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Computational earthquake performance of plan-irregular shear wall structures subjected to different earthquake shock situations

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Abstract. In this paper, irregularly designed planar reinforced concrete wall structures are investigated computationally. For this purpose, structures consisting of four regular and irregular models of short-order (two-class) and intermediate (five-class) types have been investigated. The probabilistic evaluation of seismic damage of these structures has been performed by using the incremental inelastic dynamic analysis to produce the seismic fragility curve at different levels of damage. The fragility curves are based on two classes of maximum damage indices and the Jeong-Nansha three-dimensional damage index. It was found that there is a significant increase in damage probability in irregular structures compared to regular ones. The rate of increase was higher in moderate and extensive damage levels. Also, the amount of damage calculated using the two damage indices shows that the Jeong-Nensha three-dimensional damage index in these types of structures provides superior results.

Keywords: mainshock and aftershock; plan-irregularity; non parallel system irregularity; seismic performance; shear wall

1. Introduction

Structures with non-centrally stiffness center and mass center, which called asymmetric or irregular systems in the plane, have been considered from the 70th. Plane irregularity is the most reason for damages in past earthquakes. In addition to storey drifts, the factor of damages is a torsional answer of lateral dynamic actuating of a storey. The storey drift factor of lateral torsion, significantly increase the maximum local responsiveness in structure (corner displacement of the structure). Generally, plane irregularities are produced by asymmetric mass distribution, stiffness, and resistance along with weak and unworkable members in the symmetric plane structure during the earthquake, and its damage can lead to structure irregularity. The lateral nonparallel resistant system which has been studied in this research causes asymmetric stiffness distribution in structure plane. In seismic performance studies, about plane irregular structures with the shear wall, in order to simple evaluation of response parameters, unit storey models are most intended (Tso *et al*. 1986, Ghersi *et al*. 2001). Due to accurate numerical structural analysis tools, more studies on medium and high rise plan-irregular structures have been taken in recent years. Also, in some cases, the focus is on structures accompany with Concrete shear wall (Hidalgo *et al*. 2002, Ghaleini *et al*. 2019). In later studies, probabilistic analysis of irregular structures has been performed, which generally concentrates on height irregularity (Varadharajan *et al*. 2014). In general, torsional distortions cause damages in irregular structures; therefore, the following codes tried to control this issue. These controls are constrained to static and dynamic elastic analysis. Artificial intelligence and classic numerical approaches like optimization techniques have been combined together and this leads to making new hybrid techniques that can both optimize and predict the proposed characteristics. The hybrid algorithms serve like prediction and optimization tools for scholars, which could be successfully employed to eliminate the time-consuming and costly process of experimental studies. Different types of algorithms have been used to perform numerical processes on test results, which have acceptable results and estimation. Predicting the seismic behavior of the structural elements such as shear wall could be possible through the hybrid techniques, also the dynamic performances could be enhanced due to numerical optimizations on test results (Shariati *et al*., Arabnejad Khanouki *et al*. 2011, Daie *et al*. 2011, Sinaei *et al*. 2011, Mohammadhassani *et al*. 2013, Mohammadhassani *et al*. 2014b, Toghroli *et al*. 2014, Aghakhani *et al*. 2015, Mohammadhassani *et al*. 2015, Shao *et al*. 2015, Toghroli 2015, Mansouri *et al*. 2016, Safa *et al*.

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2016, Toghroli *et al*. 2016, Sadeghipour Chahnasir *et al*. 2018, Sari *et al*. 2018, Sedghi *et al*. 2018, Shao *et al*. 2018b, Shariat *et al*. 2018, Toghroli *et al*. 2018a, Katebi *et al*. 2019, Luo *et al*. 2019, Mansouri *et al*. 2019, Milovancevic *et al*. 2019, Shao *et al*. 2019b, Shariati *et al*. 2019b, Shariati *et al*. 2019d, Shariati *et al*. 2019e, Shariati *et al*. 2019g, Shi *et al*. 2019a, Xu *et al*. 2019, Armaghani *et al*. 2020, Safa *et al*. 2020, Shariati *et al*. 2020e, Shariati *et al*. 2020f). Shear connectors are one of the most important parts of the composite structures which have been proposed to enhance the shear strength and load transmitting potential of the composite system. The shear wall as a composite system could be fortified with different types of shear connectors such as c-shaped and stud to enhance its shear strength and seismic performance (Shariati *et al*. 2010, Shariati *et al*. 2011a, Shariati *et al*. 2011c, Shariati *et al*. 2011d, Shariati *et al*. 2012a, Shariati *et al*. 2012b, Shariati *et al*. 2012d, Shariati *et al*. 2012c, Shariati *et al*. 2012e, Shariati 2013, Shariati *et al*. 2013, Shariati 2014, Shariati *et al*. 2014a, Shariati *et al*. 2014b, Shariati *et al*. 2015, Khorramian *et al*. 2016, Shah *et al*. 2016a, Shahabi *et al*. 2016a, Shahabi *et al*. 2016b, Shariati *et al*. 2016, Tahmasbi *et al*. 2016, Khorramian *et al*. 2017, Shariati *et al*. 2017, Hosseinpour *et al*. 2018, Ismail *et al*. 2018, Nasrollahi *et al*. 2018, Paknahad *et al*. 2018, Wei *et al*. 2018, Davoodnabi *et al*. 2019). Different types of elements are designed to absorb the released energy of the seismic events which could be the most devastating event for structures. Dampers and reduced section connections (RBS) are the two most applicable schemes of designers to enhance the dynamic performance and energy absorption of the building. It has been also proposed to employ specific bracing systems such as buckling restrained and composite steel-concrete systems to improve the shear strength and lateral stiffness of the structures against the seismic waves (Shariati *et al*. , Shariati 2008, Arabnejad Khanouki *et al*. 2010, Hamidian *et al*. 2012, Jalali *et al*. 2012, Shao and Vesel 2015, Khorami *et al*. 2017a, Khorami *et al*. 2017b, Shao *et al*. 2018a, Sajedi *et al*. 2019, Shao *et al*. 2019a, Shao *et al*. 2019b, Shi *et al*. 2019a, Shi *et al*. 2019b, Shariati *et al*. 2020a, Shariati *et al*. 2020b, Shariati *et al*. 2020d). Cold-formed upright systems have been employed in industrial applications, especially for store cases. These systems are vulnerable to seismic loads and lateral forces. Different studies have been conducted on the characteristics of new upright systems, which employed bracing systems and other reinforcing provisions. Shear wall operation could be useful to enhance the lateral stiffness and shear strength of these systems, however, the use of typical shear walls are not applicable due to their executive procedure and heavy weight. Accordingly employing new shear walls with lower unit weight and handy installing process is an appealing way to reinforce the rack systems (Mohammadhassani *et al*. 2014a, Shah *et al*. 2015, Shah *et al*. 2016b, Shah *et al*. 2016c, Shariati *et al*. 2018, Chen *et al*. 2019, Taheri *et al*. 2019, Trung *et al*. 2019, Naghipour *et al*. 2020). Since the concrete is an important part of the shear walls, the performance of concrete could directly affect the shear wall behavior. Accordingly, employing a suitable mixture and concrete type always is important step in the shear wall design. Different types of the concrete mixes are available, where have been categorized in order of aggregates types and sizes, cement type, additive powders and supplementary or reinforcing materials. Shear walls are typically consisting of a dense reinforcement lattice which could challenge the concrete cast or executive process, hence using self-consolidating concrete could be a smart choice not only for better workability but also for its enhanced mechanical properties (Suhatril *et al*., Hamidian *et al*. 2011, Shariati *et al*. 2011b, Sinaei *et al*. 2012, Mohammadhassani *et al*. 2014c, Arabnejad Khanouki *et al*. 2016, Toghroli *et al*. 2017, Heydari *et al*. 2018, Nosrati *et al*. 2018, Toghroli *et al*. 2018b, Ziaei-Nia *et al*. 2018, Li *et al*. 2019, Safa *et al*. 2019, Shariati *et al*. 2019a, Shariati *et al*. 2019c, Shariati *et al*. 2019f, Shi *et al*. 2019b, Xie *et al*. 2019, Shariati *et al*. 2020c).

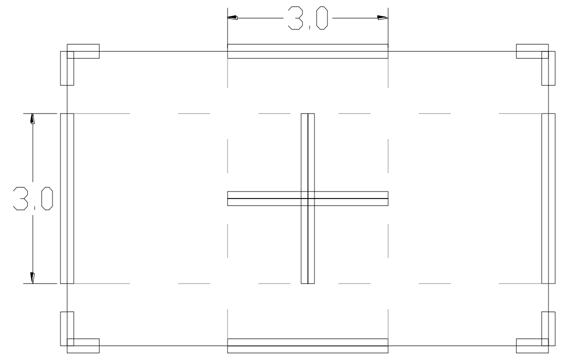

Fig. 1 Regular structure plan

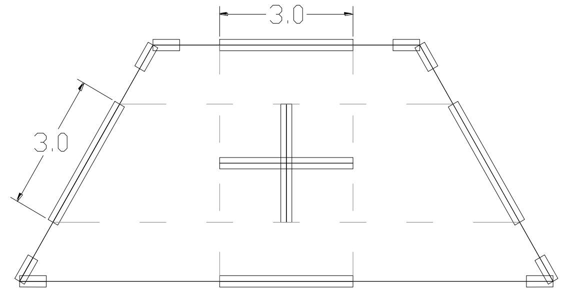

Fig. 2 Irregular structure plan

Table 1 Plane modality

Model	No. of stories	Irregular and Regular Classification
2stRSW	2	Regularity
2stISW	2	Horizontal Irregularity
5stRSW	5	Regularity
5stISW	5	Horizontal Irregularity

Plane-irregularity buildings which have been described in ASCE/SEI7-10 (Engineers 2010), are characterized as buildings contain bents nonparallel with the orthogonal axis, or asymmetrical buildings causes by nonparallel lateral bearing systems. This kind of irregularity in structures has

Table 2 Material properties

Density	2500 Kg/ m^3
Concrete compressive strength, f_c	21 N/ mm^2
Concrete modulus of elasticity, E_c	21540 N/ mm^2
Poisson's ratio, ν	0.2
Specified yield strength of Longitudinal reinforcements, F_Y	400 Mpa
Specified yield strength of transverse reinforcements, fish	300 MPa

Table 3 Design parameters

Seismic design category	Type
Site class	D
Occupancy	Residential
Risk category	II
Structural system	Bearing wall system
Seismic force-resisting system	Special reinforced Concrete shear wall

Table 4 Shear walls section properties

Model	Storey	Inner walls				Corner walls	
		l_{Tot}	t_w	l_f	t_f	l_{Tot}	t_w
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
2stRSW, 2stISW	1	Varies	25	--	--	60	25
	2	Varies	25	--	--	60	25
5stRSW, 5stISW	1	Varies	30	30	40	60	25
	2	Varies	30	30	30	60	25
	3 ~ 5	Varies	30	--	--	60	25

Table 5 Shear walls reinforcement details

Model	Storey	Mid walls			Corner walls	
		$\rho_{l.w}$	$\rho_{t.w}$	$\rho_{l.BE}$	$\rho_{l.w}$	$\rho_{t.w}$
		[%]	[%]	[%]	[%]	[%]
2stRSW, 2stISW	1	0.25	0.25	--	0.25	0.25
	2	0.25	0.25	--	0.25	0.25
5stRSW, 5stISW	1	0.75	0.3	1.65	0.75	0.3
	2	0.6	0.3	1.0	0.6	0.3
	3 ~ 5	0.3	0.3	--	0.3	0.3

not been noted yet. Hence this studies, investigate irregularity caused by nonparallel systems.

2. Modelling details

2.1 Investigation on models

In this study, a group of reinforcement buildings with the concrete shear wall and flat slab without beam has been considered. They are plane-regular or irregular buildings, which are classified into two groups, including two-storey low rise buildings and five-storey medium-rise buildings. Regular Plane is shown in Fig. 1 with 9×5.2 dimension and width/length ration of 1.73. Irregular Plane is indicated in Fig. 2 which has a knee angle trapezoidal rule of 60^0. Storey heights are equal to three meters. Plane modalities are shown in Table1.

The dimensions have been selected in a way that floors mass is almost identical. In structures design, bearing reinforcement Concrete shear walls are selected for the bearing system. Structures have been modelled in ETABS 2016 and designed with an elastic analysis approach. Material specifications and design assumptions are characterized in Table 2 and Table 3, respectively. Design results detail is indicated in Fig. 3 and Table 4. Also, reinforcement details are shown in Table 5.

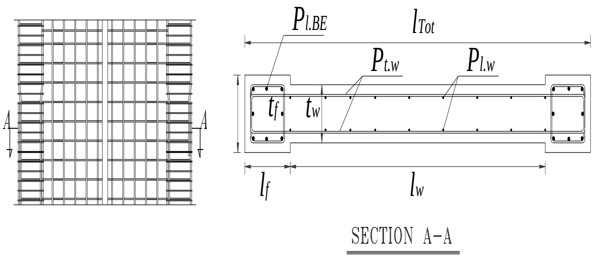

Fig. 3 Shear walls section

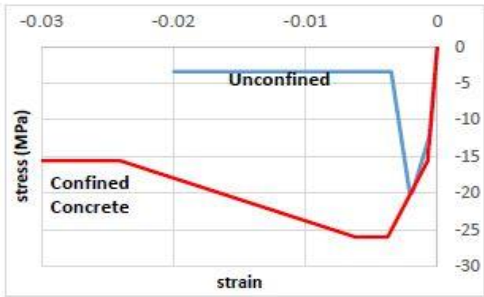

Fig. 4 Perform-3D Covered and uncovered

2.2 Unelastic former material model

In order to model the shear wall in PERFORM-3D, vertical unelastic fibre elements, boundary, and web elements of walls have been selected as Covered and Uncovered Concrete models, respectively.

Mander optimised model used for stress-strain relations in covered concrete (Mander *et al*. 1988) and neglected tension strength and regarding stress-strain diagrams are characterised by four hotspots. Therefore, it is essential to have four nodes to satisfy this requirement. Also, due to the selection of wall elements as fibre elements in the program, sufficient stiffness is not regenerated. The unelastic shear behaviour has been described as double line stress-strain shear material. Elasticity Modulus has been recommended as 0.4 (ASCE41-13, Table 10, and 5). However, this value is considered 0.3 due to program guidance. Reinforcement stress-strain behaviour is modelled as the double diagram.

3. Verify program results

Research by (Hidalgo *et al*. 2002) who worked on shear walls to verify the considered models and compare the experimental results with structural analysis program results. The 2nd specimen was selected from over 26

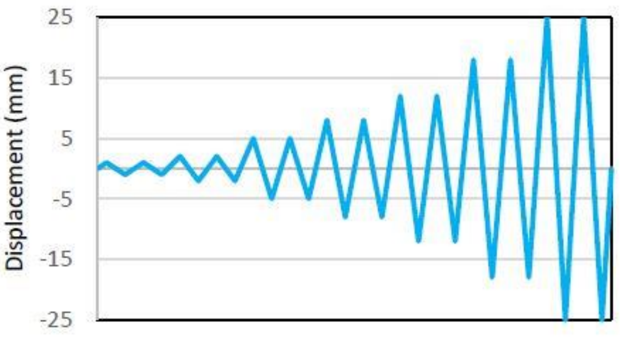

Fig. 5 Lateral loading sequence

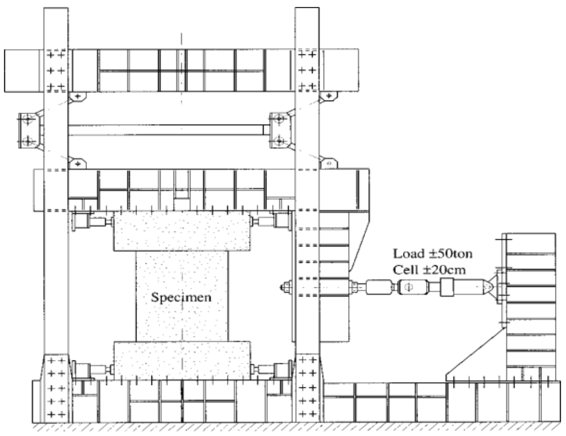

Fig. 6 Test setup

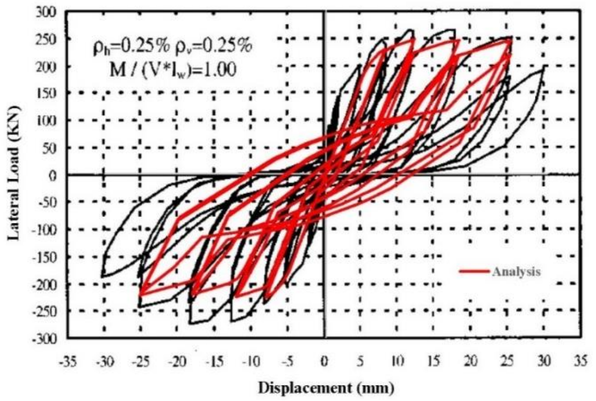

Fig. 7 Verification of analysis results by test results

Table 6 characteristics of the sample shear wall

Sample (ID)	$t_{w\,(mm)}$	$l_{w\,(mm)}$	$h_{w\,(mm)}$	$\rho_{h\,(\%)}$	$\rho_{v\,(\%)}$	$f_{y\,(MPa)}$	$f'_{c\,(MPa)}$
2	120	1000	2000	0.246	0.251	402	19.6

specimens. The characterised shear wall parameters are shown in Table 6. The lateral loading sequence, test setup, and analysis results are indicated in Figs.5, 6 and 7, respectively.

4. Select and modify applied accelerographs

The demanded graphs have been selected concerning: (a). Seismic magnitude over 5, (b). Maximum ground acceleration for tremors over 0.2 times of gravity acceleration, (c). Soil type equivalent with D class of ASCE 41-13 code and graphs, records related to far source ones with minimum 20 km distance from the hypocenter. For dynamic analysis, according to ASCE 41-13 recommendation, nine double direct accelerographs (Table 7) with the principal component in irregular axis direction have been described. Between each two-component, the graph with more significant maximum ground acceleration or with a bigger spectral response in a natural structural period with 5% damping is described as the main component. Recorded graphs of Christchurch and Tohoku tremors have a higher durability life of strong ground motions. Therefore by two conventional approaches, durability graphs time are modified first with Bracketed Duration (recommendation peak acceleration described as ±0.05) and second with Significant Duration Method (according to Trifunc and Novikova recommendation 95%, 5% as bounds described in order to modify the durability graphs time). The graphs are derived from three energetic ground motion data centres. This data insist on three groups: (a). Two graphs from Japan`s National Research Institute for Earth Science and Disaster Resilience website (www.kyoshin.bosai.go.jp), (b). Three graphs from the Offical Source of Geological Hazard Information for New Zealand (www.geonet.org.nz) and (c). Four graphs from PEER (Pacific Earthquake Engineering Research) website (www.peer.berkeley.edu).

5. Damage index assessment

In this research, in order to find the damage index of structures, two groups of damage index are described: (a). Damage index based on maximal storey drifts, (b). Jeong-Elnashai recommended Three-dimensional damage index. In maximal storey drifts, Damage thresholds based on FEMA research (HAZUS) (Neighbors *et al.* 2012) presented by pre observations in federal status has been determined. In HAZUS, for high-risk zone structures, structural system, and the number of stories (in this case shear wall system with two storeys as C2L and with five storeys as C2M classified) parameters are tabulated in Table 8. The new damage index by (Jeong *et al*. 2006) is one of the recommended approaches to consider the effect of structure torsion in-plane and bidirectional responses, which can describe the three-dimensional behaviour of the structure. First of all, in investigation procedure of the Jeong`s damage 3D structure are decomposed to plane frames, then local damage index will be calculated, and each frame concerning tributary area and local damage indices will be weighted by local energy absorption, latter with combining local damage indices with respect to the frame`s share of global damage index (in order to determine weight) the global damage index will be found.

In the proposed local weight coefficient methodology, local damage index is defined by the following equation (1)

$$W_i = w_i \cdot A_{Ci}(D_i) \tag{1}$$

Where, $\boldsymbol{w_i}$= gravity load on contribution area $(\boldsymbol{A_{ci}})$ which is a function of the local damage level $(\boldsymbol{D_i})$. The weighting factor is calculated by taking the ratio of $\boldsymbol{w_i}/\sum \boldsymbol{w_i}$. By using local contribution $(\boldsymbol{w_i})$ global damage index $(\boldsymbol{D_g})$ in structure is expressed as follows (2)

$$D_g = \frac{\sum W_i \cdot D_i}{W_{total}} \tag{2}$$

While there is neither torsion nor exterior response, the results of Park-Ang damage index and three-dimensional damage index in regular structures under unidirectional seismic are analogous. Also, the confined state classification of (Park *et al.* 2016) has been used in this research.

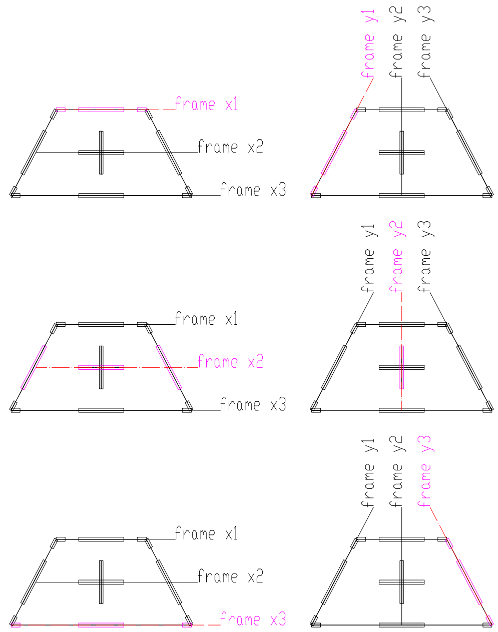

Fig. 8 Irregular structures planar decomposition

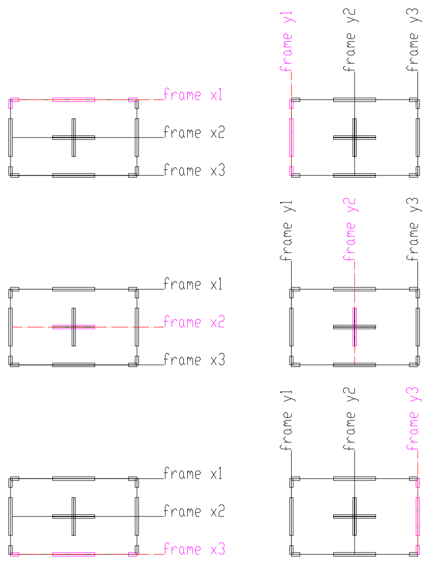

Fig. 9 Irregular Structures Planar decomposition

In order to calculate the Jeong-Elnashai damage index amount, models are analysed by first pushover analysis with a triangular envelope; then, results are depicted as frame capacity. Frames are appropriately selected by Figs.8 and 9.

6. Analysis results

6.1 Structure period

Four structure periods are tabulated in Table 10. It is obvious that irregular structure periods (5stRS W, 5stISW) are higher than irregular structures periods (2stRSW, 2stISW). It should be noted that the modal participation factor of the first four modes of two-storey irregular modes and the first five modes of the five-storey irregular structure is higher than 90%.

Irregularity in nonparallel system plane, as demonstrated in Table 11 could be conducted to high rate eccentricity. Another quantified parameter that generally has been investigated in the case of irregular structures is the rate of maximum relative storey displacement to relative displacement average in building ends. This ratio is considered for four-mode given in Table 12.

6.2 Inelastic incremental dynamic analysis

In order to evaluate the performance of structures, inelastic incremental dynamic time history analysis (IDA) has been done, and it involves subjecting a structural model to ground motion. The goal is to develop this concept in a way that could take accurately figured the demand and capacity of the structure in a vast range of elastic behavior to collapse.

Each curve of the IDA diagram shows a specific record of damage measure in a different ground motion intensity measure settle to structure. In order to do IDA, based on the main component record, scale factors of the first period of structures are found, and then they are applied to both record components. For receiving a desirable number of responses, that's how to scale intervals chosen. Then, PGA and SA diagrams, according to considered damage indices, are figured.

The response spectrum of nine records, which has been scaled by peak ground acceleration equal to 1.0g, has been demonstrated in Fig. 10. Also, the scaled response spectrum of 5stISW with 0.4g (five-storey irregular structure with a period equal to 0.45sec) is shown in Fig .11. In order to investigate the incremental damage analysis results of damage measure, selected the stories drift and the three-dimensional Jeong-Elnashai damage index and stated the intensity measure of an earthquake to the peak ground acceleration and damping equal to 5% in model`s period.

In recent investigations on inelastic IDA results, it has been found that the maximum storey drifts occurred at the roof level. This behaviour could result from the stiffness deterioration of shear walls (because of varied sections in height) or inelastic behaviour of models. However, in two and five-storey structure, maximum section rotation happens on the roof and third storey level, respectively.

An assessment of structure behaviour from the elastic

Table 7 List of earthquake records with two components

Record ID	Earthquake	Country	Date	M_w	Station
JMS1	Tohoku 2011	Japan	11^{th} March 2011	9.0	FKS016
JMS2	Tohoku 2011	Japan	11^{th} March 2011	9.0	IBR007
NMS1	Christchurch 2010	Newzealand	3rd Sep. 2010	7.1	KPOC
NMS2	Christchurch 2010	Newzealand	3rd Sep. 2010	7.1	LINC
NMS3	Christchurch 2010	Newzealand	3th Sep. 2010	7.1	SWNC
PMS1	Chi-Chi 1999	Taiwan	20^{th} Sep. 1999	7.62	TCU065
PMS2	Chi-Chi 1999	Taiwan	20^{th} Sep. 1999	7.62	CHY101
PMS3	Northridge 1994	United States	17^{th} Jan. 1994	6.69	USC 90021
PMS4	Northridge 1994	United States	17^{th} Jan. 1994	6.69	CDMG 24303

Table 8 Damage states threshold based on inter-story drift

Model	Hazus structure type label	Interstory Drift at Threshold of Damage State			
		Slight (SD)	Moderate (MD)	Extensive (ED)	Complete (CD)
2stRSW, 2stISW	C2L	0.004	0.0100	0.0300	0.0800
5stRSW, 5stISW	C2M	0.0027	0.0067	0.0200	0.0533

Table 9 Classification of the limit states based on Jeong-Elnashai Damage Index

Slight (SD)	Moderate (MD)	Complete (CD)
0.25	0.4	1.0

Table 10 first four modal period

Model	Model type	Period (s)			
		T_1	T_2	T_3	T_4
2stRSW	Regular (2 storey)	0.0901	--	--	--
2stISW	Irregular (2 storey)	0.106	0.1034	0.0698	0.0223
5stRSW	Regular (5 storey)	0.3943	--	--	--
5stISW	Irregular (5 storey)	0.4498	0.4446	0.3023	0.08649

Table 11 The eccentricity between the locations of the centre of mass and the centre of rigidity

Model type	ETABS 2013(%)
Irregular (5 storeys)	31
Irregular (2 storeys)	32.5

Table 12 Horizontal irregularity type

Model	Type	$\Delta_{max}/\ \Delta_{avg}$	ASCE horizontal irregularity type
2stRSW	Regular (2 storey)	1.06	--
2stISW	Irregular (2 storey)	1.5	1b
5stRSW	Regular (5 storey)	1.05	--
5stISW	Irregular (5 storey)	1.42	1b

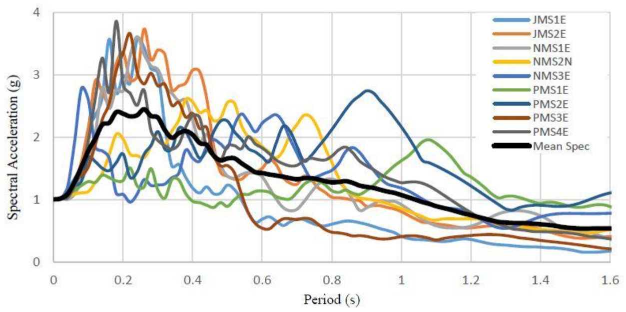

Fig. 10 The response spectrum of all records' main component scaled to PGA = 0.1 g

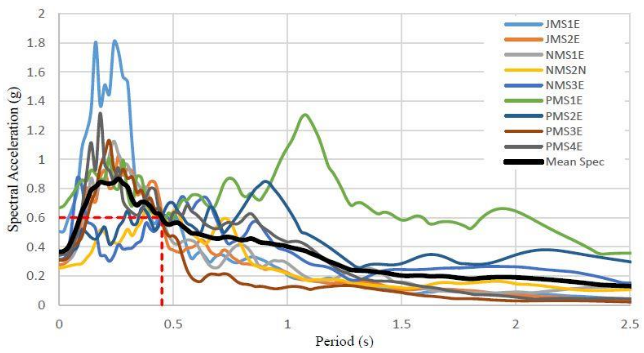

Fig. 11 Response spectrum of all records' main component scaled to Sa (T1 = 0.45s, Damping = 5%) = 0.6 g

limit till the collapse could be derived by an accurate investigation of IDA diagrams, the whole of diagrams initially run with the elastic region in the following since change in stiffness and strength of the structure, they enter to inelastic region. Through the inelastic region, when the seismic intensity increased, damage index variety increases and generally turns to a line near the end of diagrams, which is a sign of total collapse. In two-storey models, IDA diagrams have 0.2g elasticity, and for maximum ground motion, it is about 0.1g elasticity. On the contrary, in five-storey models, IDA diagrams quickly turn to the inelastic pattern, also in order to achieve the high stiffness of concrete structures in some cases, shear walls remain steady even in high seismic intensity measures. From the examination of digrams, low results ranges, especially in irregular structures, were observable in two, and five-storey PGA based IDA models due to the effect of higher modes in irregular structure results. The three-dimensional Jeong-Elnashai damage index diagram according to spectral acceleration and PGA from nine unique central seismic records are shown in Figs. 16 and 17. Incremental dynamic

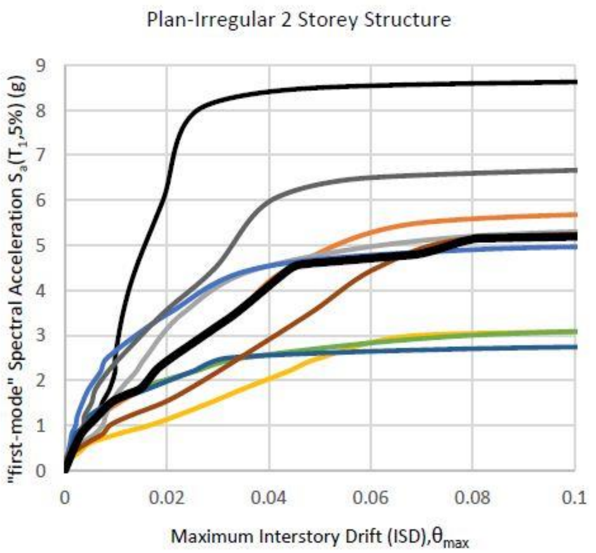

Fig. 12 IDA curves of the two-storey irregular model

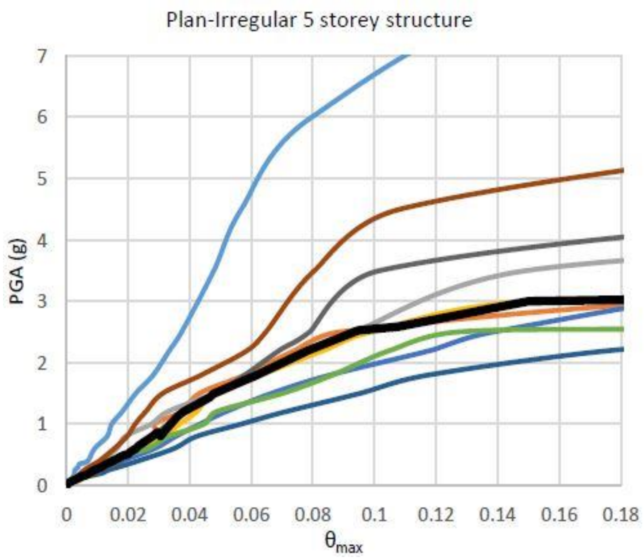

Fig. 15 IDA curves of the five-storey irregular model

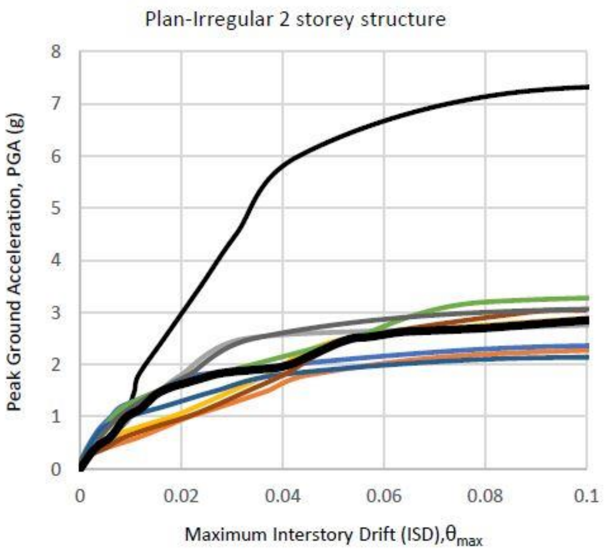

Fig. 13 IDA curves of the two-storey irregular model

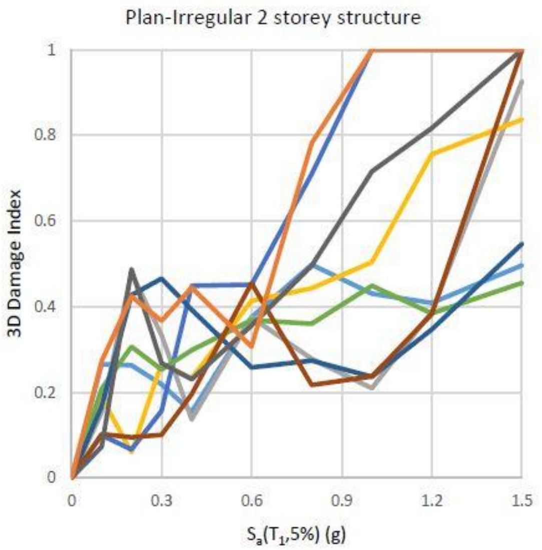

Fig. 16 Jeong-Elnashai damage index curves

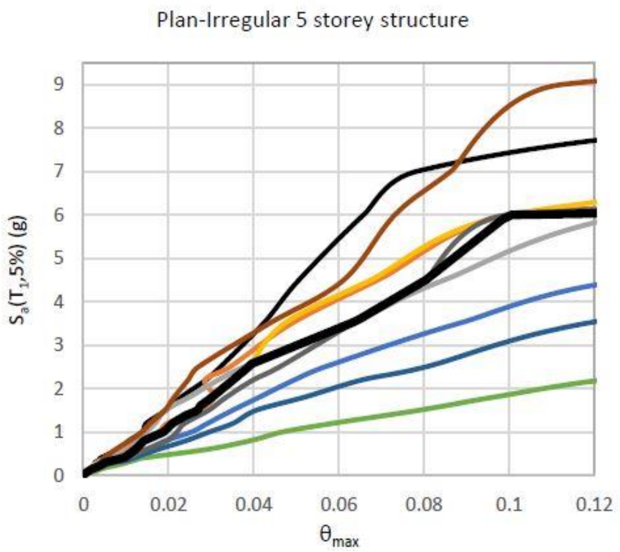

Fig. 14 IDA curves of the five-storey irregular model

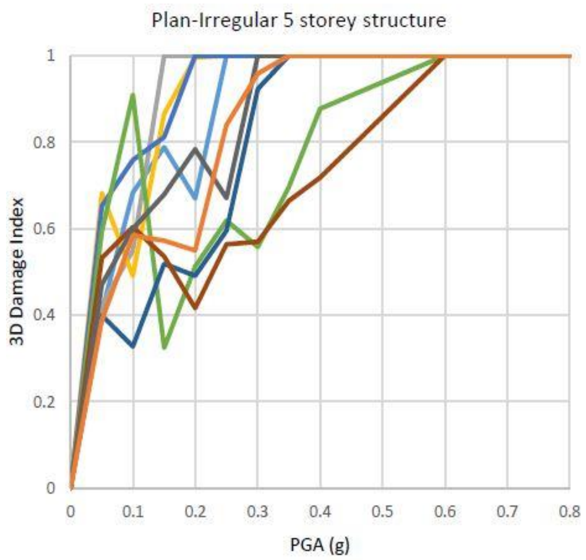

Fig. 17 Jeong-Elnashai damage index curves

analysis curves can be used to evaluate the behaviour of structures using percentiles of 16, 50, and 84, as suggested by (Cossegal *et al*. 2008), which are good indicators of the results of IDA curves. These percentiles are shown in Fig .18. As can be seen, for example, at a maximu The three-dimensional Jeong-Elnashai damage index diagram according to spectral acceleration and PGA from nine unique central seismic records are shown in Figs. 16 and 17. The acceleration of 0.5 g, the Jeong-Nensha Damage Index at all three percentiles shows higher values of damage index in the irregular structure than the regular structure, resulting in higher damage rates. By drawing the 50th percentile graph of incremental dynamic analysis based on the maximum escape of Figs. 19 and 20, similar results were obtained, and it was observed that as the earthquake intensity increased, the rate of irregular and disconnected class escalation increased.

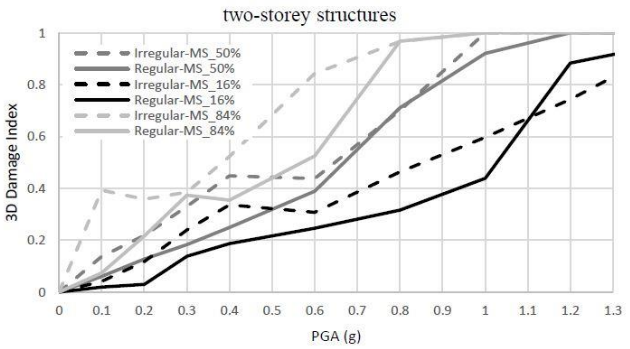

Fig. 18 Jeong-Elnashai damage index fractile curves

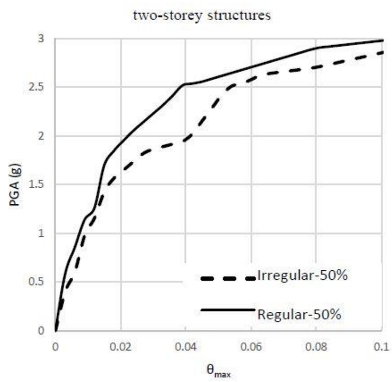

Fig. 19 IDA's 50% fractile curves for the two-storey model

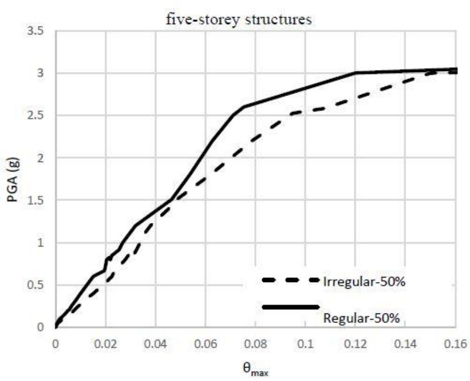

Fig. 20 IDA's 50% fractile curves for the five-storey model

7. Probabilistic evaluation and dawing of fagility curves

The damage criterion parameter in this study is considered a maximum ceiling escape as well as Jeong-Nensha three-dimensional damage index. The limits of damage used in this study, as noted in the previous sections, are for the class of evasive damage index, the values provided by HAZUS, and for the Jeong-Elshan Damage Index proposed by Jeong and Elshan. In order to obtain the fragility curves for a given earthquake intensity, the spectral response acceleration, as well as the maximum acceleration of the earth without mapping of different steps of the earthquake intensity scale, was entered into the structure, and responses were harvested. Each step counted the number of responses that exceeded the limit of damage. Next, for each damage level, log-normal distribution assumptions that exceeded the limit values were calculated and plotted for each mapping at each earthquake intensity using the statistical method of estimating the maximum likelihood curve for different levels of damage (Baker 2011). In this method, by maximising the rightmost function, the mean values and standard deviation of the log-normal distribution are obtained, and finally, by plotting the cumulative distribution function, the resulting probability diagrams of the structure are obtained from any specified boundary condition, namely the fragility curves.

According to the obtained fracture curves and Figs. 21 to 25, Irregular predicted structures using both indices of damage show a higher probability of failure. However, the three-dimensional damage index shows a higher probability of failure. This also was observed in regular studied structures because of regular structures caused by the two-way earthquake and the torsional responses in the plan of structures and, of course, in irregular structures, in addition to the factors mentioned. Irregularity and torsion also have a higher effect on the plan. The main reason that the results based on the three-dimensional damage index are higher than the class escape index is to reduce the resistance in the formulation used in this method, which is itself due to the irregular effects of the two-way seismic load.

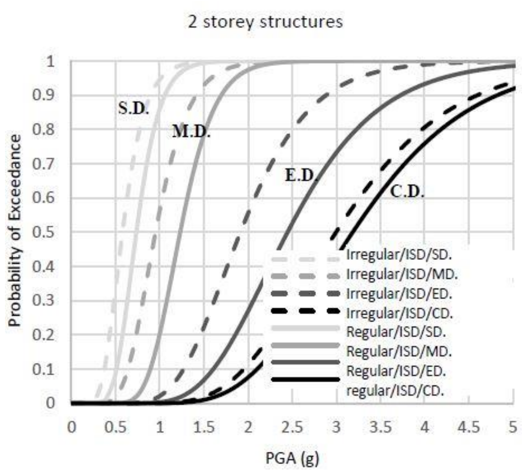

Fig. 21 Comparison of regular and plan-irregular models' fragility curves based on ISD damage index

8. Conclusions

In this study, the seismic performance of four structural models, including irregular shear wall reinforced concrete structures in the irregular plan of naming systems under earthquake, was evaluated. The studied structures included regular and irregular models in the plan, in the short-order (two-class) and intermediate (five-class) types. Incremental dynamic analyses were performed on the four models. Considering the two types of class evasion indices and Jeong-Elnashai damage indices, the capacity of structures at different levels of damage was investigated. Finally, based on the results of incremental dynamic analysis and according to the set limits of damage, probabilistic evaluation of structural models and preparation of fracture curves was performed. From the 50th percentile diagram for models with shear and parallel reinforced concrete shear walls, it is found that in short-storey (two-story) structures, the maximum floor slope of irregular structures in the plan increases sharply with increasing acceleration intensity.For example, a five-storey roof slope with a wall hanging at a maximum acceleration of 0.5 g is about 1.5 times the roof slope in a regular structure. Also, the seismic evaluation of irregular structures in the plan does not provide reliable answers due to the higher frequency modes involved in structural response by scaling incremental dynamic analysis steps based on the response spectrum on the first periodic interval of the structure.

From the examination of the fracture curves, the probability of passing through different levels of damage is significantly higher in structures with non-parallel walls than in parallel shear-wall structures. The fragility curves obtained by both the class of maximum escape indices and the Jeong-Nansha three-dimensional damage index confirm these results. Due to the different percentiles of incremental dynamic analysis curves, it was observed that Jeong-Elnai Damage Index achieves a higher degree of damage than the Maximum Class Escape Damage Index, which is due to the curvature of the floors and off-frame responses. The results also show that, in the structures with the Namibian

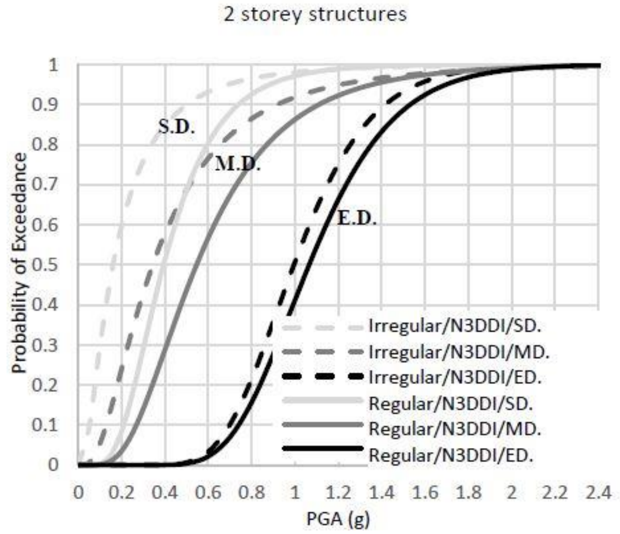

Fig. 22 Comparison of regular and plan-irregular models' fragility curves based on 3D damage index

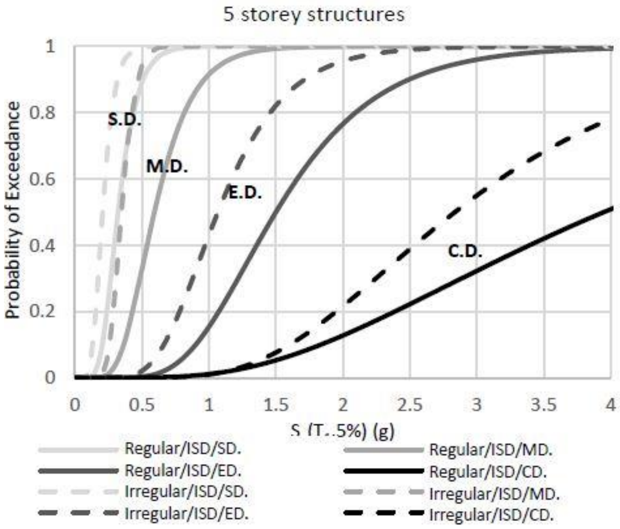

Fig. 23 Comparison of regular and plan-irregular models' fragility curves based on 3D damage index

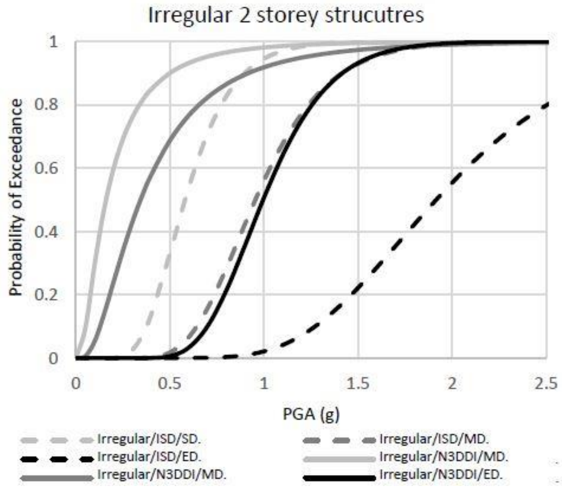

Fig. 24 Comparison of plan-irregular fragility curves based on ISD and 3D damage indices

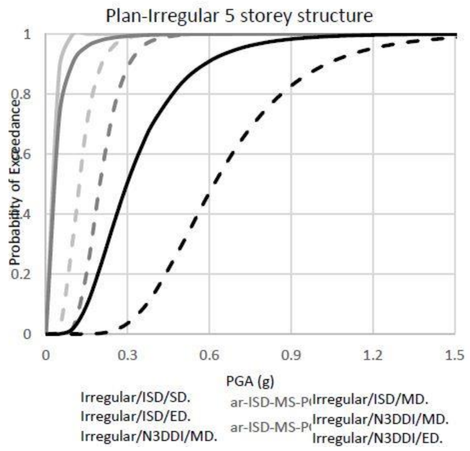

Fig. 25 Comparison of fragility curves based on ISD and 3D damage indices

shear wall, the values calculated for the Jeong-Nensha 3D Damage Index shows qualitatively behavior of the irregular structures, but the probability values of the transgression calculated based on the index, due to the fragility curves are overestimated. It is noteworthy that the calculation of the Jeong-Nansha 3D Damage Index is highly sensitive to the choice of 2D frames as well as the capacity curve and hysteresis calculation.

According to the studies, it was observed that the Jeong-Nansha 3D Damage Index is not suitable for examining the levels of damage in irregular structures in the plan caused by the shear walls, but compared to the maximum damage index of the floors, it twists in the plan of the structure. It does not mean that (and therefore offers downstream answers) the results of the 3D Damage Index are more conservative.

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