Evaluation of a Recently Proposed Ground Motion Selection Method in Case of Vertically Irregular Frames

Salar Arian Moghaddam[1] and Mohsen Ghafory-Ashtiany[2*]

1. Ph.D. Student, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
2. Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Iran,
* Corresponding Author; email: ashtiany@iiees.ac.ir

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ABSTRACT

Rapid growth of performance-based earthquake engineering has caused increasing interest in Nonlinear Time History Analysis (NLTHA) as an effective tool for the estimation of dynamic structural demand and capacity. Considering the preparation of a set of ground motions as the key step for NLTHA; many ground motion selection and modification approaches have been proposed to ensure reliable analysis results by reducing possible bias due to the random selection of ground motions. Apart from the existing differences among these methods, there is a common aspect in almost all of them, which can be considered as a limitation: They are constructed on the basis of simplifying assumptions that are not necessarily valid for irregular or complex structural systems. This paper evaluates the efficiency of a recently proposed structure-specific record selection scheme in terms of collapse simulation of vertically irregular frames. Utilization of the method is assessed by case studies on which different strength, stiffness and combined irregularity patterns are applied. The influence of proposed reduction in the number of used records on the estimated collapse capacities is evaluated by statistical tools. The results confirm the ability of the method in estimating median collapse capacity with 82% reduction in computational cost and maximum observed error of 16%.

Keywords:
Ground motion selection; Collapse simulation; Vertically irregular

1. Introduction

Selection of a limited number of Strong Ground Motion Records (SGMRs) is an important step in performance assessment of engineering structures. Knowing the role of ground motion characteristics in seismic excitation of dynamic systems; different seismic provisions and guidelines have introduced predefined sets of SGMs for Nonlinear Time History Analysis (NLTHA) [1-2]. The importance of SGMR selection becomes clearer in collapse simulation of structures, where the dynamic behavior and failure mechanism of structure cannot simply be predicted by traditional tools such as elastic spectral ordinates. Although there have been suggestions for minimum required number of records in response history analysis based on code-based procedures [3], the new generation of probabilistic seismic design and evaluation methods highlight the need for statistically unbiased reliable estimation of structural demand and capacity. Furthermore, considering the variable sources of uncertainty in recorded ground motion, the first engineering judgment is based on the idea that; the larger the number of selected SGMRs, the more reliable estimations will be resulted. For example, Incremental Dynamic Analysis (IDA), a widely used tool for seismic performance assessment of engineering structures [4], utilizes incrementally scaled up ground motions to the increased levels of intensity to capture the gradual change in seismic performance from elastic state to the collapse prevention point. Practical challenge in the application of IDA is the huge computational effort required for numerous NLTHAs. There have been a variety of studies focusing on the remedies for the mentioned limitation [5-7]. Structure-specific SGMR selection is one of these attempts that are intended to reduce the number of SGMRs as much as possible, while the accuracy and reliability of estimated response is kept in a tolerable range [8]. Structure-specific methods unlike their traditional alternatives (e.g. site-specific record selection) are not summarized in scenario based proxies that are consistent with the hazard level at the construction site. They must evaluate the potential of destructiveness of SGMRs quantitatively to introduce best possible representatives of a general set for performance (e.g. collapse) assessment of structures. The latter task can be done by defining more efficient and sufficient Intensity Measures (IMs) and involving them in the selection process [9-10]. The main shortcoming of modern IMs is their mandatory requirements to relate them with the seismic hazard levels such as ground motion prediction equations. Another alternative is to conduct a simplified analysis scheme to refine the whole general set and find a subset of smaller size that is able to reproduce the estimated results by general set approximately [11]. Following this strategy, Ghafory-Ashtiany et al. [12] have proposed an a priori set of SGMRs selected from a commonly used general set, which is introduced for collapse assessment [1]. The method first utilizes the statistical exploration of a collapse capacity database that is constructed by analyzing numerous SDOF systems each of which represents specific combination of structural features such as ductility and period. Then, by defining a quantitative similarity measure, the whole database is refined to find the optimum subset representing the general set well for any predetermined structural characteristics.

The step-by-step procedure, illustrated in Figure (1), shows the validity of proposed method in collapse simulation of a first mode dominant benchmark structure. As it is noted in their conclusions, the applicability of the method is constrained to the regular systems, the dynamic behavior of which is chiefly controlled by the first mode of vibration.This is the artefact of using SDOF systems for construction of collapse database.

There has been a wealthy background in earthquake engineering literature showing the large interest in characterization of irregular structures [13]. Different possible patterns of irregularity have been investigated to represent irregular cases that are called "non-conforming" compared to the code-based definitions of a regular structure. Most of current seismic provisions define regular buildings using criteria on the basis of distribution of mass,

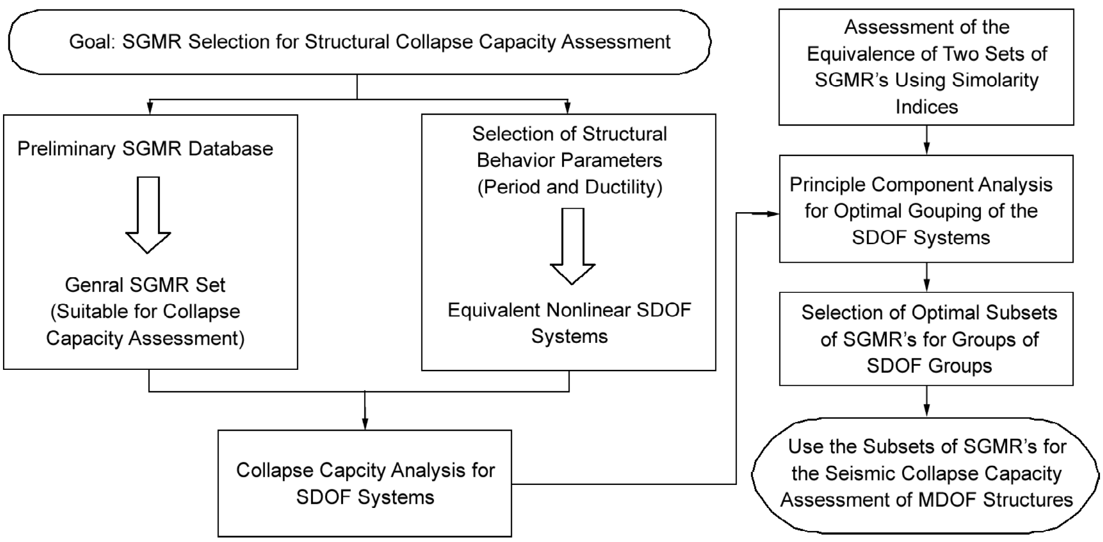

Figure 1. Steps of strong ground motion record selection for the reliable prediction of the mean seismic collapse capacity of a structure group [12].

strength and stiffness along the height of the structure. For example, the "Stiffness-Extreme Soft Story Irregularity" is defined in ASCE 7-10 [14] where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above. The previous studies have provided valuable information describing the behavior of vertically irregular structures, although, due to the different methodologies and assumptions; their results cannot easily be generalized to the cases beyond the specific structural models that are modeled in each study [15]. Following the preliminary studies to investigate the soft story effect [16]; different irregularity patterns were examined to assess the height-wise variation in structural demands [17-18]. Fragiadakis et al. [19] studied the irregularity due to mass, stiffness, strength and their combination effects using IDA. Sadashiva et al. [20] proposed relationships between the level of irregularity and the consequent change in the structural behavior. Van Thuat [21] quantified the change in the distribution of story strength demand due to the vertical irregularity. Varadharajan et al. [22] proposed an irregularity index and developed empirical equations for engineering demands in irregular frames. Recently, Zhou et al. [23] have studied the probability of failure of several vertically irregular reinforced concrete frames. Emphasizing on the fact that the study of the effect of vertical irregularity on the performance of a structure is not in the scope of the present work; readers are referred to [13-14] for a more detailed background in this field.

It is shown that the performance of a frame structure may be deeply influenced by the presence of vertical irregularity [19]. However, standard irregularity patterns [17-18] will not necessarily result in significant change in higher mode contributions, i.e. a vertically irregular frame may still be considered as a first mode dominant system in terms of elastic modal characteristics (e.g. modal participation factor), but its performance will be severely deviated from its regular counterpart. Fragiadakis et al. [19] showed that their results may be sensitive to the selection of SGMRs. They used bootstrap method to check the dependency of their results to the selected SGMRs and concluded that this sensitivity diminishes at larger drift ratios not-influencing their observations. In this paper, assuming that the collapse assessment of a first mode dominant vertically irregular frame can be sensitive to the record selection, the efficiency of the proposed method by Ghafory-Ashtiany et al. [12] is assessed by means of collapse capacity estimation via IDA.

2. Evaluation Process

As mentioned in the previous section, vertically irregular steel moment frames are selected to play the role of target structure in collapse simulation. After defining different irregular cases by modifying strength and stiffness of a regular basic model (called as Base hereafter), IDA is performed using 44 SGMRs introduced in [1] as the ordinary set of SGMRs for collapse assessment. The maximum inter-story drift ratio (IDR Max) is selected as the engineering demand parameter that has the potential of indicating possible contribution of higher modes of vibration (or failure). The 5%-damped spectral acceleration at the first modal period Sa (T1, 5%) is used as incrementally increasing IM. According to the methodology described in [12], six subsets each of which corresponds to a period range have been classified including 31 out of 44 SGMRs in general set. Subsets 1-6 are introduced for period ranges of (0.1-0.3sec), (0.3-0.5 sec), (0.5-0.7 sec), (0.7-0.9 sec), (0.9-1.25 sec), and (1.25-2sec), respectively. Each subset contains eight SGMRs that are supposed to represent the general set for collapse simulation of structures that their first modal period is placed inside the mentioned period ranges.

Median and standard deviation of the collapse capacity estimations for each subset is compared with the same values computed over all 44 IDA curves. Since the application of any subset results in the reduction of the number of used SGMRs, the sensitivity of the results to the selected input SGMRs is evaluated, too. Figure (2) shows the spectral ordinates of all 44 SGMRs in general set as well as the record-to-record dispersion in each subset of eight SGMRs.

2.1 Structural Models

A typical 2-D model of 12-story steel moment resisting frame with three bays has been selected from benchmark database of plane steel frames [23] as the Base frame. Gravity load equal to 27.5kN/m (dead and live loads of floors) is carried by beams,

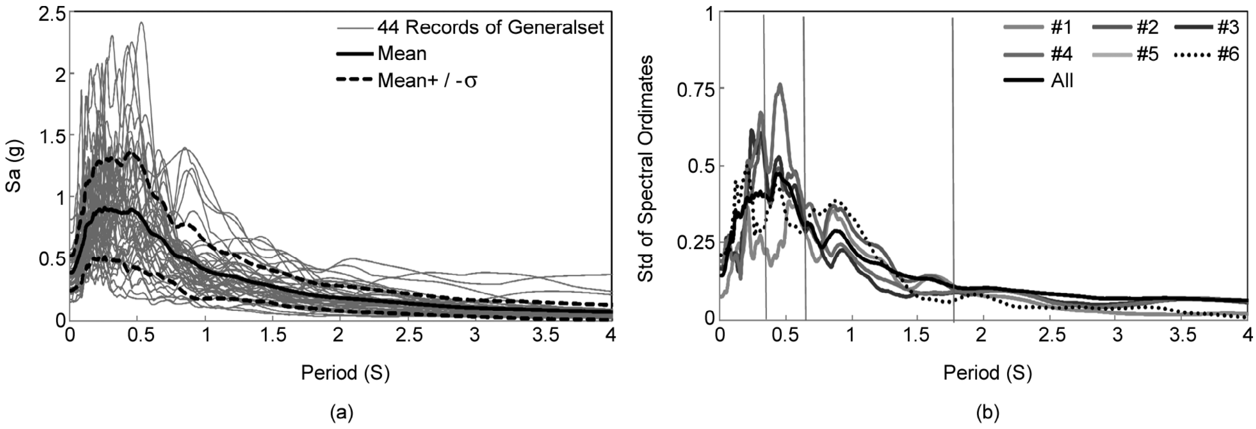

Figure 2. Spectral comparison among un-scaled SGMRs: a) the 5% damped acceleration response spectra and b) record-to-record dispersion for different groups of SGMRs [12] in terms of standard deviation (std). First three modal periods are indicated by vertical lines.

while the yield strength of the material is set equal to 235 MPa. The steel frame was designed according to Eurocode (EC3-EC8) for peak ground acceleration (PGA) of 0.36 g and soil class B [24]. Details of structural model are presented in Table (1). In the table, the number of story is indicated in parentheses, while the type of IPB and IPE sections are written before parentheses, respectively. Extensive information describing the modeling, design and seismic behavior of base frame can be found in [23-24].

Considering the most important works to quantitatively investigate the effect of vertical irregularity; the standard irregularity patterns in [17-18] are chosen. Three types of vertical irregularity have been considered [18]; stiffness (K), strength (S) and combined stiffness-strength (SK) irregularities. To model irregular frames, properties of all beams and columns in every single story are strengthened or weakened (upgraded or degraded) by two constant factors of 2 and 0.5, respectively, which is in accordance with the proposed process in [19]. Furthermore, a typical case of multi-story modification is constructed by applying the irregularity in the Lower Half (LH) of the frame (stories 1-6). Figure (3a) shows samples of developed irregular cases with their labels. The story at which the irregularity is considered is indicated in parentheses, e.g. SK0.5 (6) refers to the frame that its stiffness and strength are decreased at 6th story. The single stories of 1, 3, 6, 9, 12 and lower half of the frame are modified. The change in the first three mode shapes of the frame due to the combined strength-stiffness modification in the lower half of the structure is portrayed in Figure (3b). As it is mentioned before, single story irregularity (at least by using modification factor of 2 and 0.5) do not cause a drastic change in the modal characteristics of the base frame, while applying the irregularity pattern in the first six stories may result in a 33% shift in the first modal period. Figure (3c) illustrates the gradual variation in the modal characteristics of SK frames, which are normalized to those of the base frame.

2.2 Collapse Simulation

Considering the presented details in previous section; 37 (= 6 * 2 * 3 + 1) different structural models have been constructed in SeismoStruct [25]. The well-known IDA method [4] is used to develop IM-EDP (Sa (T_1, 5%), IDR_{Max}) curves. Total of 1626 IDA have been conducted to estimate the collapse capacity of each frame under 44 SGMRs. Intensity levels are scaled up gradually

Table 1. Details of base structural model.

Story (m)	Bay (m)	Column: (IPB) - Beams: (IPE)	Period (sec)		
			Mode1	Mode2	Mode3
3	5	450-360(1)+450-400(2-3)+450-450(4-5)+ 400-450(6-7)+360-400(8-9)+360-360(10)+360-330(11-12)	1.77	0.63	0.35

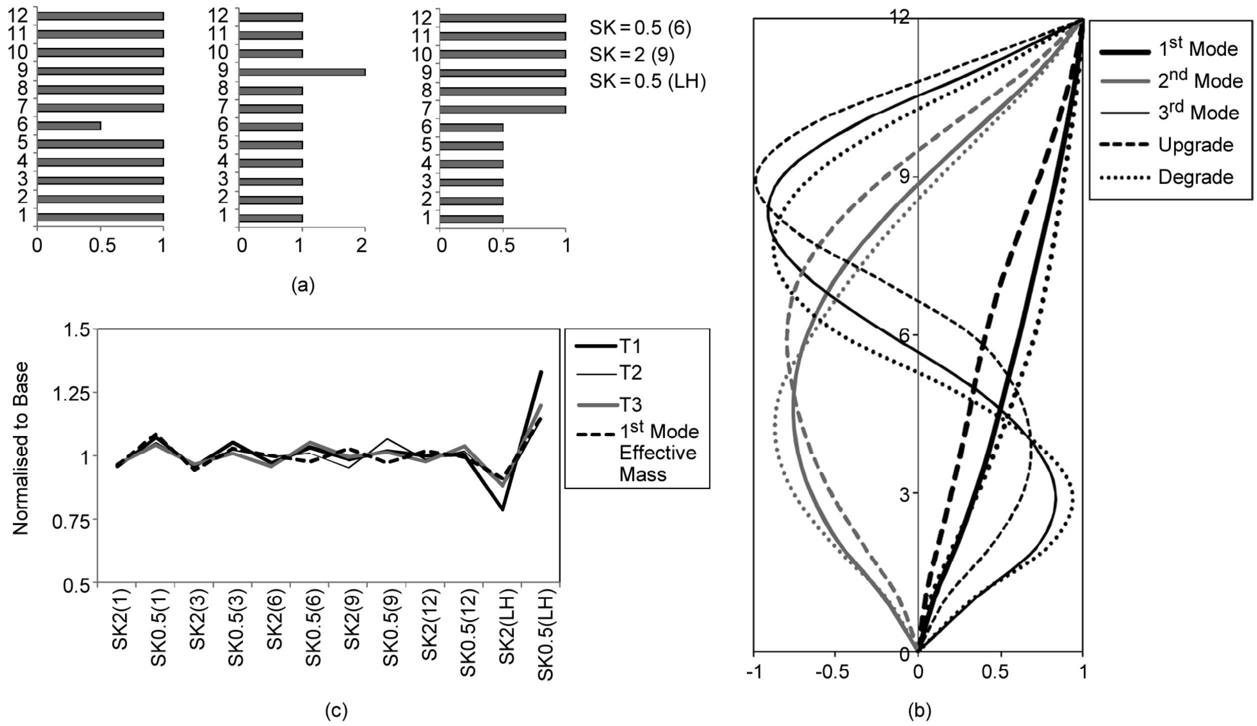

Figure 3. Modification in structural characteristics: a) Samples of irregularity pattern; b) Change in mode shapes due to the combined strength-stiffness modification in lower half of the frame; and c) Gradual variation in modal characteristics due to the combined strength-stiffness modification normalized to those of base frame.

using constant steps of 0.05 g and the corresponding demands are recorded. Considering the fact that the reliability of the results of structural analysis for frame structures experiencing IDRMax greater than 10% decreases; the collapse limit state is defined based on the observation of the structural instability (onset of flattening in IDA curve) or IDRMax equal to 10% in accordance with [1]. The median curves computed for frames modified by combined strength-stiffness pattern are presented in Figure (4). Following the proposed methodology in [19]; all collapse capacities are reported in terms of the spectral acceleration at the first modal period of the base frame (T_1=1.77 sec), hereafter. This will enable us to compare the estimated results of vertically irregular cases against base frame without being concerned about the influence of the variation in the period of the vibration of the different models (note that this is just an additional step in the post-processing phase).

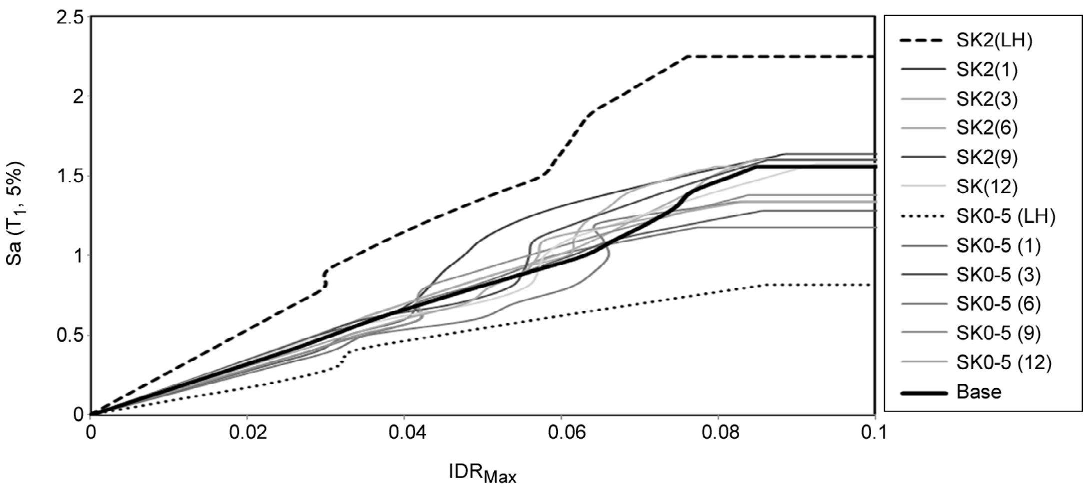

Figure 4. Individual IDA curves corresponding to the median collapse capacity for different combined irregular cases compared to the base frame.

3. Effect of Vertical Irregularity on the Collapse Capacity

Although the main objective of the present study is not to investigate the role of the vertical irregularity on the seismic performance of structures, a concise comparison with the other available researches is presented in this section to implicitly verify the results. As it is explained in the introduction, there is no consensus about the effect of the vertical irregularity on the behavior of engineering structures. There are conflicting conclusions in different studies [15], which can be attributed to the specific methodologies, case studies and simplifying assumptions. On the other hand, most of researches have focused on the elastic responses or even in the case of nonlinear Response History Analysis (RHA); the conclusions cannot easily be generalized to the near collapse performance of structures. Here, the results of performance assessment of vertically irregular versions of the nine-story SAC building by IDA that is presented in [19] are used for qualitative comparison as well as general facts reported in benchmark studies in this field [17-18]. The collapse fragility curves by statistical analysis of the IDA results are computed in Figures (5) to (7). The most important observations from these figures can be listed as:

- The stiffened/softened single story causes meaningful changes in the collapse capacity of the frame, which is in accordance, but more pronounced, with the results of the nine-story building presented in [19]. Imposing a modification (up-grade/degrade) in stiffness can result in the increase/reduction of the collapse

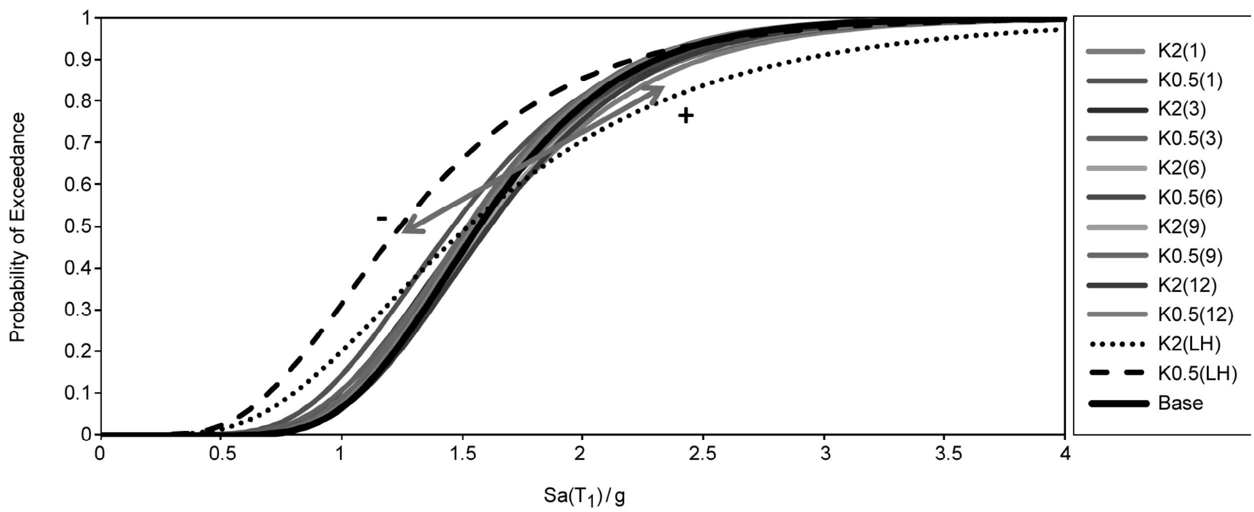

Figure 5. Collapse fragility curves computed for stiffness irregular frames.

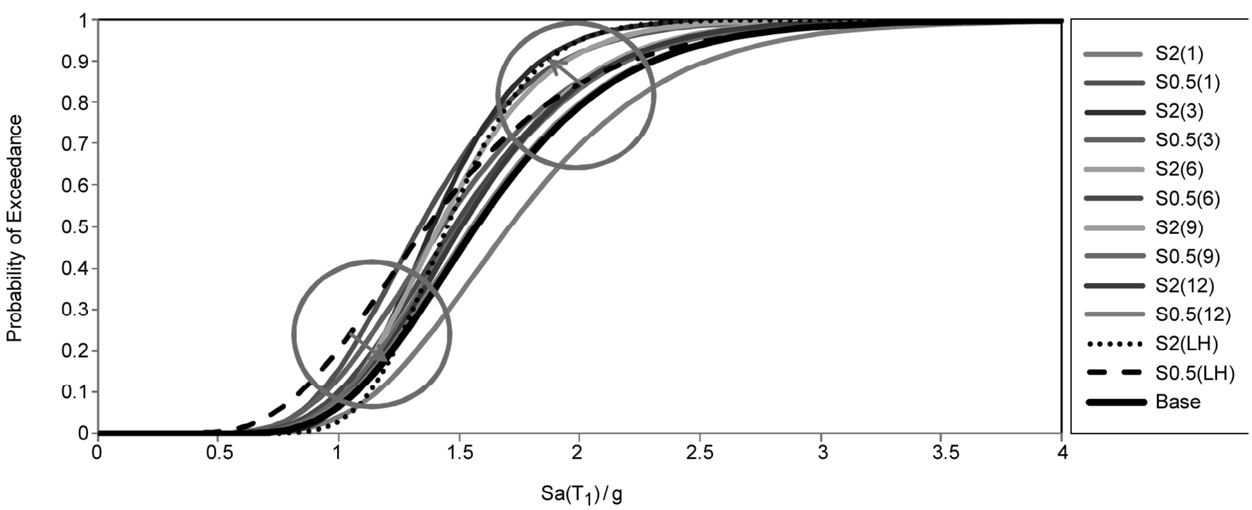

Figure 6. Collapse fragility curves computed for strength irregular frames. Two arrows indicate the change in the shape of computed fragility curve due to the increased dispersion in the results from S2 (LH) to S0.5 (LH).

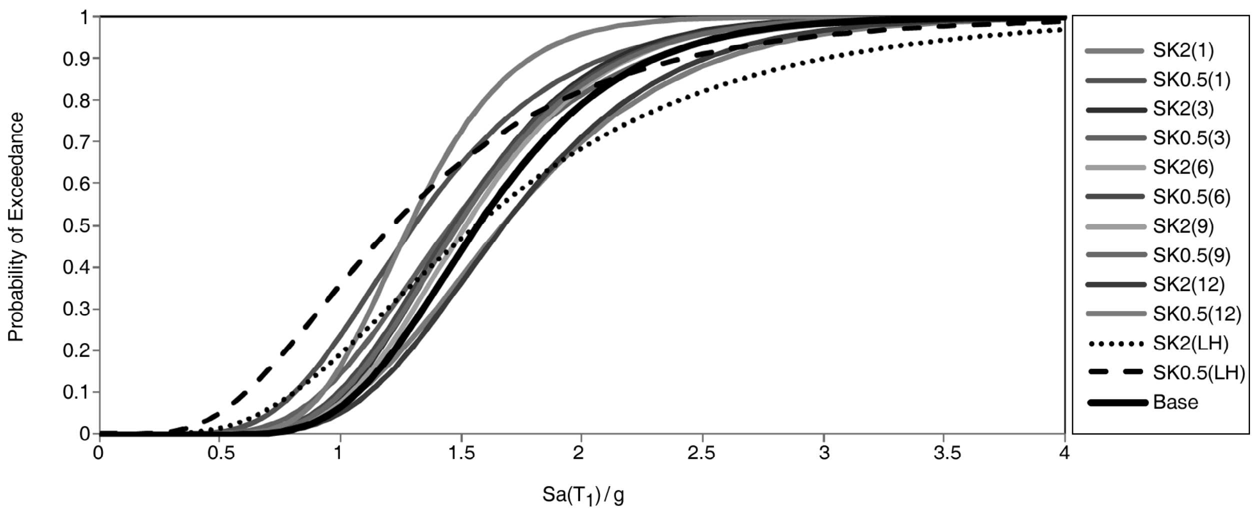

Figure 7. Collapse fragility curves computed for combined strength-stiffness irregular frames.

capacity of frame as shown in Fig.ure (5). When the modification is made in lower stories, it essentially affects the collapse capacity. These changes are the artefact of the redistribution of imposed forces in the presence of a modified single story that causes wide-spread variation in the IDR_{Max} along the height of the frame [19].

- The presence of a modified (strong/weak) single story reduces the collapse capacity of the frame with the exception of modification at first story, Figure (6). In other words, it can be observed that the single story strengthening will not necessarily result in the improvement of collapse capacity. Knowing the fact that local strengthening of a frame can control the expected demands in the neighborhood of strong story, but, shifts the location of maximum demands (e.g. the IDR at 4th story may be decreased compared to the corresponding values in base frame by applying irregularity pattern of S2 (4), while a higher IDR_{Max} may occur at the 8th story); the latter observation can be interpreted. In other words, considering several possible failure mechanism for frame structures [26]; a stronger single story may delay the main collapse mode but accelerate another potential mechanism. The IDR_{Max} in the seismically designed frames is expected to occur above the first story, then, the mentioned interpretation cannot be generalized to the first story modification. The observation that there is no direct relationship between the change in single story strength modification and the consequent collapse capacity is consistent with the results of [19], although the addressed theoretical explanation needs more extensive investigation to be confirmed.
- The effect of simultaneous strength-stiffness irregularity (SK) can be considered as the combination of the effects of strength (S) and stiffness (K) modification as shown in Figure (7).
- The influence of applying irregularity in the lower half of the frame can be considered as a magnified generalization of the first story modification.

4. Performance of Subsets of Eight Selected SGMRs in Collapse Estimation

Following the described procedure in section 2; the ability of each subset introduced in [12] in the prediction of median collapse capacity as well as the associated standard deviation is assessed. As it is clear in Figure (2c), the first modal period of all modified frames are included in the predicted range for 6th subset. It should be noted that the stiffness degradation in the lower half of the frame results in the elongated first modal period of 2.39 sec that exceeds the upper band of 2 sec for 6th subset. To compare the predicted median collapse capacities, the normalized form to the corresponding values for base frame is used as:

$$CC_n = \frac{(Sa(T_1)|_{Collapse})_i}{(Sa(T_1)|_{Collapse})_{Base}} \quad (1)$$

where i refers to any of the 36 irregular cases. The computed CC_n values are presented in Figures (8) to (10) for (K), (S) and (SK) irregularity, respectively. In these figures, the first column indicates the influence of vertical irregularity obtained by all 44 SGMRs that was investigated in term of fragility curves in the previous section. Next columns present the estimations made by using different subsets of SGMRs in [12]. The part (g) of each figure compares the associated Standard Deviation (SD) with the estimated median capacity that is normalized in the same manner to the base values:

$$SD_n = \frac{(SD(CC_j))_i}{(SD(CC_j))_{Base}} \tag{2}$$

where i refers to any of the irregular case and j denotes any of the subsets of selected SGMRs. Based on the results shown in Figure (8), subset 6 can predict the direction of changes in collapse capacity in most of the stiffness irregular cases, i.e. the possible reduction (CC_n<1) or increase (CC_n>1) can be captured. Besides the 6th subset, the performance of subset 1 and 3 are acceptable for collapse capacity prediction. Other three subsets (2, 4 and 5) fail to effectively estimate the changes almost in all cases.

The simple error term defined by Eq. (3) is used

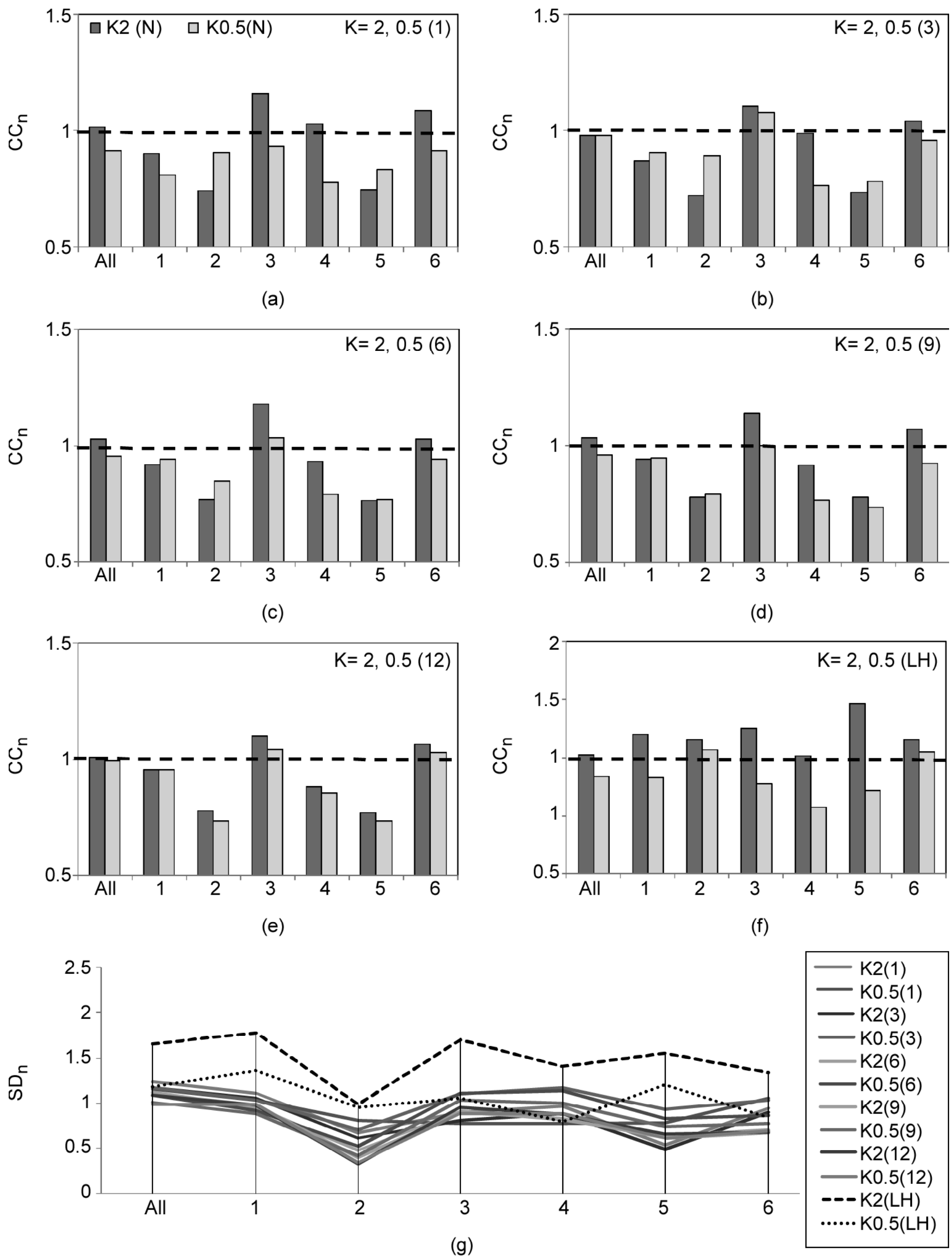

Figure 8. Comparison of collapse capacity values of stiffness irregular frames normalized to the collapse capacity of base frame: Median (a-f) and standard deviation (g) estimated by different subsets [12]..

to compare the predicted CC_n by different subsets:

$$Error = \frac{(CC_n)_{All} - (CC_n)_{Subset}}{(CC_n)_{All}} \times 100 \quad (3)$$

where the $(CC_n)_{All}$ and $(CC_n)_{Subset}$ denote the normalized collapse capacity estimated by general set and a selected subset, respectively. The mean computed error over all (K) cases are 6, 8 and 10% for subsets 6, 1 and 3, respectively. It is worth noting that these three subsets are corresponding to the first three modal periods of base frame and most of its irregular counterparts. The latter observation is in accordance with the better performance of modal pushover analysis in case of irregular frames [18]; however, it needs a more comprehensive study to confirm such a robust correlation between modal characteristics and collapse capacity of irregular frames. When the whole lower half of the structure becomes stiffer/ softer, all subsets show good performance, which can be attributed to the fact that the different failure mechanism in LH case is less sensitive to the ground motion characteristics [19]. Based on the part (g) of the figures, the application of any

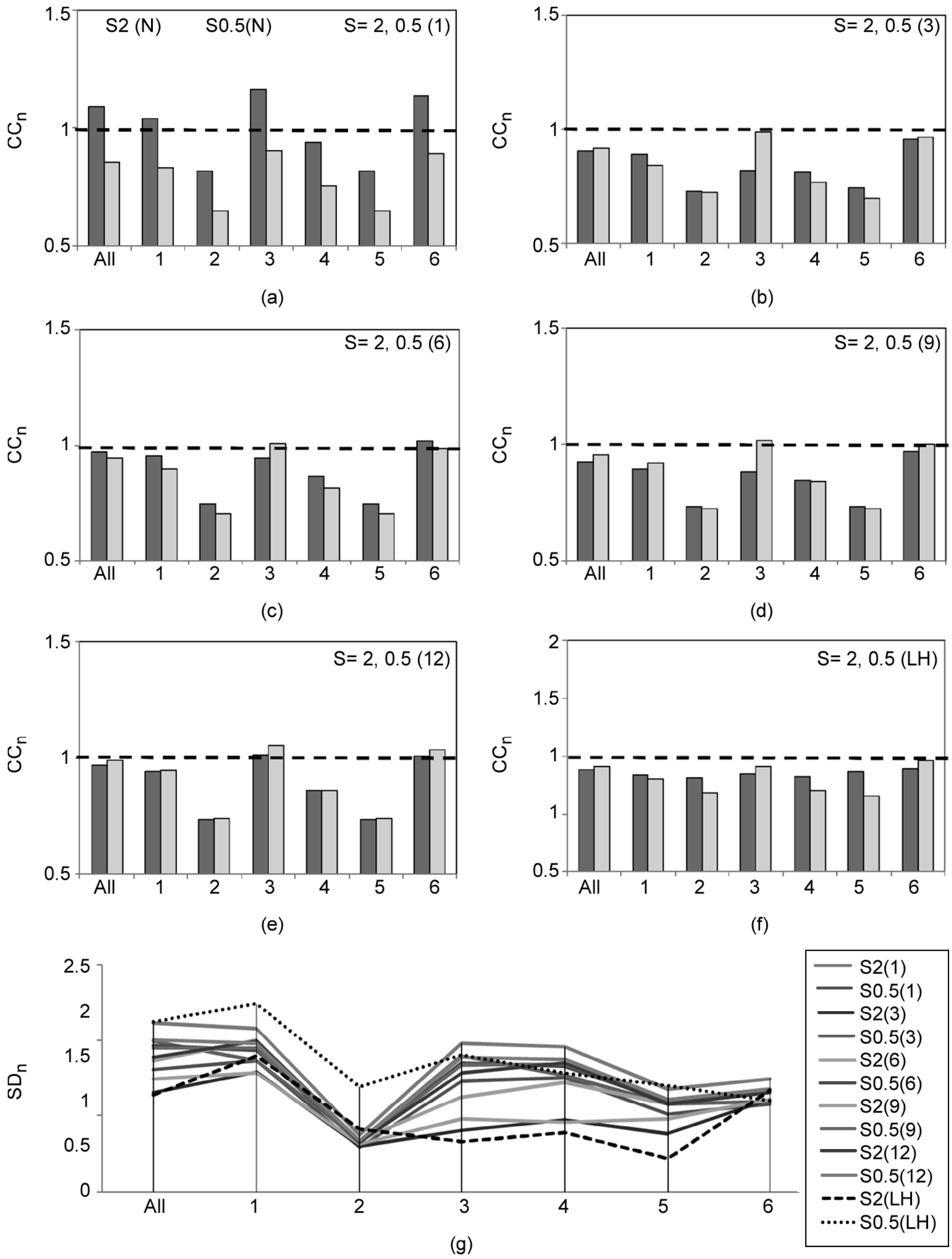

Figure 9. Comparison of collapse capacity values of strength irregular frames normalized to the collapse capacity of base frame: Median (a-f) and standard deviation (g) estimated by different subsets [12].

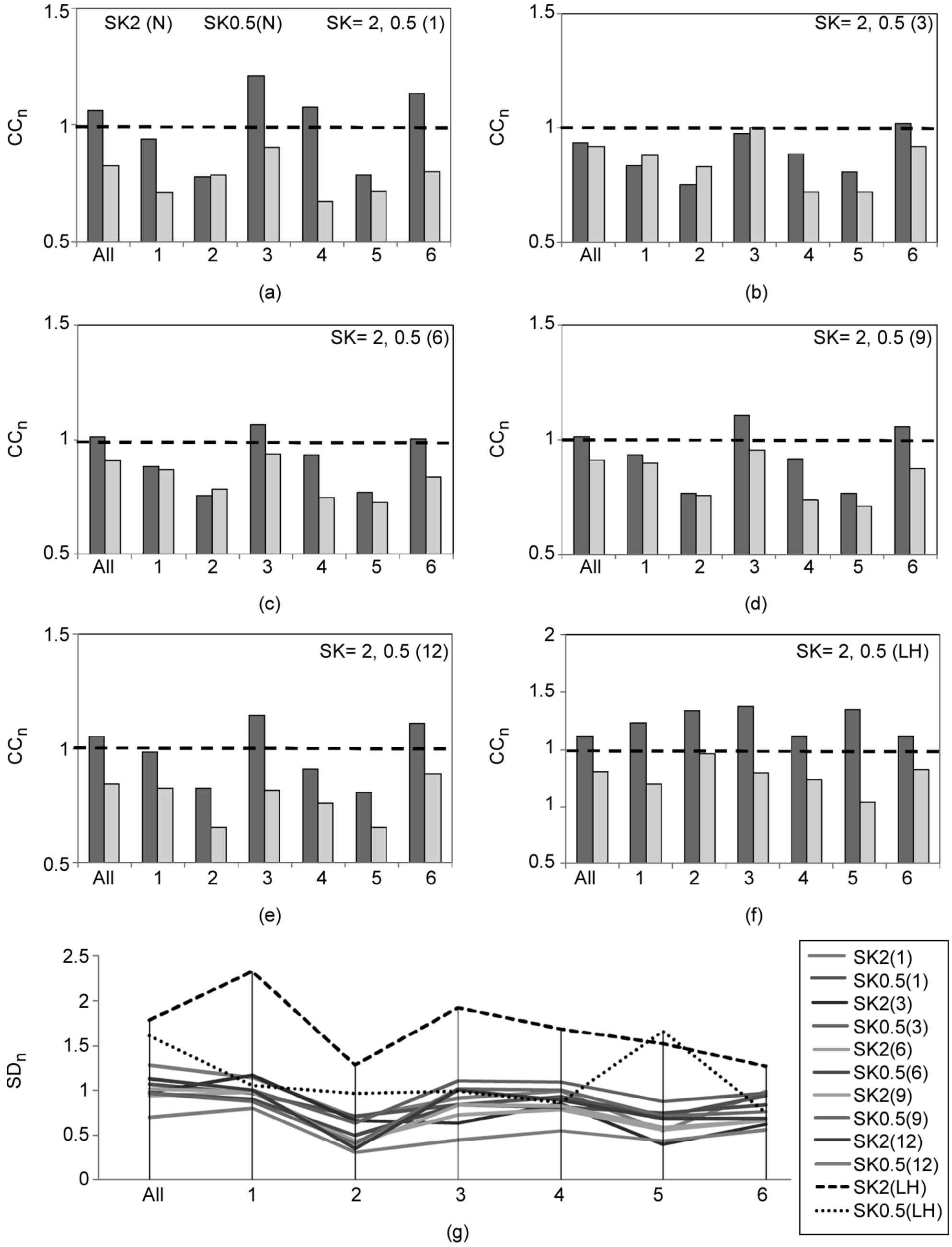

Figure 10. Comparison of collapse capacity values of combined strength-stiffness irregular frames normalized to the collapse capacity of base frame: Median (a-f) and standard deviation (g) estimated by different subsets [12].

subset of 44 SGMRs reduces the dispersion in the estimated collapse capacity for almost all single-story modified models, which is due to the lower record-to-record dispersion that has been previously illustrated in Figure (2b) (around the first modal period). The latter observation is not generalized to the cases experiencing increased stiffness at the whole lower half because of the tangible shift in the fundamental period (T_1 = 1.34 sec) to the spectral region at which the record-to-record variability is higher. As it can be easily seen in Figure (9), even-though the perfor-mance of different subsets in the collapse prediction of (S) irregular cases is similar to the (K) irregular frames, the best predictors are subsets 6, 1 and 3 with associated errors of 4, 5 and 6%, respectively. Again, lower dispersion in the subset's estimations compared to that of general set is clear, while a large difference in the associated dispersion with the estimated median of collapse in case of S2(LH) and S0.5(LH) is clear that is expected from Figure (6), too. Remembering the conclusions of the section 3; one should expect that the (SK) cases resemble the combination of (S) and (K) frames in terms of estimated collapse capacities. This can be concluded from Figure (10). Mean error terms for CC_n and SD_n (computing by replacing CC_n with SD_n in Eq. 3) are calculated over all 36 irregular cases that are reported in Figure (11). Subset 6 shows best predictions for CC_n, although may yield up to 31% deviation in SD_n. As it can be inferred from Figures (8) to (11), each subset including eight selected SGMRs produces a different pair of median and standard deviation for the collapse capacity.

A reasonable way to compare the ability of the collapse simulation statistically is the comparison of developed confidence intervals associated with pairs of median and standard deviation values [12]. Based on the results summarized in Figures (8) to (11), there are two candidate subsets for best collapse predictors; subset 6 and 1. The 99% confidence intervals for the collapse capacities for these two subsets are presented in Figure (12) and compared to the corresponding intervals estimated by general set. The black lines represent the estimations by all 44 SGMRs, while those of subset

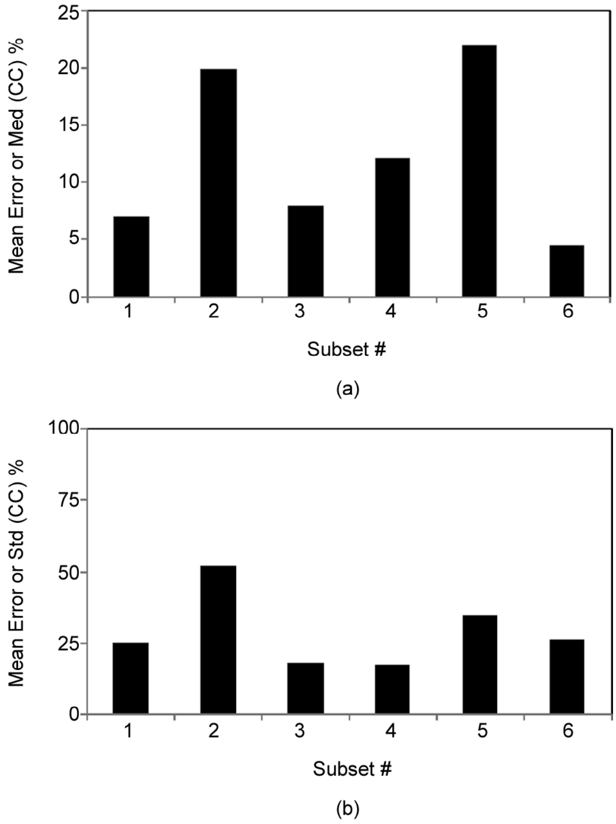

Figure 11. Comparison among the ability of different subsets in the collapse simulation in terms of mean error on estimated median (a) and standard deviation (b).

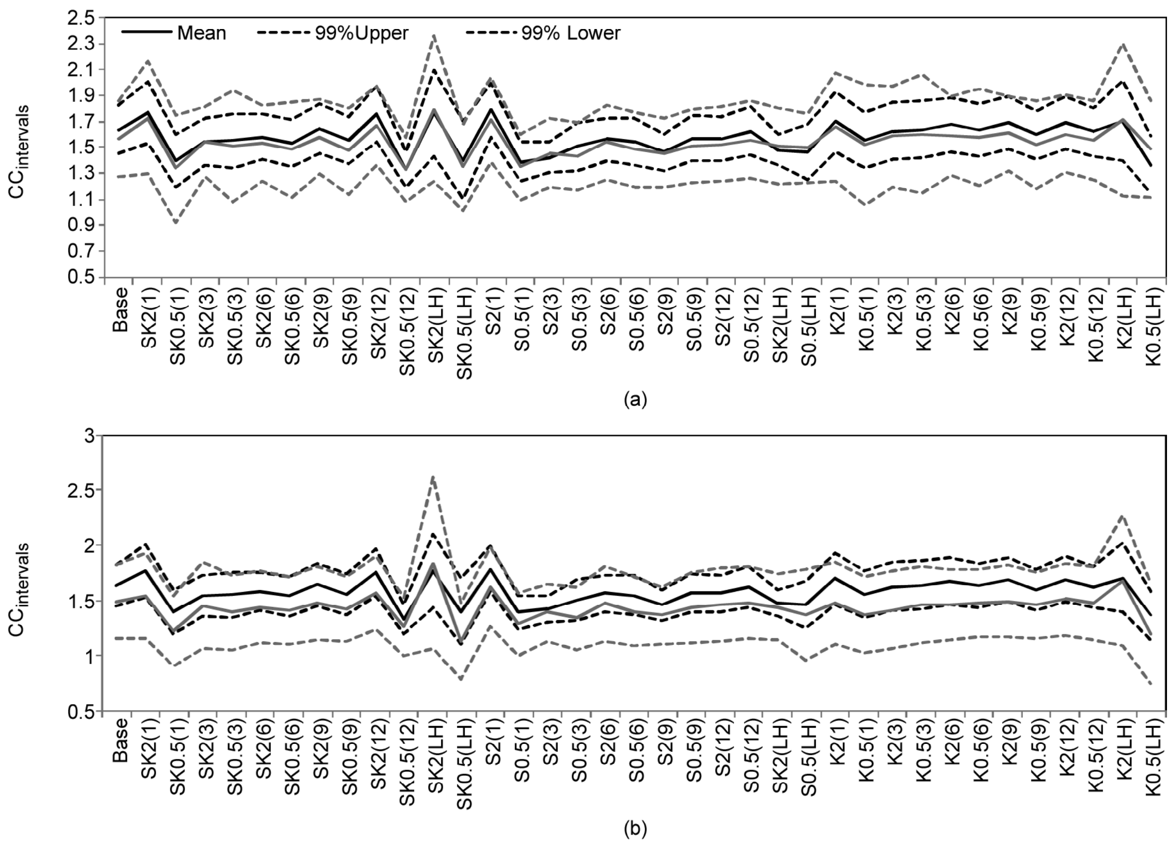

Figure 12. Collapse capacity 99% confidence intervals estimated by subset 6 (a) and subset 1 (b) compared to those of all SGMRs. Black and grey lines denotes the estimation by general set and individual subset, respectively.

6 and 1 are indicated by gray lines in parts (a) and (b), respectively. By comparing similarity in the developed confidence intervals, the superiority of subset 6 is confirmed almost in all cases.

5. Hypothesis Testing for Verification of the Results

It is shown that the computed IDA curves may reflect large record-to-record variability, especially in the near collapse estimations. Therefore, greater minimum required number of SGMRs for IDA is recommended compared to the traditional RHA [1]. An 82% reduction in the computational cost can be attained by using refined subsets of SGMRs for group structures [12] instead of the whole general set. This reduced number of SGMRs can also affect the accuracy of the results and the subsequent conclusions about the effect of irregularity on the seismic behavior of the frames. Fragiadakis et al. [19] proposed the application of hypothesis testing to eliminate any doubt on the source of their observations about the performance of irregular cases against base structure. In other words, they highlighted the fact that the limited size of selected dataset (20 SGMRs in [19]) can question the accuracy of the attribution of results to the irregularity instead of the record-to-record variability [19]. They used bootstrap method [27] to compare the median capacity estimations between the base frame and any modified case. Following their footsteps, a classic case of paired bootstrap samples is used to impose the same level of randomness to both the base and modified frame. Sampling with replacement from 44 SGMRs for general set and eight SGMRs for any individual subset is done to generate alternate suites of SGMRs and compute the median collapse capacities. By repeating this process for 1000 random sample, confidence intervals are developed for CC_n values. Assuming the superscript α represents the sample's α% fractile, the following is the (1-α)*100% confidence interval of the CC_n:

$$\left([CC_n]^{(\alpha/2)},[CC_n]^{(1-\alpha/2)}\right) \qquad (4)$$

Any confidence interval containing unity implies that there is no acceptable evidence with the (1-α)* 100% level of confidence to confirm that the observed CC_n values are artefact of the vertical irregularity rather than selected SGMRs. By choosing 90% confidence level (α = 0.1), the upper and lower bands of confidence intervals are calculated and depicted in Figure (13) for the general set.

The width of intervals indicates the sensitivity to the selected SGMRs. Although intervals containing the unity are considered as the rejection of our hypothesis, when one of the bands is close to the unity, we still can defend our observations [19]. Based on the results shown in Figure (13), the estimations using all 44 SGMRs are valid in 8, 7 and 6 cases for (SK), (S) and (K) cases, respectively.

The same process is done for eight SGMRs in

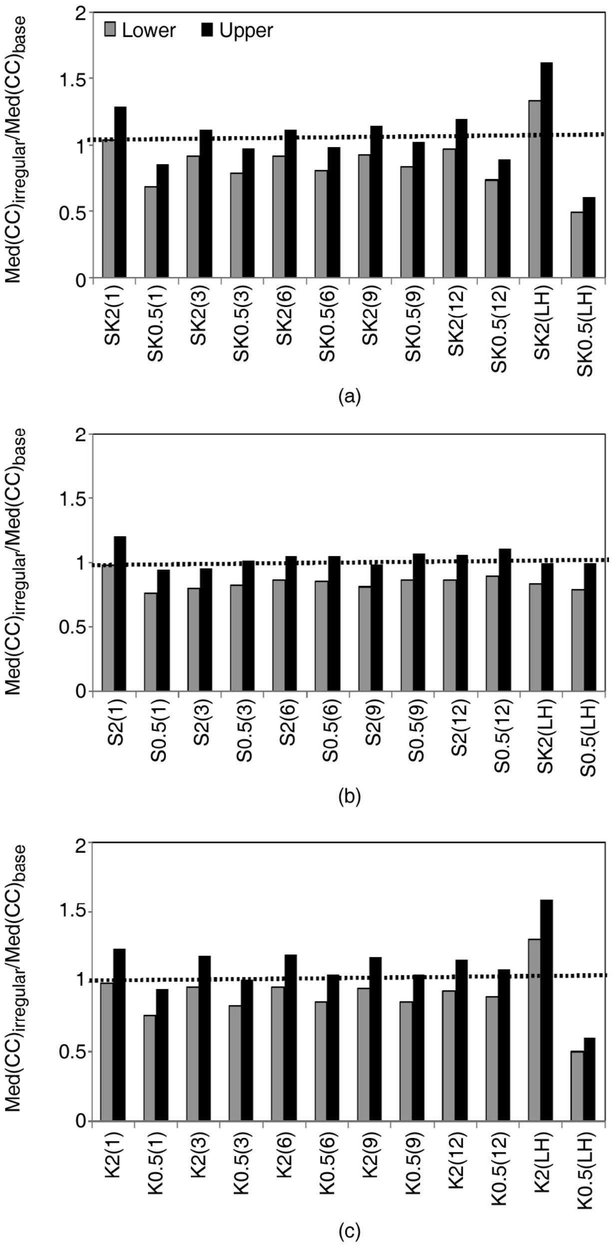

Figure 13. Bootstrap 90% confidence intervals on the collapse capacity estimation normalized to the base frame values by using all SGMRs for: a) combined strength-stiffness, b) strength and c) stiffness irregular frames.

subset 6 that is shown in Figure (14). The figure shows that there are wider intervals (more sensitivity to the SGMRs) with valid cases of 7, 7 and 4 for (SK), (S) and (K) frames, respectively. This confirms that the reduced number of introduced SGMRs by the selection method will not affect the level of reliability in the results compared to the application of whole general set. One different subset (#4) is analyzed by bootstrap method in Figure (15) to show tha the mentioned reliability can be affected by the application of wrongly selected subset. As it can be seen in this figure, there are 3, 1 and 2 valid instances for (SK), (S) and (K) cases, respectively. It should be noted that the effectiveness of the bootstrap method can be influenced by the size of the original set of observations. In other words, the original sample with size of 44 (general set) provides possible bootstrap samples that are richer than the subsets with 8 observations. However, the number of observations equal to 8 can still be considered large enough to be used as a reliable input for the bootstrap analysis [28].

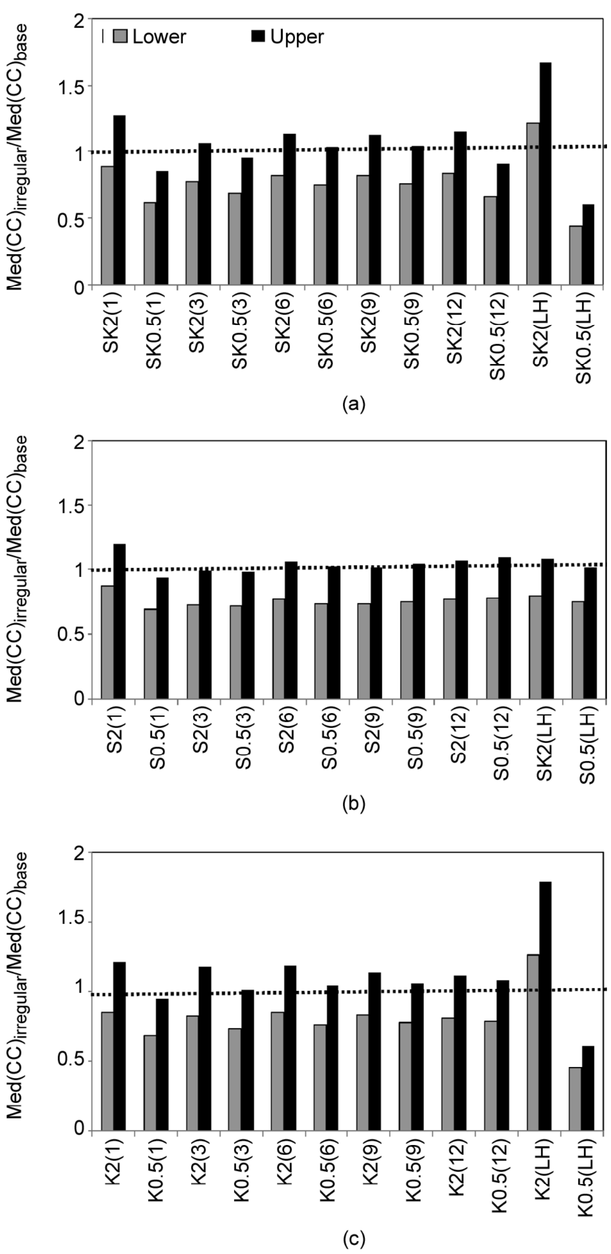

Figure 14. Bootstrap 90% confidence intervals on the collapse capacity estimation normalized to the base frame values by subset 6 for: a) combined strength-stiffness, b) strength and c) stiffness irregular frames.

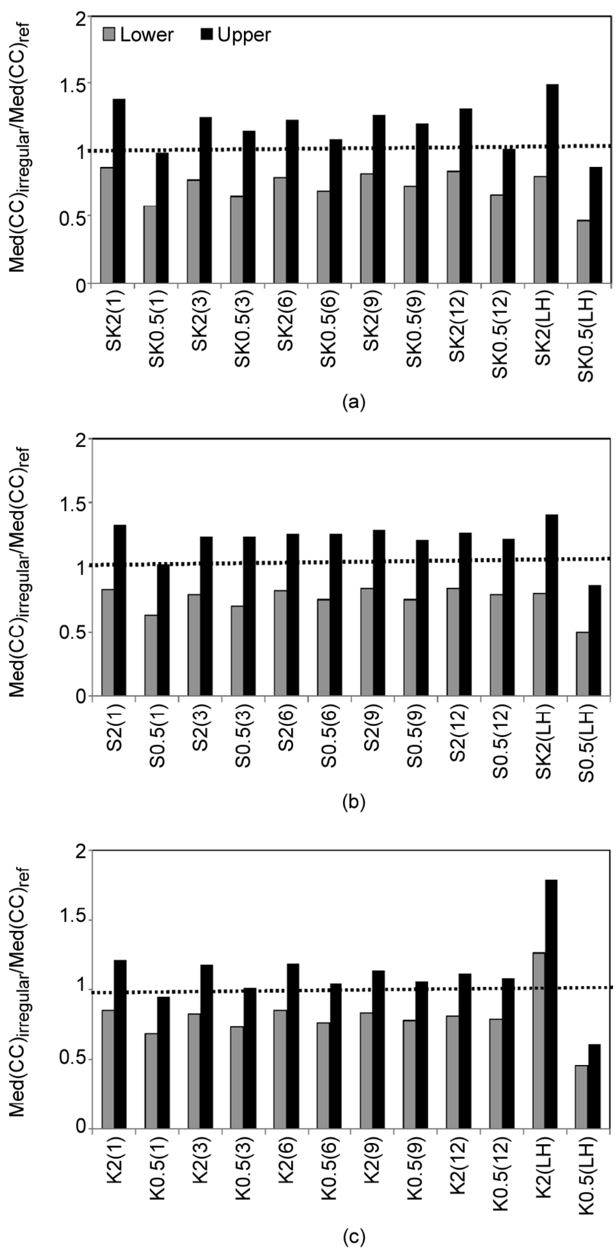

Figure 15. Bootstrap 90% confidence intervals on the collapse capacity estimation normalized to the base frame values by subset 4 for: a) combined strength-stiffness, b) strength and c) stiffness irregular frames.

6. Conclusions

A recently proposed structure-specific ground motion selection method is evaluated by means of collapse simulation of a series of vertically irregular 2-D frames. The selection scheme introduces eight selected SGMRs according to the first modal period of the target structure. The efficiency of method in the estimation of collapse capacity through well-known IDA approach is investigated. By applying the stiffness, strength and combined stiffness-strength irregularity with the factors of 0.5 and 2, modified frames have been constructed. Following the latter process for stories 1, 3, 6, 9, and 12 as well as the lower half of the benchmark 12-storey frame; a total of 37 structural models have been constructed. Using a general set of 44 ordinary SGMRs, 1626 IDA have been performed. The most important results are:

- The collapse capacity of a single story irregular frame can be improved/reduced by upgrading/degrading the stiffness values. The strength modification in a single story with the exception of first story can result in the reduction of collapse capacity. This observation needs more investigation to be characterized; however, statistical hypothesis testing has confirmed it as an artefact of vertical irregularity. The combined stiffness-strength irregularity resembles the combination of both single modifications.
- The change in collapse capacity of a vertically irregular frame in its whole lower half can be considered as the magnified generalization of the observed changes due to the first story modifications.
- Dispersion in the estimated capacities is reduced by using any selected subset of eight SGMRs from a total of 44 that implies the reduction of the record-to-record variability as a result of structure-specific selection process. The latter trend is not observed for multi-story modifications.
- The best subset is the same proposal of selection method based on the first modal period producing mean deviation of 5% with the maximum of 16% from the estimations computed by the general set.
- Two other subsets (#1 and #3) are ranked in the next places based on their acceptable performance in the prediction of collapse capacities. These subsets are the suggestions of selection methods for the third and second modal periods of frames; however, an exclusive investigation must be conducted to verify the presence of such correlations.
- Bootstrap method is utilized to check the level of confidence in attributing the observed results to the vertical irregularity rather than characteristics of SGMRs. Results confirms the validity of conclusions in more than 58% of cases. The most probable case to be sensitive to the SGMRs is the combined modification in stiffness and strength, where, different failure mechanism may be involved in the collapse of frames. The bootstrap results for predictions by subset 6 confirms its ability in representing the general set based on the computed pattern of 90% confidence intervals similar to the general set.
- Although the results confirm the efficiency of selection method in the case of vertically irregular frames, the conclusions cannot be generalized to the structures with significant higher mode effects, because, the irregularity patterns will not necessarily result in a frame which its dynamic behavior is not dominated by first mode of vibration.

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