PROBABILISTIC ASSESSMENT OF VERTICAL IRREGULARITY EFFECTS ON THE SEISMIC PERFORMANCE OF STEEL MOMENT RESISTING BUILDINGS

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ABSTRACT

In this paper, the effects of different types of structural vertical irregularities on the seismic performance of steel moment resisting frame structures are evaluated based on the probabilistic approach. For this purpose, the seismic performance of structures with geometric and non-geometric vertical irregularities are assessed by studying (i) the limit-state capacities, (ii) the mean annual frequency of exceeding different limit-states and (iii) the confidence levels in meeting performance objectives. The results have shown that the non-uniform distribution of lateral resisting properties over the height of structure (i.e. the non-geometric vertical irregularities), influences the seismic performance levels close to collapse prevention (CP) onto global dynamic instability (GI) limit-states. These irregularities can affect the seismic intensity capacity and/or the ductility capacity of the structure based on the type and the position of vertical irregularities. In addition, the assessment of structures with geometric vertical irregularities (i.e. setback structures) demonstrates the poorer seismic performance of these code-designed structures relative to the regular structure, depending on the ratio of irregularities. The confidence levels to satisfy the LS performance objective for the studied code-designed setback structures is decreased more than 10%, compared to the regular structure. It is shown that the more respective limitations for vertical irregular buildings may be essential in the current seismic design code, in order to improve the seismic performance reliability of this type of buildings.

INTRODUCTION

In the past decade of earthquake engineering science, the probabilistic seismic performance assessment of structures has grown as a measurement for predicting the reliability of structural systems under seismic excitations. This methodology assesses the structural performance of buildings by probabilistic estimation of the responses under ground motion records. In particular, the estimation of the mean annual frequencies (MAFs) of exceeding the structural performance levels and the confidence level for satisfying the performance objectives has been applied as a decision making framework for design and assessment of common regular structures (Cornell et al., 2002). On the other hand, the prediction of the seismic performance of structures with special features such as vertical irregular buildings is important for earthquake engineers from viewpoint of designing new structures or rehabilitating existing vulnerable buildings. In general, vertical irregularities can be classified as non-geometric and geometric irregularities. In the geometric irregularity, the plan dimensions suddenly change over the height of building but in the non-geometric irregularity, the distribution of seismic lateral resisting properties, such as mass, lateral stiffness and strength, individually or in combination is non-uniform throughout the height of the building. The non-geometric vertical irregularities appear in the buildings due to such conditions as different use of one floor compared to the adjacent ones or elimination of lateral resisting elements such as column, brace or shear wall in the parking or other stories due to architectural compulsions. The main types of geometric irregularities are setback buildings. Setbacks may be introduced for several reasons. The three most common ones are architectural regulations for tall buildings that entail upper floors to be set back to admit light and air to adjoining sites, program requirements that necessitate smaller floors at the upper levels, or stylistic requirements related to the building form. The lower level of a setback building with the largest floor area is usually termed the base, while the upper level with the smallest floor area is the tower. Setback buildings can be classified as one-side or two-side setbacks, based on their configurations. If the floor area of the tower is reduced from one side of the base floor plan, the structure is called a one-side setback structure, which is always asymmetric about the vertical axis of the structure. Therefore, a torsional response arises in these types of structures due to the eccentric location of the tower center mass/stiffness with respect to the base center mass/stiffness. On the other hand, if the floor area of the tower is reduced from two sides of the base floor plan, the structure is called a two-side setback structure.

Most seismic codes enclosed limiting criteria for vertical irregular structures in order to prevent the discontinuity problems in these structures. Some seismic codes such as ASCE (2006) do not permit to design the structures with extreme stiffness and strength vertical irregularities for very high seismic zones. Furthermore, when irregularity exceeds certain nominal limit, the linear response spectrum analysis is necessitated by most seismic codes. The definitions of vertical irregularities in the third edition of Iranian seismic codes (2010) have very similarities with UBC97 (1997) except that the geometric vertical irregularity does not exist in this seismic code.

Experiences from the past earthquakes have shown that the vertical irregular buildings may exhibit inadequate behaviour in spite of being designed according to the seismic codes (Duan and Chandler 1995). In fact, it is known that introducing a soft and/or a weak story lead to increase the drift demands in this story and some adjacent stories (Chintanapakdee and Chopra 2004); but there is still not confident about the limit values to distinguish regular from irregular buildings and also about the adequacy of simplified seismic code design procedures when applied to vertically irregular structures. A review on the recent studies indicates that the vertical irregularities can influence the seismic performance of structures, depending on the limit-state or the level of seismic intensity considered (Fragiadakis et al. 2006; Pirizadeh and Shakib 2013). In this study, a probabilistic reliability-based approach is used for seismic performance evaluation of vertically irregular buildings. For this purpose, the effects of geometric and non-geometric vertical irregularities on the seismic performance of steel moment resisting frame buildings are investigated by studying (i) the limit-state capacities, (ii) the mean annual frequency of exceeding different limit-states and (iii) the confidence levels in meeting performance objectives.

STRUCTURAL MODELS

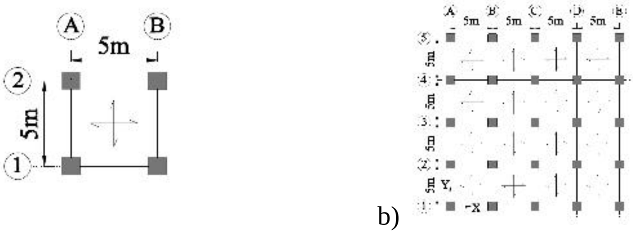
The regular structures used in this study are 10-story buildings with plan shown in Figure 1. The height of the stories is 3 meters, and the plan bay widths in two directions are equal and assumed to be 5 meters. The floors consist of rigid diaphragms. The lateral force resisting system in two orthogonal directions of the structure is special steel moment resisting frame. The fully restrained moment connections are assumed to be cover-plated flange type. The regular structures are designed for a very highly seismic zone with a site-specific earthquake acceleration of 0.35 g (Tehran) according to the Iranian Seismic Code (2010), in which the life safety performance level for the hazard level of 10% probability of exceedance in 50 years is satisfied. The structures are modeled three-dimensionally for nonlinear analyses. The inelastic behavior of beams and columns is modeled by the formation of lumped plastic hinges at their ends. The effects of axial loading on the column bending strength are considered with P-M-M interactions. The component backbone curve for fully restrained moment connections is modelled at the ends of beams. The panel zone deformations of the joints are modeled by an inelastic element according to Krawinkler's model. The cyclic deterioration of components is modeled by assuming a moderate cyclic deterioration in the loading and unloading stiffness in the beam, column and panel zone components (Pirizadeh, 2013). The seismic performance of structures (regular & irregular) are evaluated by using the incremental dynamic analysis (IDA) method, under a set of 20 earthquake records according to the methodology adopted by Pirizadeh and Shakib (2013).

The structural models for non-geometric and geometric vertical irregularities are considered as the following:

NON-GEOMETRIC VERTICAL IRREGULAR STRUCTURES

Vertical irregular structures are modeled by changing the distribution of seismic lateral resisting properties (lateral stiffness and strength) along the height of the regular structure (i.e. the structure with the plan shown in Figure 1a). For this purpose, the stiffness or strength of the story, in which the irregularity is imposed, is changed by a modification factor. The modification factor is defined as the ratio of stiffness or strength of the irregular story to that of the above story.

In this study, the stiffness, strength and combined stiffness & strength vertical irregularities with level of 60% in three different locations including bottom half stories of structure, first bottom story and middle story of structure have been investigated. The cases of vertical irregularities that are considered in this study are shown in Figure 2, where the three types of irregularities considered are denoted as K (stiffness), S (strength) and KS (combined stiffness & strength). The modification factor for each case is indicated inside the parenthesis and then, the story or stories, in which the irregularity occurs, has been mentioned. For example, K(0.6)1:5 refers to the stiffness irregularity with level of 60% in the stories 1 to 5. In the comparison between the regular and irregular structures, the only variable are considered to be the distribution of lateral resisting properties. Therefore, the main specifications of regular and irregular structures (including the fundamental period, yield base shear and damping properties) are kept the same by uniform scaling of all stories (The coefficients α, β and λ in Figure 2). It is notable that the fundamental period of these irregular structures and corresponding regular structure are equal to 2.01 sec.



a) b)

Figure 1. Plan of the regular structure for investigating: a) non-geometric, b) geometric vertical irregularities

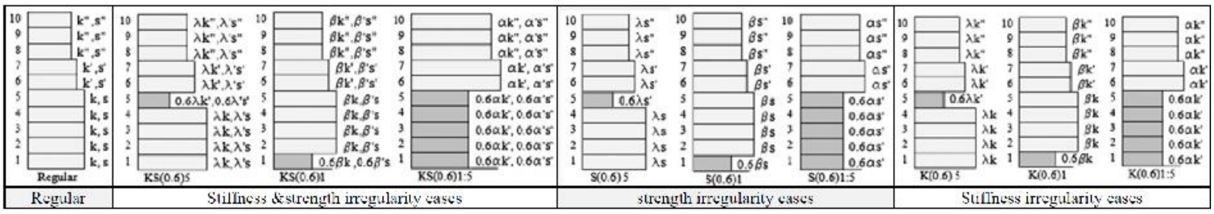


Figure 2. The cases of vertical irregular structures (The distribution of stiffness and strength over the height of irregular structures in comparison with the regular structure)

GEOMETRIC VERTICAL IRREGULAR STRUCTURES

For investigating the effects of geometric vertical irregularities, the regular building is the 10-story structure with the plan shown in Figure 1b. The setback structural models considered are 12 different structures with 25% (one missing bay along the X structural axis), 50% (two missing bays) and 75% (three missing bays) reductions in the floor area. The setbacks occur in different height levels at the 3th, 5th and 7th stories of the structure. These setback configurations are defined by two ratios, R_A and R_H. R_A (the area setback ratio) is defined as the relative area of the tower to base, and R_H (the height setback ratio) is defined as the relative height of the tower to base (Shahrooz and Moehle, 1990). The setback ratios considered are R_A = 0.25, 0.5, 0.75 and R_H =3/7, 5/5, 7/3, such as shown in Figure 3. Three cases of structures have symmetric setbacks about the vertical axis of the structure (two-side setback) and the other cases have asymmetric setbacks (one-side setback). The setback structures have geometric vertical irregularities in accordance with the seismic codes such as ASCE (2006). Despite the symmetric plan of setback buildings, a torsional irregularity exists in at least one of the base stories of the one-side setback structures with R_H =5/5 and 7/3.

In the design of regular and setback structures, there are no compulsions in the seismic codes for implementing nonlinear analysis methods. Therefore, these structures are designed on the basis of the linear response spectrum analysis method by applying the orthogonal combination procedure, as detailed in Pirizadeh (2013). All structures are designed in such a way that the maximum estimated inelastic drift ratio response of structures under the design response spectrum is approximately close to 0.02 (i.e. the maximum allowable inelastic response lateral drift ratio according to the Iranian seismic code (2010)). The fundamental period of the code-designed regular structure is equal to 2.59 sec and the fundamental period of the code-designed setback structures vary from 2 sec to 2.4 sec.

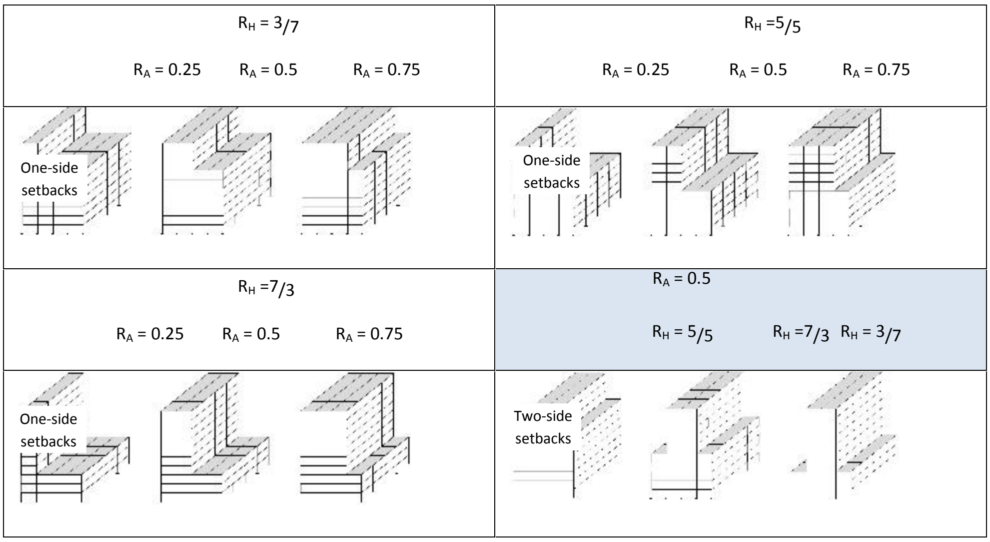


Figure 3. 3D view of the geometric vertical irregularities (setback structures)

SEISMIC PERFORMANCE EVALUATION OF THE NON-GEOMETRIC VERTICAL IRREGULAR STRUCTURES

For investigating the effects of non-geometric vertical irregularities on the seismic response and capacity of the structure, the median IDA curve of each case of irregular structures is compared with the corresponding curve of regular structure according to Figure 4. According to this figure, in the cases of stiffness, strength and combined stiffness & strength vertical irregularities, when these irregularities occur at the bottom first story or at the bottom half stories, the irregular structure exceeds the CP and GI limit-states at the lower inter-story drift ratio capacities in comparison with the regular structure. It means that the global collapse and especially global dynamic instability will be formed earlier in these types of irregular structures. These types of vertical irregularities lead the structure to exceed the limit-state of global dynamic instability at the minor inter-story drift ratio values; while regular structure has the capacity to resist larger inter-story drift ratio values until exceeding this limit-state. In other words, irregularity causes that the structure cannot be able to make use of its reserve ductility at the limit-states away from collapse. For investigating this pattern, the profile shape of the peak inter-story drift ratio along the height of the regular and three cases of irregular structures is plotted for four intensity levels in Figure 5. The first intensity level is selected such that the elastic response of structures can be observed and the other intensity levels are selected in the ranges that cover the structural responses close to CP onto GI performance levels. For each intensity measure (IM) level, the peak inter-story drift ratio from time history response of each story is read and the median value of peak inter-story drift ratios across all scaled records is evaluated. Then, the story-to-story profile of the median peak inter-story drift ratios is plotted in this figure for each of structures. According to this figure, in the cases of strength and combined stiffness & strength vertical irregularities, when the position of these irregularities located in the first story of the structure, the maximum drift moves from the middle stories of the regular structure towards the bottom stories of the irregular structure. It is notable that due to the low story strength and stiffness ratio of these stories respect to the upper stories, and also due to the major axial loads in the columns of bottom stories, the plastic hinge rotation capacity of the columns components and as a result, the ductility of these stories are less than those of the upper stories. Therefore, by concentrating higher drifts in these stories, the irregular structure cannot make use from its ductility capacity, especially near the collapse until the dynamic instability. Therefore, an earlier global dynamic instability occurs in these irregular structures respect to the regular structure. According to Figure 4, the influence of stiffness vertical irregularities on the median IM capacity of the structure is negligible (less than 2%); but the strength and combined stiffness & strength irregularities decrease the median IM capacity of the structure up to 10% in the inelastic limit-states based on the position of these irregularities. In the limit-states between IO onto CP, the IM capacity of structure is more influenced when the position of irregularities located at the middle stories of structure. However in the limit-states over CP onto GI; it is more influenced by bottom story irregularities. According to Figure 5, the shape of drift profile at lower intensity levels (< 0.3g) is significantly changed in the cases which have stiffness vertical irregularity types such as K(0.6)1:5 in a way that the maxima of drift ratio profile shifts towards the soft stories. Whereas, at higher intensity levels (>0.55g), the cases which have strength vertical irregularity types, such as S(0.6)1, alter the shape of drift profile by shifting the maxima towards the weak stories. Thus, in the combined stiffness & strength irregularities, maximum deformation occurs in the neighborhood of the soft and weak stories at all ranges of intensity levels.

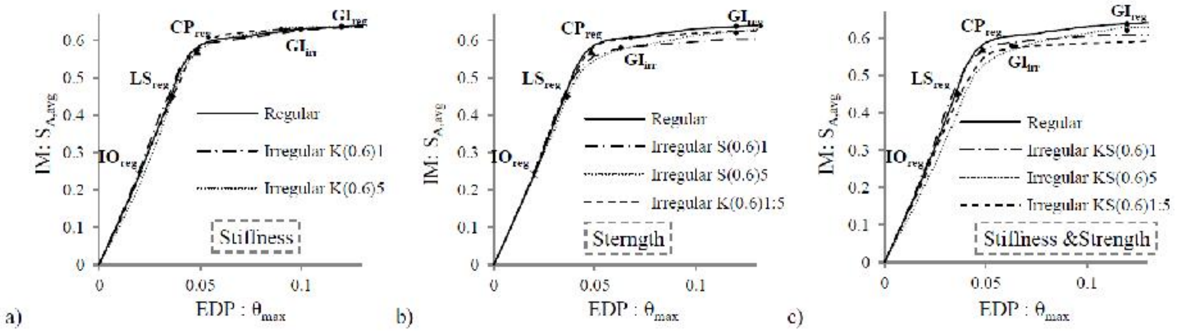


Figure 4. The median IDA curve of various vertical irregular structures in comparison with regular structure

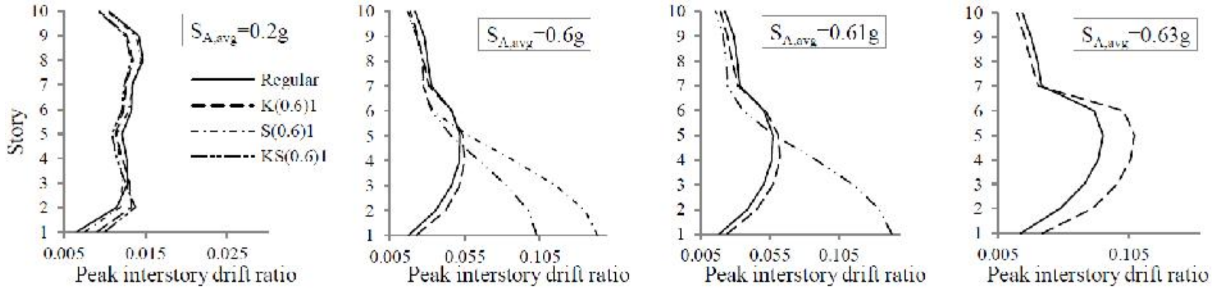


Figure 5. The distribution of demand along the height of structures with various types of vertical irregularities in the lowest story (story 1) in comparison with the regular structure for four intensity levels

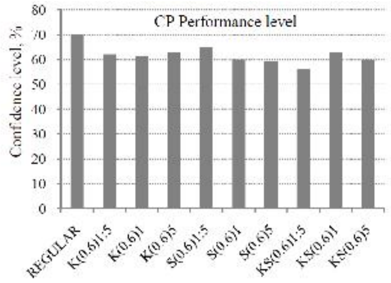


Figure 6. The confidence level for the CP performance level for the 2/50 hazard level

Following the seismic performance evaluation of irregular structures, the confidence levels for satisfying the CP performance objectives are calculated for different irregular structures as shown in Figure 6. According to this figure, the confidence level of the regular structure for satisfying the CP performance objective is about 70%. However, the non-geometric vertical irregularities lead to decreasing the confidence levels of satisfying these performance objectives. According to Figure 6, the confidence levels of satisfying the CP performance objective for the irregular structures are obtained in the range of 80% to 95% of that of the regular structure. Keeping in mind that the main specification of irregular and regular structures are kept the same in these comparisons, so the confidence levels are decreased just for this reason that the stiffness or strength distributions are non-uniform over the height of these structure. Now, by considering the fact that the presence of stiffness and strength vertical irregularities in the structures is usually associated with the reductions in the total capacity of structures, we should expect the more reductions in the confidence levels of performance objectives of the actual vertical irregular structures with respect to these amounts.

SEISMIC PERFORMANCE EVALUATION OF GEOMETRIC VERTICAL IRREGULAR STRUCTURES

In this section, the influence of the presence of setbacks, as the main type of geometric vertical irregularities, on the seismic performance of steel moment resisting frame structure are investigated. For this purpose, the median IDA curves of the code-designed structures with different setback ratios are compared to the regular structure in Figure 7. According to this figure, the median IM capacities of the setback structures over the entire range of limit-states are lower than that of the regular structure. Also for a certain level of IM, the maximum inter-story drift ratio demands of setback structures are larger than the value for the regular structure. However this status is more serious in one-side setback structures with respect to the two-side setback structures, which is mainly due to the torsional responses that arise in the one-side setback structures under two orthogonal components excitation. Therefore, it can be said that the presence of setbacks (i.e., geometric vertical irregularities) decreases the capacity of structure and the torsional effects of one-side setbacks (i.e., torsional plan irregularities) intensify this problem. Based on the results, the direct compulsion for simultaneous application of orthogonal ground motion to the geometric vertical irregularities, such as one-side setback structures seems to be necessary because the simultaneous influence of two horizontal ground motion components on the seismic performance of these structures is obtained significant over the entire range of structural responses from the elasticity to global instability (Shakib and Pirizadeh, 2014).

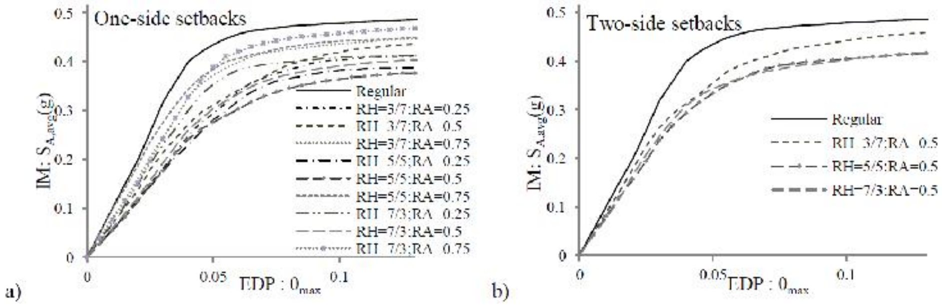


Figure 7. The median IDA curve of various setback structures in comparison with regular structure: a) one-side, b) two-side setbacks

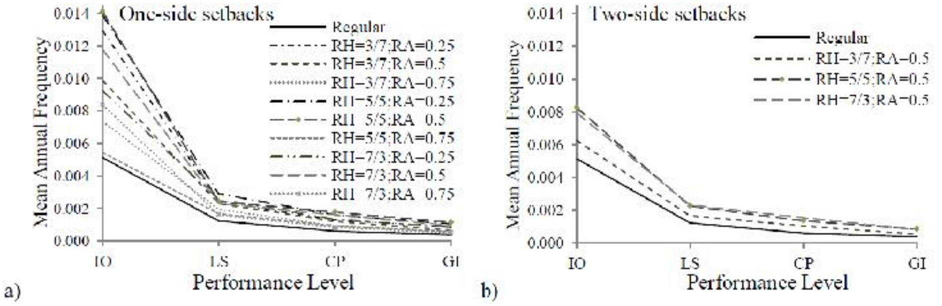


Figure 8. The probabilistic performance curve of various setback structures in comparison with the regular structure a) one-side, b) two-side setbacks

The probabilistic performance curves of structures with different setback ratios are compared to that of the regular structure in Figure 8. According to this figure, the probability of exceeding limit-states for all setback structures is increased to that of the regular structure. The MAFs of the one-side setback structures are between 1.1 to 2.7 times that of regular structure for the IO and LS performance levels, based on the ratio of setbacks. For CP and GI performance levels, the ratios of the MAFs of one-side setback structures to the MAF of the regular structure are obtained from 1.5 to 2.9, based on the ratio of the setbacks. These patterns are more predominant at lower area setback ratios (i.e., R_A=0.25,0.5), which correspond to backing the tower floors more than 50% of the plan dimensions of the lower floors. Moreover, the ratio of the confidence level to satisfy the LS performance level against the 10/50 hazard level is shown in Figure 9, for each setback structure to that of the regular structure. According to this figure, the confidence levels of satisfying the LS performance objective for the two-side setback structures are obtained in the range of 70% to 85% of that of the regular structure and in the range of 50% to 85% of that of the regular structure for the one-side setback structures. Therefore, the seismic performance assessment of setback buildings, designed according to the current code procedures, demonstrated that these procedures cannot be expected to satisfy the reliability requirements in this type of irregular structures compared to the regular structure. In fact, the geometrical configuration of setback structures caused to increase the seismic demands of these structures under the certain intensity level of seismic excitation, compared to the regular structure. This issue was not recognized in designing setback structures by using the linear spectrum method, the method is allowed by most seismic codes. Therefore, the revision of the current seismic code provisions for geometric vertical irregularities seems to be essential to stipulate the explicit compulsions for implementing more accurate analysis methods for predicting the seismic response of structures with critical setback ratios, such as proposed in Pirizadeh and Shakib (2015).

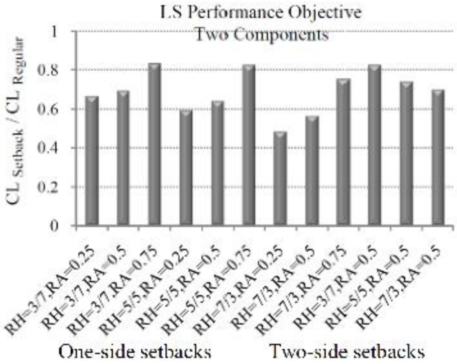


Figure 9. The ratio of confidence level of setback structures to that of the regular structure to satisfy the LS performance objective

CONCLUSIONS

In this paper, by using the probabilistic performance-based earthquake engineering approach, the effects of geometric and non-geometric vertical irregularities on the seismic performance of steel moment resisting frame structures was evaluated in terms of the limit-state capacities, the mean annual frequency of exceeding different limit-states and the confidence level of performance objectives. The assessment of the seismic performance of vertically irregular buildings indicated that the limitations for this type of buildings should be defined preferably in accordance with: (i) the expected performance objective for structure, (ii) the level of seismic intensity, (iii) the diverse positions of irregularities over the height, (iv) the numbers of vertically irregular stories, (v) the combined action of non-geometric and geometric vertical irregularities with the torsional irregularities.

Moreover, the following main conclusions were derived:

- The non-uniform distribution of lateral resisting properties over the height of structure, in spite of fixing the main specifications of the structure, influences the seismic performance levels especially over the CP onto GI limit-states. These effects maybe on the seismic intensity capacity and/or on the ductility capacity of the structure; based on the type of vertical irregularity and its position over the height of the structure.
- In the stiffness, strength and combined strength & stiffness vertical irregularities, when the position of these irregularities is in the bottom stories of the structure, the CP and specially GI limit-states occur earlier (in the lower drift capacities) in comparison with the regular structure. These vertical irregularities cause that damage concentration shifts towards the bottom stories and so the structure cannot make use of its reserve ductility at the limit-states away from the collapse. This effect is more predominant in the strength and the combined strength & stiffness vertical irregularity types.
- The stiffness, strength and combined stiffness & strength vertical irregularities with level of 60% lead to decreasing the confidence level of structure for satisfying the CP performance objective by about 5 to 14%.

Therefore, the extreme soft story and extreme weak story irregularities shall not be permitted to design especially for high and very high seismic zones.

- The seismic performance assessment of setback buildings, designed according to the current code procedures, demonstrated that these procedures cannot be expected to satisfy the reliability requirements in this type of irregular structures.
- The confidence levels to satisfy the LS performance objective for two-side setback structures are obtained in the range of 70% to 85% of that of the regular structure and in the range of 50% to 85% of that of the regular structure for the one-side setback structures. The greatest influences on the confidence level of structures are observed in the low area setback ratios (R_A=0.25;0.5), which correspond to pulling back the tower floors more than 50% of the plan dimensions of the base floors.
- The revision of seismic code provisions for geometric vertical irregularities seems to be essential to stipulate the explicit compulsions for implementing more accurate analysis methods for predicting the seismic response of structures with critical setback ratios. Also, the geometric vertical irregularity limitations for one-side setback structures should be defined more restrictively with respect to two-side setback structures due to the torsional responses that arise in these types of buildings.

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