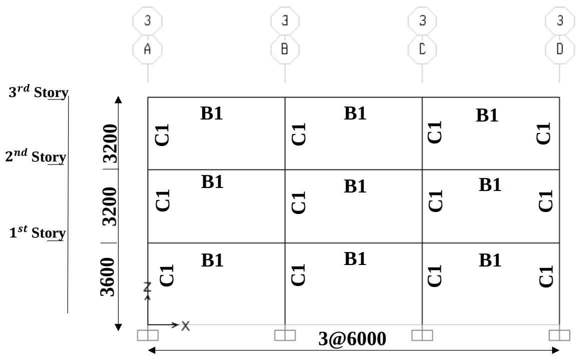


(a) Plane view (b) Side view and cross-sections

Fig. 2 The plan and side view of the reference structure (dimensions are in mm)



(a) The structure with setback irregularity (b) The structure with short column irregularity



(c) The structure with soft story irregularity

Soft Story:

$$K = \frac{EI}{L^3}$$

$$K^{3rd} = 3EI/3.6^3$$

$$K^{2nd} = 3EI/3.2^3$$

$$K_i < 0.7\ K_{i+1}$$

Setback Irregularity:
horizontal dimension of the lateral force resisting systems in 3rd story =18000mm
horizontal dimension of the lateral force resisting systems in 2nd story=12000mm

$$\frac{L^{3rd}}{L^{2nd}} = \frac{18}{12} = 1.5 > 1.3$$

(d) A summary of the irregularities calculations

Fig. 3 The irregular frames

Table 1 The parameters of recorded earthquakes for the study here

NO	Earthquake	Year	Station	Mw	PGA	PGV	Component
1	Cape Mendocino	1992	Rio Dell Overpass	7.0	0.55	44	RIO270
2	Hector Mine	1999	Hector	7.1	0.34	42	HEC000
3	Imperial Valley	1979	El Centro Array#11	6.5	0.38	42	H-E11140
4	Kocaeli Turkey	1999	Duzce	7.5	0.36	59	DZC180
5	Landers	1992	Coolwater	7.3	0.42	42	CLW-LN
6	Loma Prieta	1989	Capitola	6.9	0.53	35	CAP000
7	Northridge	1994	Canyon Country-WLC	6.7	0.48	45	LOS000

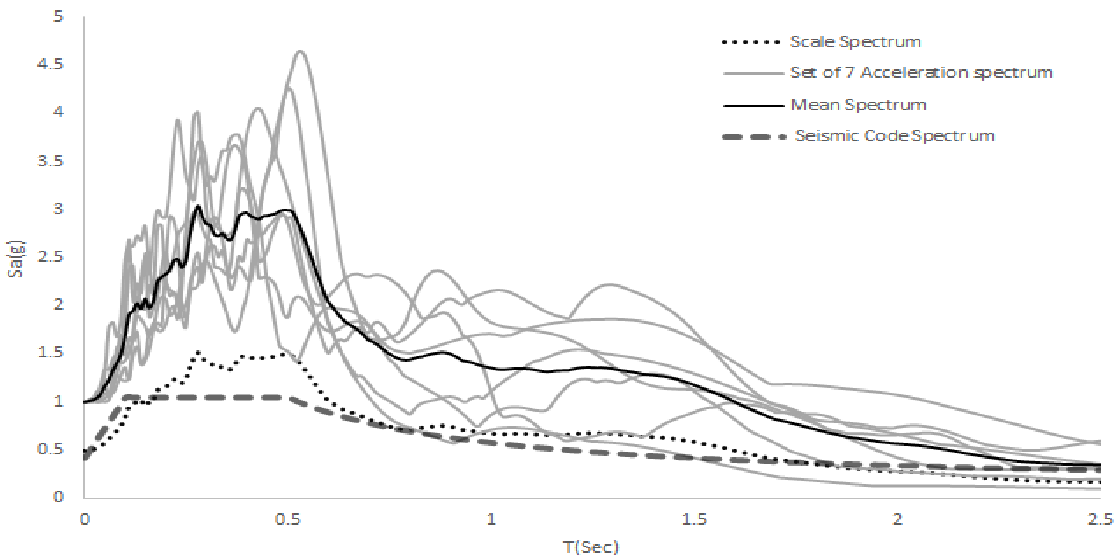


Fig. 4 The acceleration spectrums for *PGA* of 0.3 g

structural members are shown in Fig. 2.

After designing of the reference building, three setback, soft story, and short column irregularities are intentionally considered to the reference building. Figs. 3(a)-(c) show the side views of the irregular structures; Fig. 4(d) provides a summary of the irregularities calculations based on FEMA 310 (1998).

4. Modelling

To perform a nonlinear analysis, the gravity loads are initially applied to structures and are kept constant while the seismic loads are applied at the next stage. The seismic analysis is performed, employing SAP2000 package (SAP2000-V14 2002) and based on seven selected earthquake accelerations. Many analyses can be considered among which only a fully nonlinear method including the p-delta effects can guarantee accurate estimation of demands required for evaluating performance levels such as life safety (LS) and collapse prevention (CP). The selected far-filed records have magnitudes between of 6.5 and 7.0 on the Richter scale as introduced in Table 1.

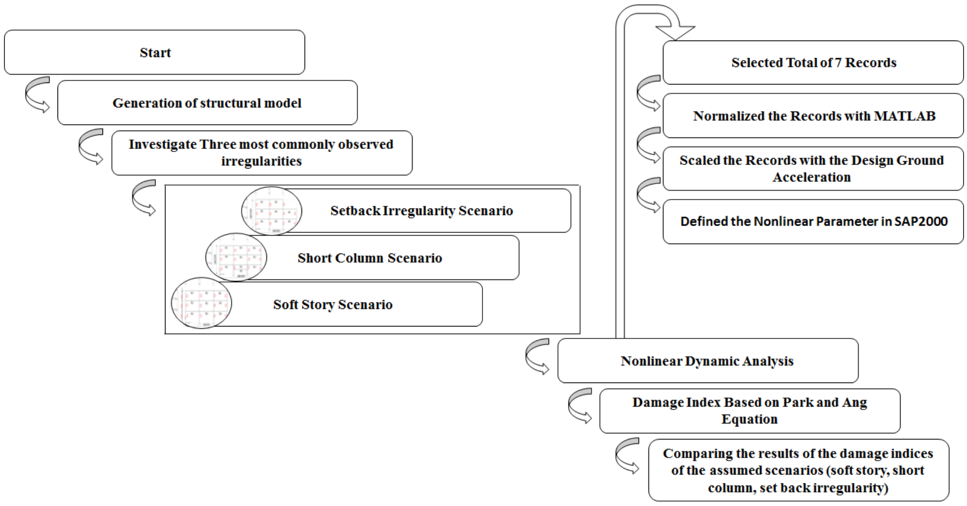


Fig. 5 Procedure of determining the damage indices of the cases studied

Since the analyses are performed in two dimensions (only one horizontal direction is considered), the larger spectrum of a horizontal record pair is selected. An average is then obtained from the two records normalized by the maximum value of the selected spectrum. This procedure is implemented using MATLAB package for obtaining a normalized 5%-damped acceleration spectrum representing each record pair. Each average spectrum is then scaled in a way that its value does not exceed more than 10% below 1.3 times of the standard design spectrum at a 0.2T-1.5T period range (with T being the fundamental period of structure). The standard design spectrum here refers to ASCE/SEI 41-06 (2007). Using this, all the records are scaled to a PGA=0.3 g level as shown in Fig. 4.

The Hilber-Hughes-Taylor (Hilber *et al.* 1977) direct integration method employing γ=0.7 and β=0.36 acceleration interpolation factors is used for performing time-history analyses. The α parameter of this method should be assigned values between-1/3 and 0. In this study, to achieve solution convergence, the value of α factor is determined differently for various models. The two coefficients required for assigning a mass- and stiffness-proportional Rayleigh damping are computed by averaging the frequencies related to the 1-3 and 4-10 modes, respectively. Lumped plasticity is used for representing nonlinear behavior of elements (SAP2000-V14 2002). Then, flexural hinges that use section properties are assigned to beam elements. For column elements, due to significance of axial forces and the axial-flexural interaction, flexural-axial hinges are defined. These hinges use instantaneous axial loads to extract yield moment of the hinge at any stage of the analysis (SAP2000-V14 2002). The hysteresis moment-rotation curves obtained from seismic loading were then used in MATLAB package for computing the energy dissipated at each element. The outputs are used for computing the Park-Ang DI for each element and finally for the entire structure. The procedure used for this computation is illustrated in Fig. 5.

5. Results

Eq. (1) is employed for computing story DIs. Story DIs are used, in turn, for extracting the

Table 2 The damage indices determined for the cases studied

Earthquake	structure	Reference frame		Setback		Short column		Soft story	
	Story	DI	Global DI	DI	Global DI	DI	Global DI	DI	Global DI
	3rd	0.24		0.29		0.25		0.51	
Cape	2nd	0.24	0.23	0.28	0.27	0.27	0.25	0.78	0.72
	1st	0.22		0.24		0.22		0.76	
	3rd	0.22		0.24		0.26		0.67	
Hector	2nd	0.27	0.26	0.25	0.26	0.27	0.33	0.76	0.74
	1st	0.26		0.27		0.38		0.8	
	3rd	0.32		0.39		0.34		0.8	
Imperial	2nd	0.31	0.29	0.36	0.33	0.33	0.35	0.85	0.85
	1st	0.26		0.28		0.37		0.88	
	3rd	0.27		0.26		0.26		0.51	
Kocaeli	2nd	0.3	0.27	0.28	0.27	0.29	0.27	0.6	0.6
	1st	0.25		0.26		0.26		0.64	
	3rd	0.36		0.4		0.38		0.75	
Landers	2nd	0.37	0.34	0.38	0.35	0.37	0.39	0.87	0.68
	1st	0.3		0.3		0.4		0.68	
	3rd	0.25		0.22		0.26		0.57	
Loma Perieta	2nd	0.3	0.27	0.26	0.24	0.31	0.41	0.86	0.77
	1st	0.26		0.24		0.52		0.8	
	3rd	0.35		0.33		0.41		0.88	
Northridge	2nd	0.39	0.37	0.34	0.32	0.45	0.48	0.88	0.78
	1st	0.35		0.3		0.51		0.77	

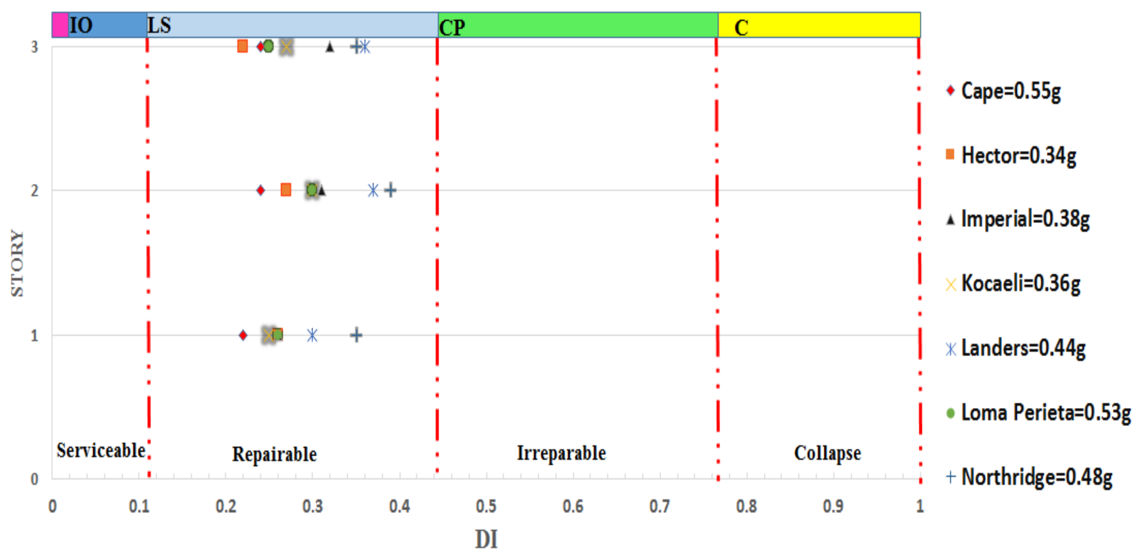


Fig. 6 The damage indices of the reference frame under the considered earthquakes

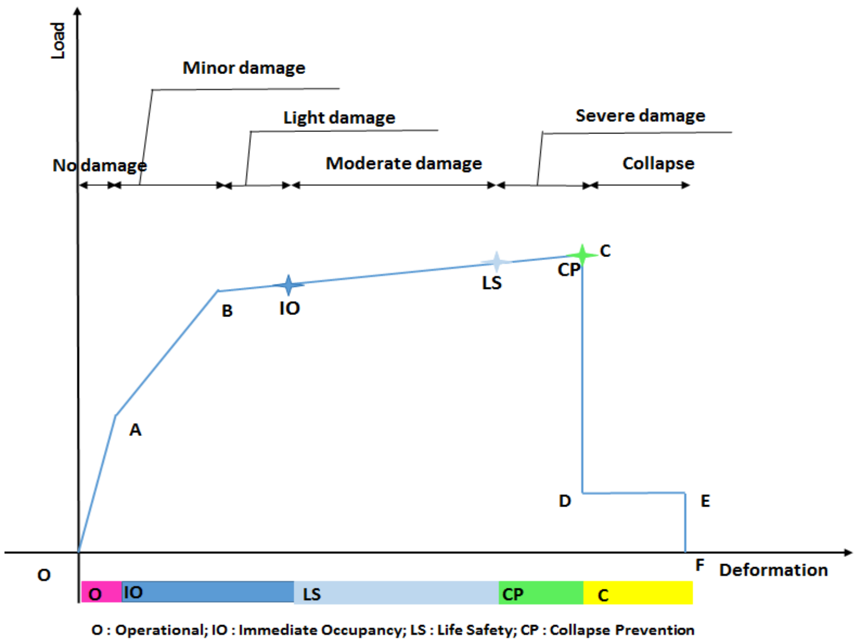


Fig. 7 Damage states and performance levels

structural DIs using Eq. (4). For each earthquake record, the story and overall DIs are presented in Table 2. Based on the modified Park-Ang equation, the categorizing of the damage states corresponding to different DI values are changed. Accordingly, DIs less than 0.11, between 0.11 and 0.44, between 0.44 and 0.77, and larger than 0.77 were interpreted as functional with low damage, repairable with average damage, irreparable with high damage and complete destruction, respectively.

To provide a better understanding, the Table 2 values are also presented in a graphical form. The story DIs obtained for the reference regular structure are illustrated in Fig. 6 where the DIs values are presented in the horizontal axis and the story number are shown in the vertical axis. The figure provides values of the modified Park-Ang DI for all seven earthquakes along with the limit values of different damage states (dashed lines). According to the chart values, a low damage-reparable state (DI<0.44) is experienced by the reference structure under all the applied records.

It is worth mentioning that in RC structures; even a minor cracking can be considered as a damage even though the damage has no effect on the seismic structural response. In this line, Fig. 7 shows that although after point A the structure might experience some cracking, there would not be any meaningful damage until the structure passes point B, which is corresponding to yield response in a way the DI is equal to DI_y. The damage then increases over the point B and C as can be understood from the figure. The damage sustained between of point B and C can also be categorized as three known performance levels that are IO, LS and CP (ASCE41-06 2007). In terms of a qualitative explanation, the introduced points (A, B, and C), three light, moderate and severe damage states can be associated.

Using the damage states presented in Fig. 7, it can be understood that the regular structure can meet the LS performance level in all the earthquakes introduced. It is yet worth noting that, the largest DIs are obtained in the 1st, 2nd and 3rd stories belong, respectively, to Northridge,

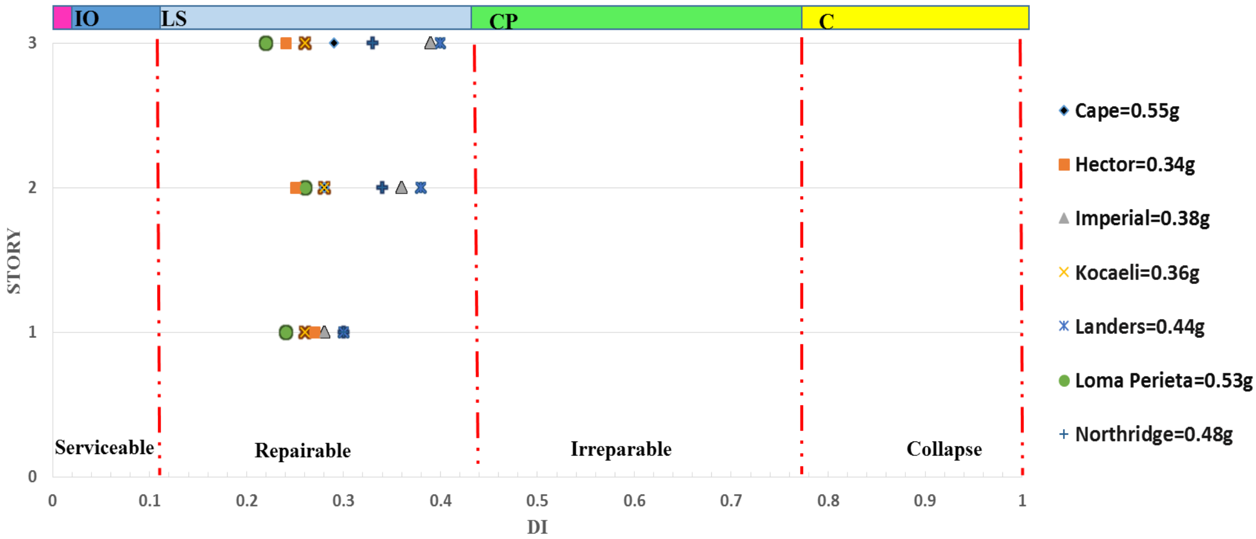


Fig. 8 The damage indices of the setback irregular frame under the considered earthquakes

Northridge and Landers earthquakes. This means that earthquakes with PGAs around 0.4 g can induce rather high damage. Also, the smallest DIs with values around 0.22 are induced by the Cape and Hector earthquakes that possess, respectively, the largest and smallest PGA values. The DI values observed in the 3rd story for two earthquakes with PGAs around 0.5 are very close to each other. Nevertheless, the DIs caused by these records get away in lower stories while the largest DIs are observed for records with PGAs around 0.4. These observations highlight the effect of other earthquake parameters that should be involved in addition to the PGA. The average DI computed for all records reaches a value around 0.29 indicating an acceptable seismic performance to be provided in all the stories.

The data similar to those presented in Fig. 7 are illustrated in Figure 8 for the structure setback irregularity. As seen, the first and second ranked DIs observed in all the stories belong, respectively, to the Imperial and Landers earthquakes. The smallest DIs observed in the 1st, 2nd and 3rd stories belong to Loma or Cape, Hector and Loma, respectively. These observations imply that records with PGA=0.38-0.48 have induced the most intense damages while those with PGA>0.5 or PGA<0.38 are rather light. Overall consideration of DI values suggest that the structure has fulfilled the LS performance level. In earthquakes with more damaging effects, more damage is observed in the 2nd and 3rd stories (where setback irregularity occurs) than the 1st story. This shows the records with low damage have caused more damage on the 1st story than the uppers. It can be concluded that in high-damaging earthquakes, damage is more concentrated on the irregular regions. For earthquakes causing lower levels of damage (and higher performance levels), however, damage is more concentrated on the lower stories. It is evident that Dis of beams and columns s participate differently in the formation of the story DI. That is, although more severe damages are experienced by the beams adjacent to the irregular regions, the damage of these member does not have a determining role in the overall damage sustained by stories. This observation may result from the larger weights attributed to the columns (compared to beams) in extracting the overall story DI. Under earthquakes causing minor damage, the irregularities have not significantly affected the story and overall DIs. Under such records, larger DIs are observed at

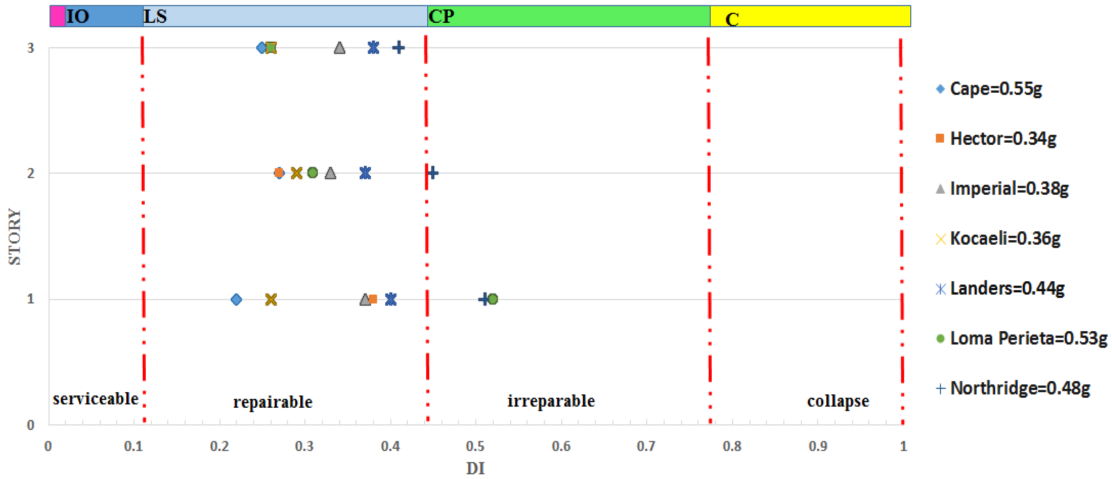


Fig. 9 The damage indices of the frame with short column irregularity under the considered earthquakes

stories with no irregularities compared to the irregular stories. This observation, however, vanishes by increase of the overall DI value and intensification of the irregularity effects. The average story DI has a value of 0.29, in this case, denoting a performance similar to that provided by the reference (regular) structure.

Fig. 9 shows the same results for the structure with a short column irregularity. According to this figure, the Cape and Northridge earthquakes cause, respectively, the lowest and largest DIs observed among all stories. From an overall point of view, the Northridge, Landers and Imperial earthquakes have led to the largest DI values. However, despite the two former structures, the Loma record has induced the largest damage in the 1st story. Although the semi-story beam has experienced a complete damage with DI>1 under all earthquakes, still around 80% of results indicate a reparable damage state at the LS performance level. The Northridge earthquake causes the only violation of the reparability level in all stories. This record, however, does not possess the largest PGA value and its severe damaging effect should be attributed to other parameters representing the frequency content of this record. Except for the two earthquakes of Cape and Kocaeli, other records have caused larger damages in the 1st story with a short column irregularity. The larger damage of this story is more significant under records with higher damaging effects. The average DI value of this structure has increased to 0.34 indicating wider damages to have occurred compared to the regular structure and the structure with a setback irregularity.

Fig. 10 presents the results of the structure with a soft-story irregularity. From an overall perspective, this structure has experienced the largest DIs. All records have induced irreparable damage. The lowest DI is observed in the 3rd story to reach around 0.51 under the Cape and Kocaeli earthquakes. The largest DI is around 0.88 and is induced by the Northridge and Imperial earthquakes. An average DI of 0.74 is computed for this structure which indicates its unacceptable performance.

Under earthquakes with PGA<0.4, the largest DI occurs in the 1st story which is the softened story. For earthquakes with higher PGAs, the largest damage alternates between the 2nd and 3rd stories. It is also worth noting that the overall DI is in direct relation with the 1st story DI. That is, although the maximum story DIs are observed at the 2nd and 3rd stories, the maximum overall DI occurs under the record causing the largest DI at the 1st story. On the other hand, the record

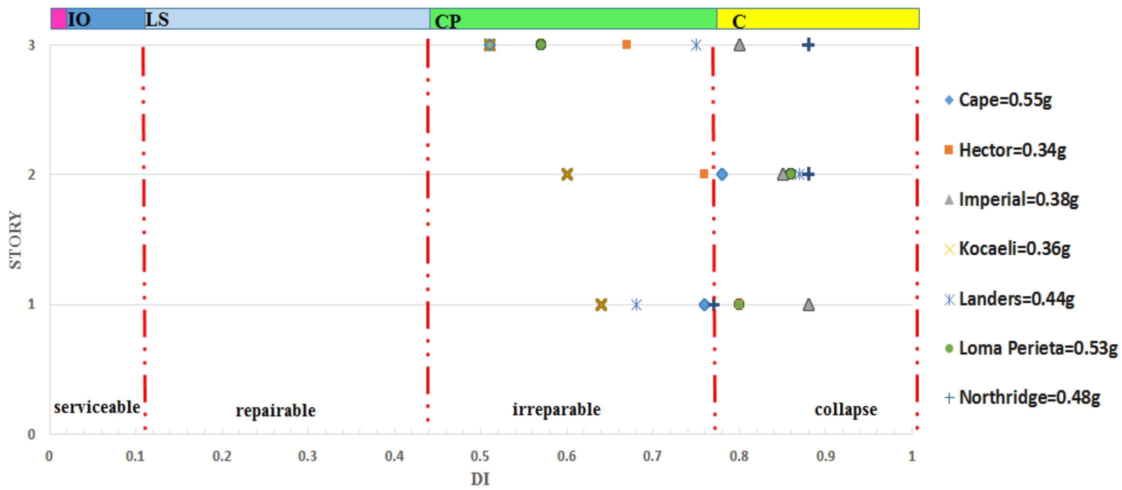


Fig. 10 The damage indices of the frame with soft story irregularity under the considered earthquakes

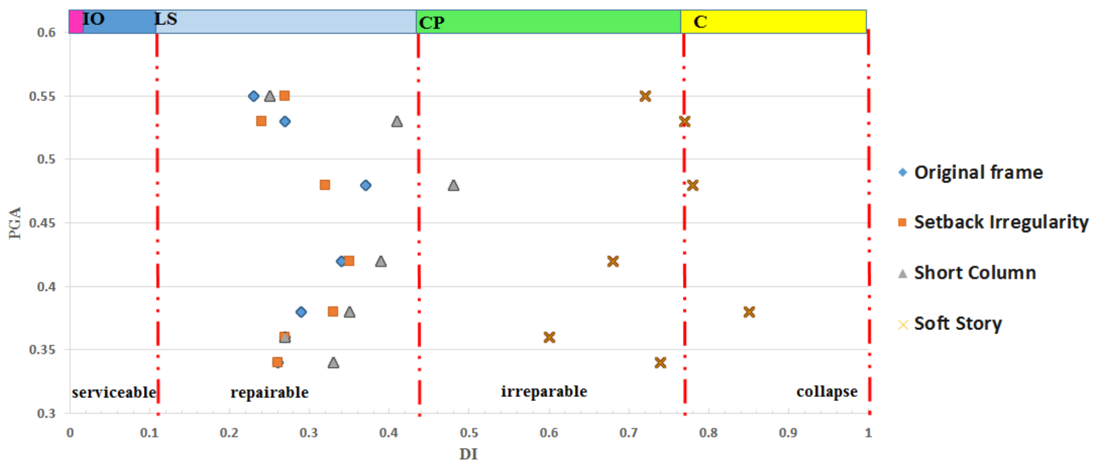


Fig. 11 The damage indices of the cases studies versus PGAs

causing the smallest 1st story DI induces the largest overall damage. This observation can denote the significance of earthquakes with PGA<0.4 in the low-rise structures having short-column irregularity. In the previous structures with plan and soft-story irregularities, effect of damaging earthquakes was more pronounced at the irregular story. As stated, this observation is in contrary to the short-column structure due to the complete destruction of building under severe earthquakes.

Fig. 11 shows the variation of overall DIs against PGA values for different structures. According to this figure, it is understood that except for the 0.46<PGA<0.54, the irregular structures undergo DIs greater than or equal to the regular structure. In the pointed out PGA range, the setback irregular structure has shown a better performance compared to the regular building. Except for PGA=0.55records, the structure with short column irregularity has experienced DIs that are in excess of the two former structure. In the 0.46<PGA<0.54, the DI observed for this structure has violated the reparability and LS levels. According to the performance provided by the setback irregular structure, this building can be said to have provided a better performance than the other

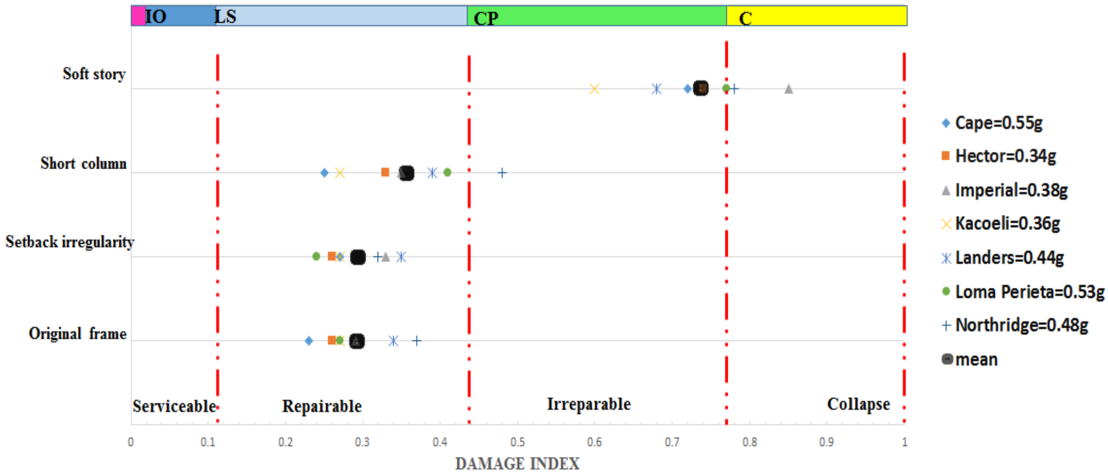


Fig. 12 The mean of damage indices for the cases studied

irregularities in the 0.46<PGA<0.54. The largest DI belongs to the structure with soft story irregularity. The PGA<0.4 range is especially considered to pose the largest DIs (as was stated for PGA=0.38 in previous cases) on this structure. In such cases, the DI undergone at the first soft story directly influences the overall DI of structure.

To compare overall effect of irregularities on seismic performance of structures, Fig. 12 is provided. According to this figure, the setback irregular structure is shown to provide a LS performance level similar to the regular building. The damage experienced by the structure with short column is more than the two former buildings. This structure is still capable to provide an LS level of performance depending on the applied earthquake. The building with a soft story irregularity is however shown to violate the LS level saying that even low-rise structures require stringent design limitations in presence of a soft story.

6. Conclusions

The vulnerability of most urban buildings to earthquake events has stimulated especial attentions to adopt. To address this, the vulnerability of urban structures under the design earthquake is assessed defining a damage index. Building irregularities, on the other hand, pose structures to more severe damages that increase the necessity to seismic evaluations. Various irregularities can be assumed in a structure among which this article focuses on vertical irregularities. For this purpose, a 3-story regular RC building was designed based on ACI-318 specifications. Three irregularities were then applied to the regular structure including setback, soft story, and short column irregularities. Each of these structures was then subjected to dynamic time-history analyses under seven earthquake records (including Kocaeli, Hector, Cape, Loma Perieta, Northridge and Imperial earthquakes) leading to investigating 28 scenarios. The dynamic time-history analyses were performed using SAP2000 software and the computations related to hysteretic curves and normalization of the applied earthquakes were performed using MATLAB program. The Park-Ang equation was then used for extracting building DIs under different earthquakes. The DIs were computed at the story and structural levels for each earthquake. The results indicated that the regular and setback structures generally performed similarly and successfully fulfilled the Life Safe (LS) level of performance. In addition, under earthquakes with more severe damage, larger DIs were observed at the second and third stories where the irregularities were applied. The earthquakes with less severe damage, however, were shown to induce larger DIs at the lower stories where a regular geometry was considered. This revealed the high damage potential of irregular stories in cases where large seismic damages were induced by earthquakes. The structure with short column experienced larger DIs than the regular building under all the earthquakes except for the Kocaeli earthquake. This demonstrated the relatively poor performance provided by the short-columned structure compared to the previous buildings. Although the average DI undergone by this structure under different earthquakes did not violate the LS level, this structure did not meet the reparability criteria and the LS level in the 0.46 g-0.54 g PGA range. The DI experienced by the plan-irregular structure was seen to be less than all other structures including the regular building. It was seen that the records inducing a large DI in the regular structure also result in a large damage in the short-columned structure. The setback-irregular structure was, however, seen to provide a better performance and a smaller DI under the aforementioned earthquakes. The soft-storied structure was seen, on the other hand, to experience the largest DIs among all the irregularities and to violate the LS level in the irreparable damage state. It is worth to mention that despite the similarly large damage experienced by this structure in the 0.46 g-0.54 g PGA range, it showed a differently large DI in PGA values less than 0.4 g. The largest DI was undergone by this building at PGA=0.38 g.

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