World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:10, 2016

# Fragility Assessment for Vertically Irregular Buildings with Soft Storey

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Open Science Index, Civil and Environmental Engineering Vol:10, No:10, 2016 publications.waset.org/10005540.pdf

***Abstract*****—**Seismic behavior of irregular structures through the past decades indicate that the stated buildings do not have appropriate performance. Among these subjects, the current paper has investigated the behavior of special steel moment frame with different configuration of soft storey vertically. The analyzing procedure has been evaluated with respect to incremental dynamic analysis (IDA), and numeric process was carried out by OpenSees finite element analysis package. To this end, nine 2D steel frames, with different numbers of stories and irregularity positions, which were subjected to seven pairs of ground motion records orthogonally with respect to Ibarra-Krawinkler deterioration model, have been investigated. This paper aims at evaluating the response of two-dimensional buildings incorporating soft storey which subjected to bi-directional seismic excitation. The IDAs were implemented for different stages of PGA with various ground motion records, in order to determine maximum inter-storey drift ratio. According to statistical elements and fracture range (standard deviation), the vulnerability or exceedance from above-mentioned cases has been examined. For this reason, fragility curves for different placement of soft storey in the first, middle and the last floor for 4, 8, and 16 storey buildings have been generated and compared properly.

***Keywords*****—**Special steel moment frame, soft storey, incremental dynamic analysis, fragility curve.

## I. INTRODUCTION

MANY structures are in some way vertically irregular. Some have been designed on purpose, e.g. in the case of a soft first-storey. Others have become so accidently, for instance, due to inconsistencies or even errors in the course of construction process, while many have been evolved irregular over their lifetime owing to accidental damage, rehabilitation or change of use. Therefore, it is vital for structural engineers to gain a deeper understanding of the seismic response of buildings with vertical irregularities.

Different kinds of vertical irregularities have different impacts on seismic response. Therefore, the effect of these irregularities must be considered and incorporated in present seismic design codes. The research works concerned with vertically irregular structures started in early 1970s with Chintanapakdee and Chopra [1] who investigated the seismic response of series of eight storey shear buildings which have been subjected to pairs of orthogonally ground motion records. The main aim of the author was to establish the effect of yielding of first storey on adjacent stories. Al-Ali and Krawinkler [2] followed by Cahintanapakdee and Chopra [1] performed the most systematic method on the effect of vertical irregularities on the seismic response of simple mid-rise single-bay frames. Valmundsson and Nau [3] broadly concentrated on comparing the sufficiency of simplified seismic code design process when assigned to vertically irregular frames. Lagaros [4], [5] has considered impact of weak storey, short column effect, and column discontinuity in the fragility curves.

Vulnerability of the buildings due to seismic damage can willingly be quantified through fragility curves. A fragility curve can be measured through empirical [6], [7], analytical [8]-[10], and educational [11] based methods. Local damage evaluation tool, such as HAZUS-MH [12], for instance, utilizes fragility curves to assess the building vulnerability estimation. However, HAZUS does not regard the presence of various irregularities in the assessment, and consequently, it can underestimate level of expected losses. In general, vertical irregularities increase building vulnerability.

In this paper, impact of different stages of soft storey on probabilistic seismic demand model (PSDM) and seismic fragility of special steel moment frames (4-, 8-, and 16-storey frames) are analytically carried out.

## II. STRUCTURAL MODELS

### *A. Definition of Structures*

Three, 3-bay steel frame structures, 4-, 8- and 16-storey with different placement of soft storey in the first, middle and the last floor, are considered to evaluate the effect of various location of soft storey in PSDM and consequently in seismic fragilities. Figs. 1-4 show the floor plan and the three 2D frames. As shown in Fig. 1, bay lengths in both directions are 5 meters and with regard to Figs. 2-4 typical stories and storey soft storey heights are supposed to be 3.2 and 5 meters, respectively.

The 4-, 8- and 16-storey, 3-bay special steel moment frames have been modeled with elastic beam-column element linked by zeroLength elements which serve as rotational springs as an emblem of structure`s nonlinearity. The springs follow a bilinear hystertic response based upon the Modified Ibarra-Krawinkler Deterioration Model (Fig. 5). A leaning column with gravity loads has been connected to the frame by truss elements to produce P-Delta impacts. The leaning column has been located one width away from the frame. The leaning columns were modeled as elastic beam-column elements. These Columns and truss elements have moment of inertia and areas about two orders of value larger than the frame columns and beams in order to represent aggregate effect of all the

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gravity columns. The columns are connected to the beam-column joints by zeroLength rotational spring elements with negligible stiffness values so that the columns do not absorb remarkable moments.

Distributed dead and live loads on the floors are 600 kgf/m$^2$ and 200 kgf/m$^2$ and for roof are 500 kgf/m$^2$ and 150 kgf/m$^2$, respectively. The slab system is assumed adequately stiff for prohibiting the lateral movement in the normal direction of the frame. An idealized schematic of sample 2-storey, 1-bay 2D frame [13] is presented in Fig. 6.

The mass is concentrated at the beam-column joints of the frame. Gravity loads tributary to the frame members are allocated to the frame nodes, while the remaining gravity loads are assigned to the leaning columns.

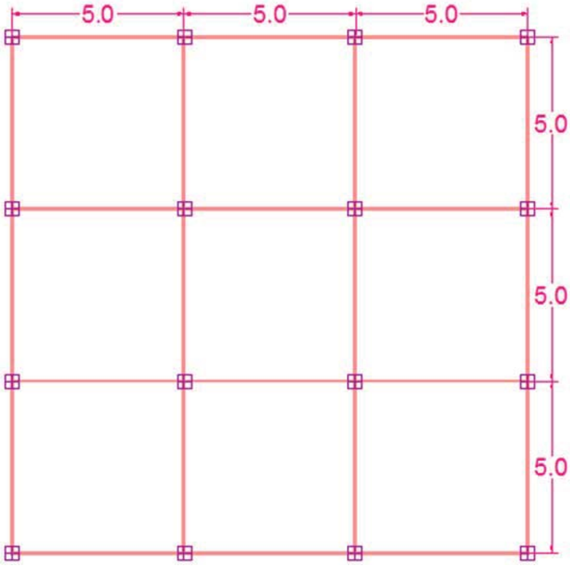
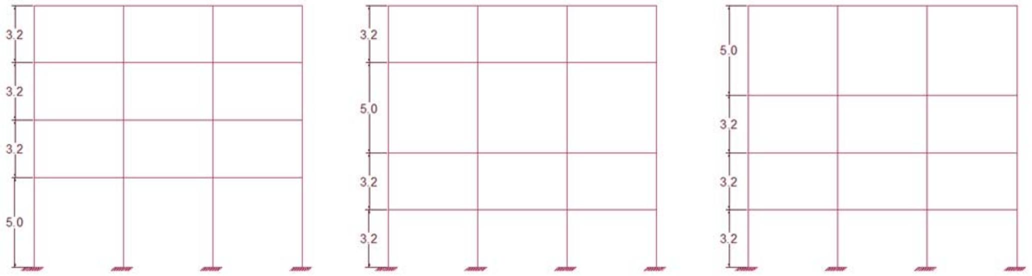
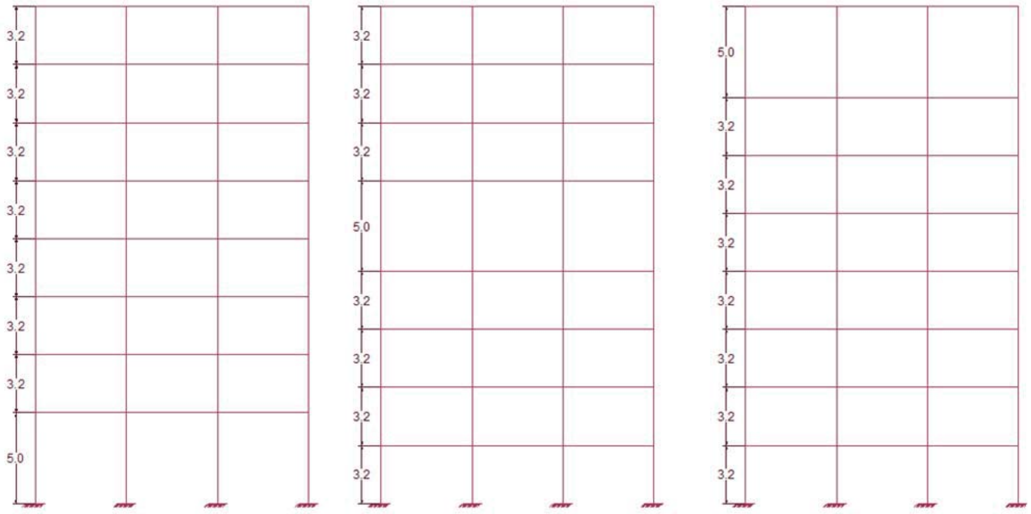


Fig. 1 Typical plan of models



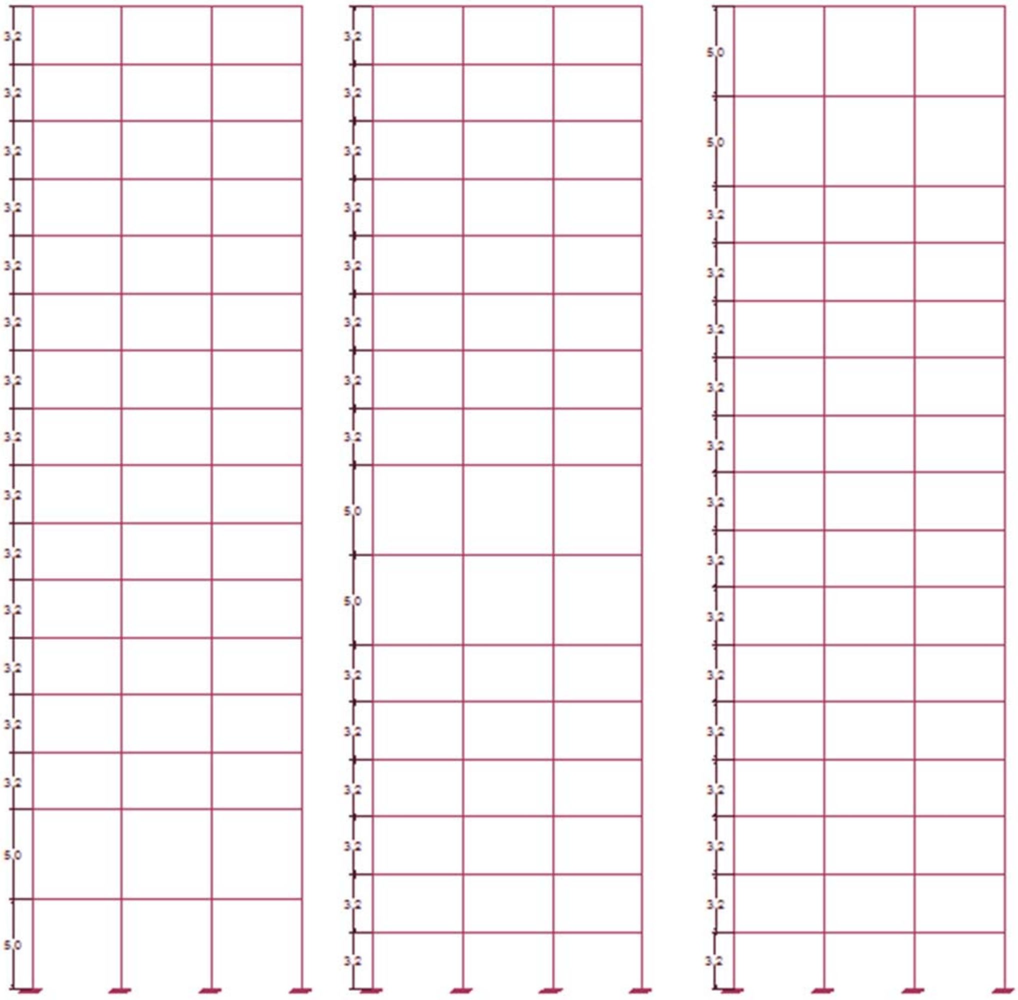
(a) 4Storey 1st SS (b) 4Storey Mid SS (c) 4Storey Top SS

Fig. 2 4-storey configuration, (a) SS at 1$^{st}$ floor (b) SS at middle floor (c) SS at last floor



(a) 8Storey 1st SS (b) 8Storey Mid SS (c) 8Storey Top SS

Fig. 3 8-storey configuration, (a) SS at 1$^{st}$ floor (b) SS at middle floor (c) SS at last floor



(a) 16Storey 1st SS (b) 16Storey Mid SS (c) 16Storey Top SS

Fig. 4 16-storey configuration, (a) SS at 1st floor. (b) SS at middle floor (c) SS at last floor

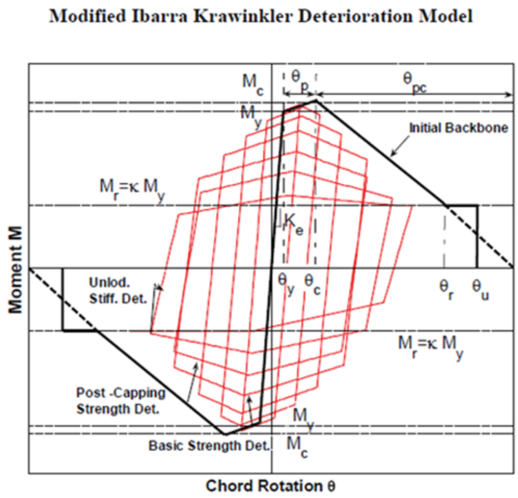


Fig. 5 Modified Ibarra-Krawinkler Detorioration Model

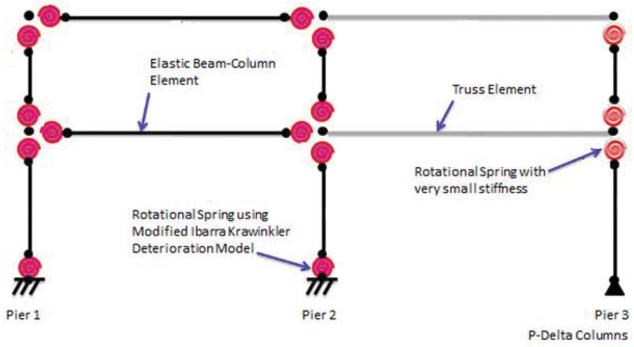


Fig. 6 Sample of 2D modeling in OpenSees

### *B. Frames with Different Placement of Soft Storey*

Typical stiffness irregularities emerge as soft storeys. In many practical cases, strength changes happen together with stiffness, e.g. when the cross section of the member is changed both the moment of inertia and the plastic moment capacity are modified.

The soft storey is defined by the stiffness of lateral force resisting system in any stories being less than 70% of the stiffness in adjacent storey (above or below) or less than 80% of the average stiffness of the three storeys (above or below) FEMA 310 [14]. In this paper, to generate soft storey, a higher height of column is assigned to a particular storey. In order to compare the response of regular and irregular structures, soft storey is assigned to different stages (first, middle and the last floor) of 4-, 8- and 16-storey. However, the relative storey stiffness at the other storeys remains unchanged and equals the corresponding storey stiffness of regular structure.

In order to have a significant comparison between regular and irregular buildings, the stiffness ratio at all the storeys other than the irregular storey was retained the same.

## III. METHODOLOGY

IDA [15] is considered as one of the best analysis procedure available, since it can provide accurate assessments of the complete scope of the model`s response. IDA includes providing a series of non-linear dynamic analysis for each record by scaling it to several stages of intensity that are properly chosen. Each dynamic analysis is specified by two scalars, an intensity measure (IM), which represents the scaling factor of the ground motion record, and an engineering demand parameter (EDP) which monitors the structural response of the model. For the purpose of this research, an appropriate choice for the IM is peak ground acceleration (PGA), while the maximum inter-storey drift $\theta_{max}$ of the structure is a proper candidate for the EDP.

To perform IDA, seven pairs of orthogonally ground motion records have been subjected to structures simultaneously. These records belong to a bin of relatively large magnitudes of 6.5-7.7 and moderate distances, which adopted from PEER ground motion data base (Table I).

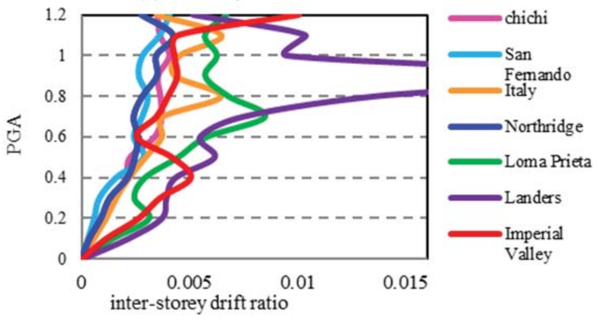
TABLE I
GROUND MOTION RECORDS

| No | Event | Year | station | $M^+$ | Rjb (km) |
|---|---|---|---|---|---|
| 1 | Northridge | 1994 | Beverly | 6.69 | 12.39 |
| 2 | Irpinia_Italy-01 | 1980 | Brienza | 6.9 | 22.54 |
| 3 | Chi-Chi | 1999 | CHY045 | 7.62 | 26 |
| 4 | Loma Prieta | 1989 | Anderson Dam | 6.93 | 19.9 |
| 5 | Imperial Valley | 1979 | Cerro Prieto | 6.53 | 15.19 |
| 6 | San Fernando | 1971 | Lake Hughes#9 | 6.61 | 17.22 |
| 7 | Landers | 1992 | Fun Valley | 7.28 | 25.02 |

The structures are analyzed under gravity loads before IDAs are carried out. The gravity loads are assigned by using a load-controlled static analysis with 10 footsteps. So that the gravity loads remain on the structure for further analysis, the loadConst command has been used after gravity analysis is completed.

For solving the systems of nonlinear analysis, Modified Newton algorithm (OpenSees, [13]) was utilized. For each ground motion of increasing intensity, IDA curves have been depicted as PGA vs. $\theta_{max}$. Figs. 7 (a) and (b) demonstrate typical result of IDA for 8-storey Mid SS.

(a) 8Storey Mid SS - X Dir



(b) 8Storey Mid SS - Y Dir

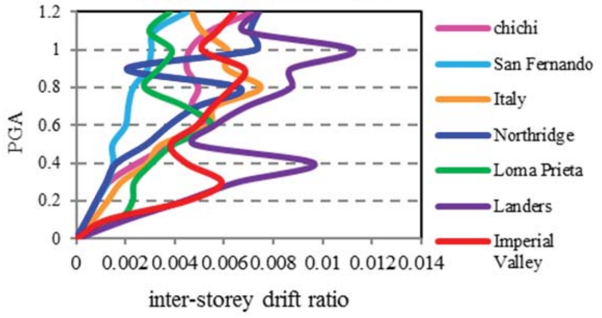


Fig. 7 IDA curves for 8-storey Mid SS (a) X Direction, (b) Y Direction

## IV. SEISMIC FRAGILITY MODELING

Fragility [16] curve is a statistical tool responding the probability of exceeding a given damage state (or performance) as a function of an engineering demand parameter (EDP) that represents the ground motion. The most common form of a seismic fragility function is the lognormal cumulative distribution function (CDF). It is of the form

$$F_d(x) = P[D \geq d|X = x]; d \in \{1,2,\dots,N_D\} = \phi\left(\frac{\ln(x/\theta_d)}{\beta_d}\right) \quad (1)$$

where P[A|B] is probability that A is true given that B is true, D and d denote uncertain damage state of a particular component and a particular value of D, respectively. X represents uncertainty excitation, while x is a particular value of X. In (1), $\theta_d$ and $\beta_d$ are median capacity and standard deviation of the natural logarithm of capacity.

In this paper, seismic fragilities have been generated upon IDA`s outputs with regarded to HAZUS technical manual [12], hence criteria of damage states (Slight, Moderate, Extensive and Complete) for mid- and high-rise steel moment frame have been utilized. Structural fragility curve parameters have been chosen as high code seismic design level according to S1M (steel moment frame for mid-rise structures) and S1H (steel moment frame for high-rise structures) and were presented in Table II.

The probability of exceeding each damage state is calculated by counting cases where the performance points are exceeding each damage state. Fragility curves for different placement of soft storey in the first, middle, and the last floor for 4-, 8- and 16-storey buildings have been generated (Figs. 8-10).

TABLE II
STRUCTURAL FRAGILITY CURVE PARAMETERS

| | Damage states | Interstory drift |
|---|---|---|
| S1M | Slight | 0.004 |
| | Moderate | 0.008 |
| | Extensive | 0.02 |
| | Complete | 0.0533 |
| S1H | Slight | 0.003 |
| | Moderate | 0.006 |
| | Extensive | 0.015 |
| | Complete | 0.04 |

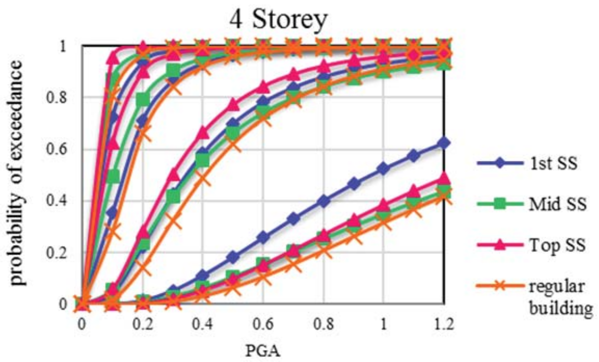


Fig. 8 Fragility curve for 4-storey structure with different placement of soft storey

Figs. 8-10 demonstrate the effect of soft storey on the performance of models. It can be observed that when the soft storey is located at 1st storey, it mostly influences the complete damage-state. Soft storey in the middle of the building seems to have negligible influence regardless of damage-state. On the other hand, when the soft storey appears at last storey, significant changes occur in the extensive damage-state.

Figs. 8-10 denote that for low intensities, structures have been acted remarkably similar which means in low-intensity, structures response regardless of soft storey placement. In higher intensities, sensitivity have been increased.

To compare the critical location of soft storey in various levels, fragility curves of 4-, 8- and 16-storey with specific details have been brought up in Figs. 11-13.

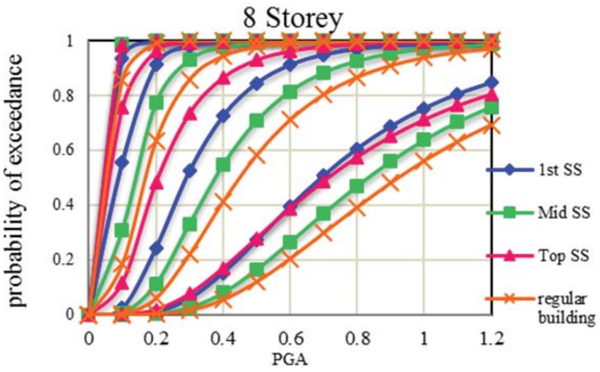


Fig. 9 Fragility curve for 8-storey structure with different placement of soft storey

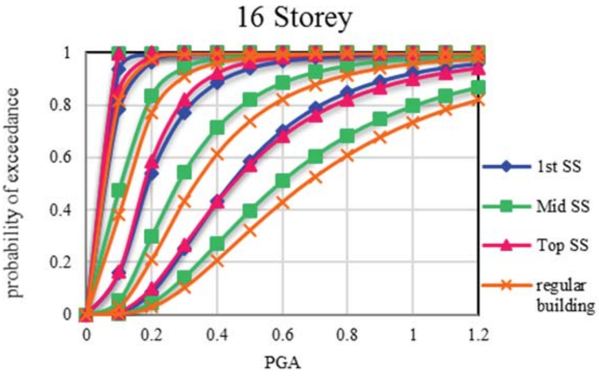
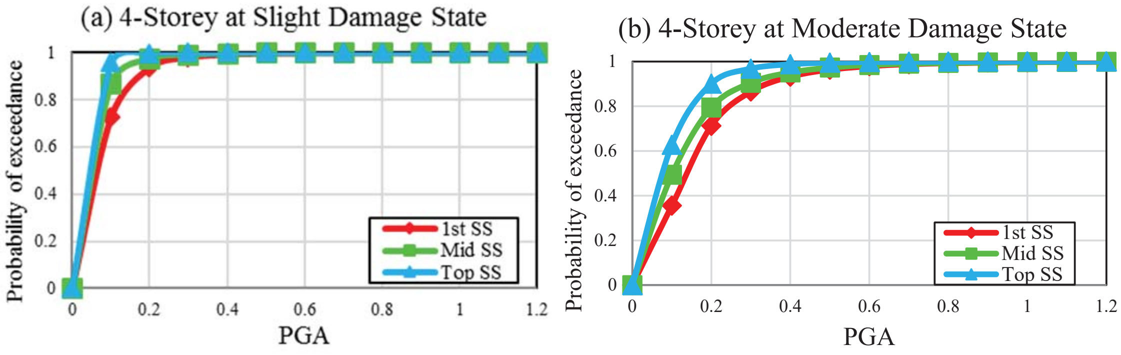


Fig. 10 Fragility curve for 16-storey structure with different placement of soft storey



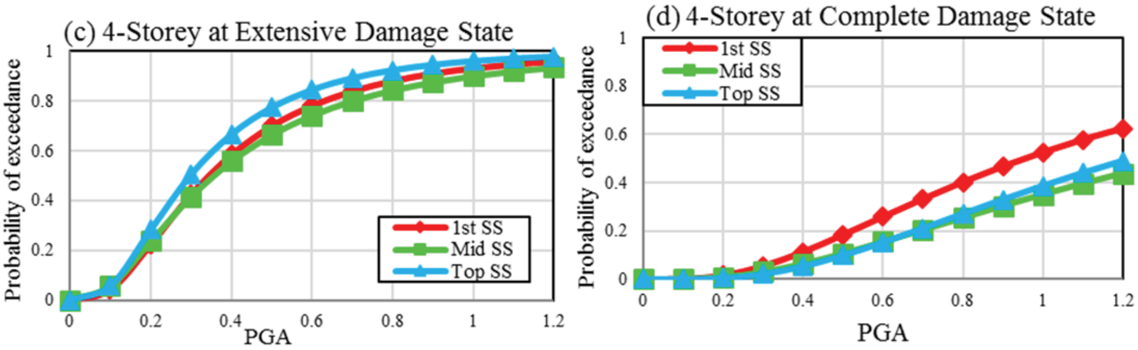


Fig. 11 Fragility curve for 4-storey structure with different placement of soft storey at (a) Slight. (b) Moderate. (c) Extensive. (d) Complete damage of state

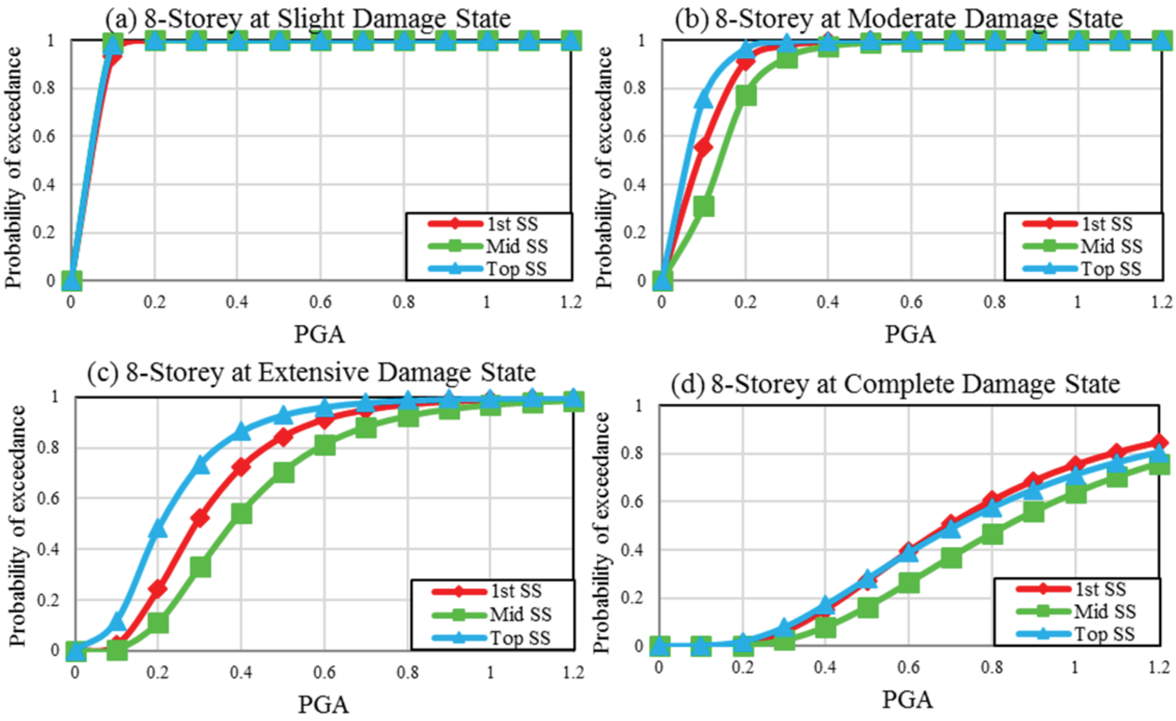
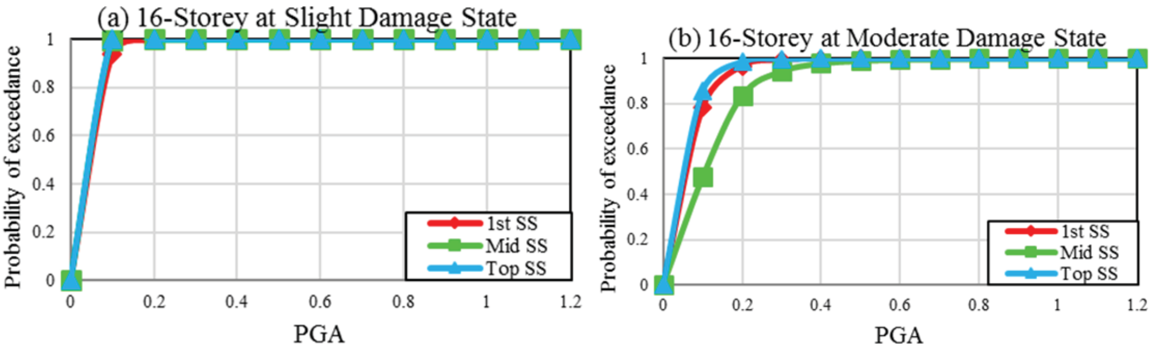


Fig. 12 Fragility curve for 8-storey structure with different placement of soft storey at (a) Slight. (b) Moderate. (c) Extensive. (d) Complete damage of state



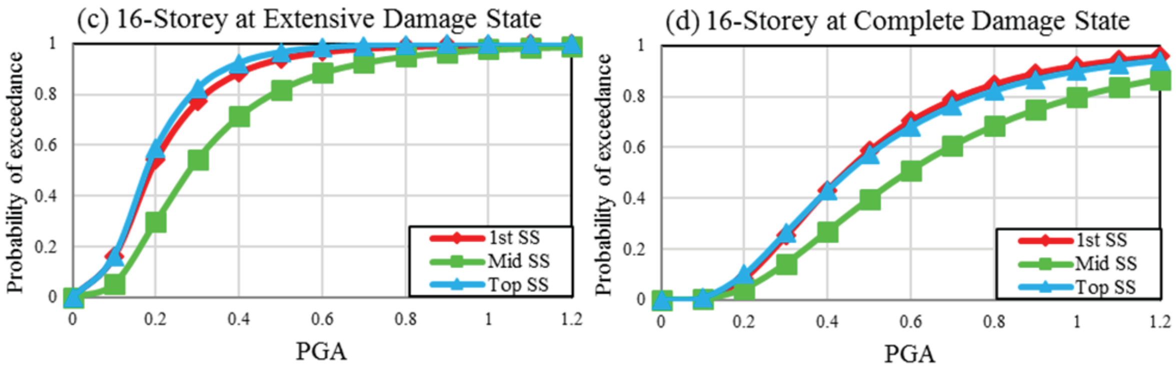


Fig. 13 Fragility curve for 8-storey structure with different placement of soft storey at (a) Slight, (b) Moderate, (c) Extensive, (d) Complete damage of state

It can be clearly concluded that largest change in structures vulnerability has been happened at complete level of damage. Also it can be deduced that while soft storey assigned to the 1st floor, it can be considered as a critical situation.

In general, structures with different number of stories have various performances and seismic responses. To evaluate vulnerability of structures with various floor fragilities, curves have been generated as shown in Figs. 14-16.

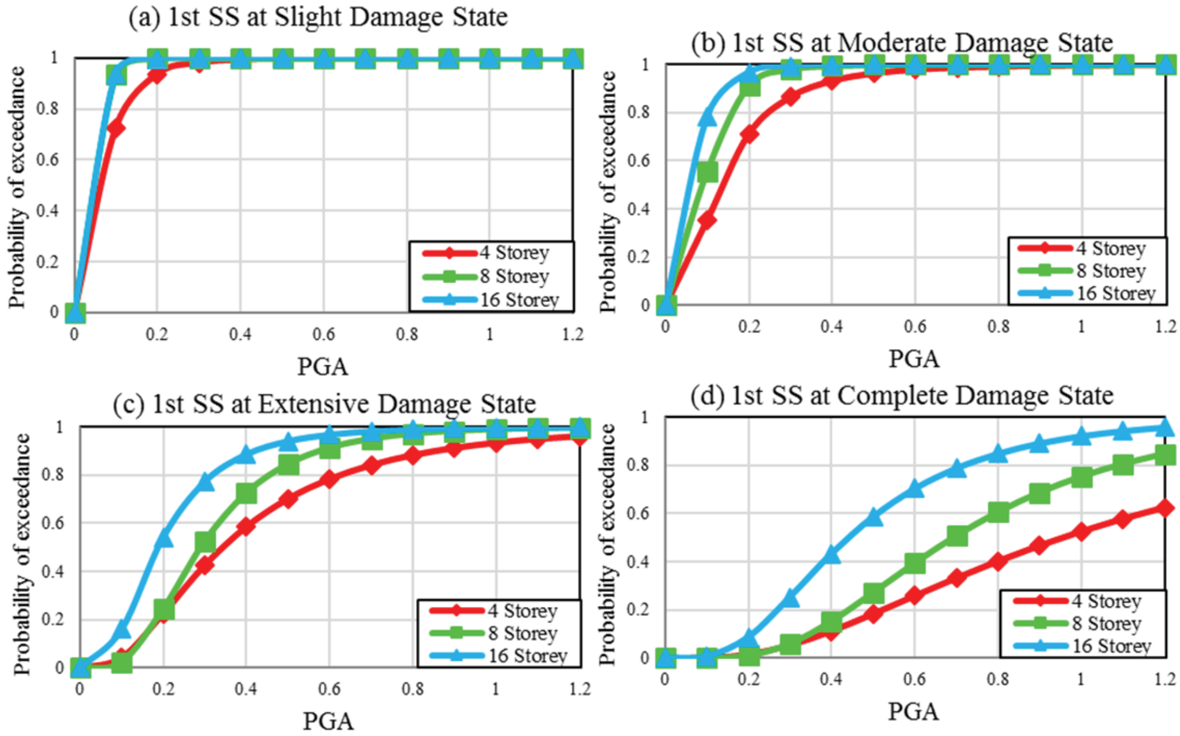


Fig. 14 Fragility curve for 4-, 8- and 16-storey structure with 1st soft storey at (a) Slight, (b) Moderate, (c) Extensive, (d) Complete damage state

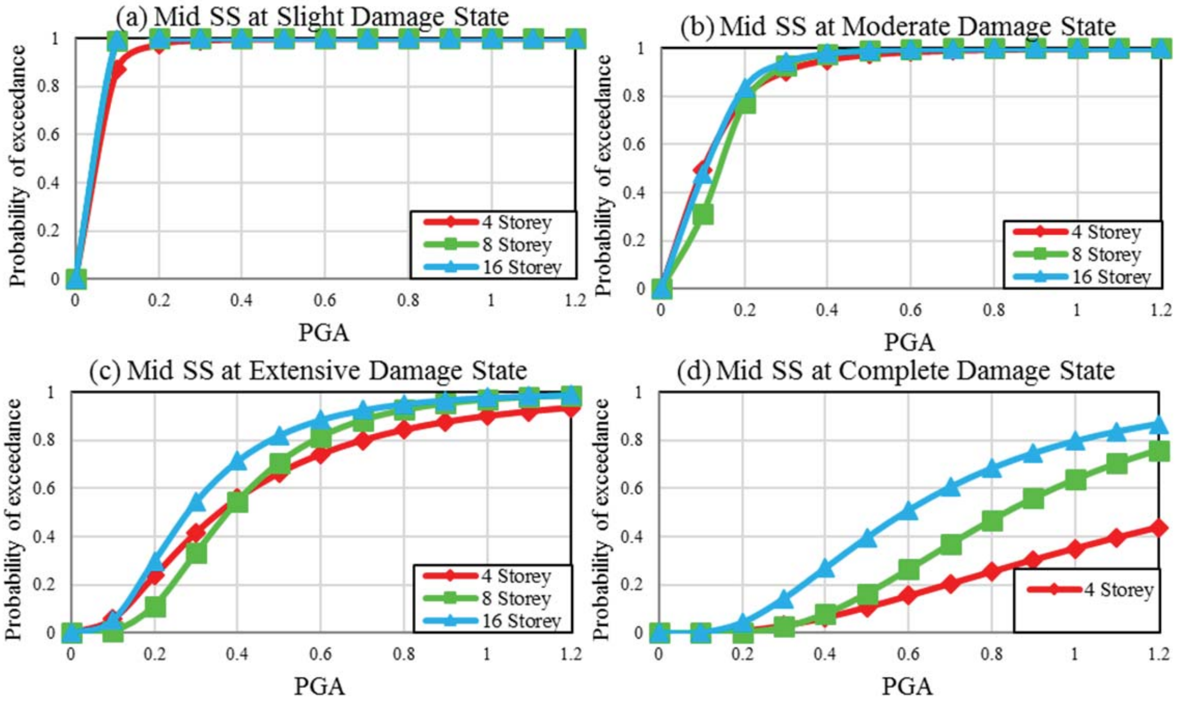


Fig. 15 Fragility curve for 4-, 8- and 16-storey structure with middle soft storey at (a) Slight, (b) Moderate, (c) Extensive, (d) Complete damage state

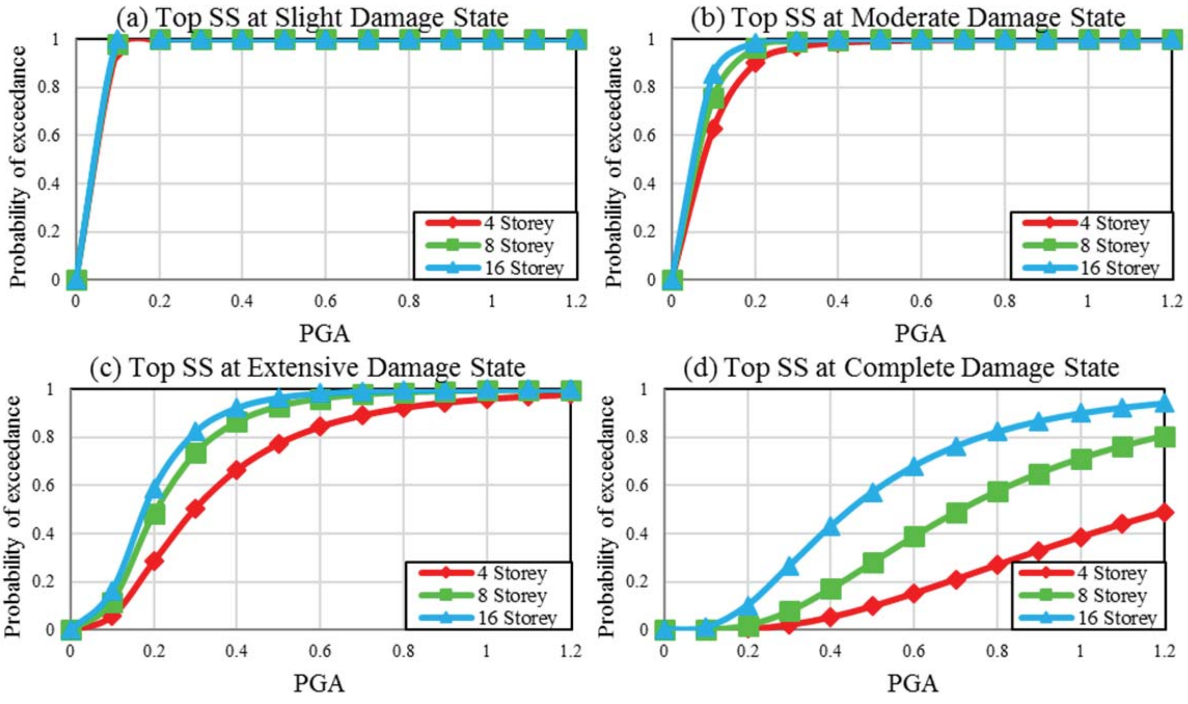


Fig. 16 Fragility curve for 4-, 8- and 16-storey structure with Top soft storey at (a) Slight, (b) Moderate, (c) Extensive, (d) Complete damage state

Figs. 14-16 shows structures have been presented the same performance regardless of number of storey at slight level of damage, also it can be concluded that in high-rise structures rather than mid-rises, the vulnerability and probability of exceedance of structures have been increased. It means that high-rise structures have much more sensitivity to the reduction of stiffness.

In all cases, the ductility demand decreases and displacements increase as stiffness is reduced. For reduction in stiffness, drift increases, and ductility demand decreased. This apparent anomaly may be explained by the fact that as the structure becomes softer, drift increases, but since the strength

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is constant, the yield displacement increases. Therefore, the ductility demand decreases.

## V. CONCLUSION

The effect of soft storey on the PSDM and seismic fragility of special steel moment frame structures is carried out. A 4-, 8-, and 16-storey 3-bay steel-frame is considered for analysis. A methodology based on IDA for comparing the capacities of different structural designs has been proposed to study the effect of soft storey on seismic performance.

From the analytical work, it is observed that the structural irregularities have significant influence on the PSDM parameters. Also, it is can be seen that the soft storeys have significant influence on seismic fragility. As a conclusion, consideration of vertical irregularities in seismic risk assessment has a significant influence in the decision making phase. In brief, it was found that:

- The effect of any stiffness modification significantly differs depending on the limit-state or level of intensity considered.
- The effects of irregularities are highly dependent on the record selection. In each case, only the most prominent effects observed stand out from the record-to-record variability and are thus found to be statistically significant.
- For most of the cases, the impact of soft storey on seismic fragility and structural vulnerability remarkably varies greatly by variation of position that if the soft storey locate on 1st storey, it would change the seismic performance of structure the most and make it more vulnerable.
- In high-rise structures rather than mid-rises, the vulnerability and probability of exceedance of structures have been increased. It means that high-rise structures have much more sensitivity to reduction of stiffness.

The proposed approach of developing a predictive tool can enhance regional damage assessment tool, such as HAZUS, to develop enhanced fragility curves for known soft storey. However, the irregularity considered is for illustration purpose only, and further studies considering other irregularities are warranted.

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