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Evaluation of Seismic Behavior of Irregular Structures in Plan and Height by Using Non-Linear Static Analysis

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Abstract

According to the architectural and operational considerations and creation of a variety of irregularities in plan and height of buildings, studying seismic behavior of these buildings has always been in the center of researchers' attention. This study investigated seismic behavior of irregular buildings in plan and height by using non-linear static analysis. Selected irregularities were defined to evaluate in two ways including geometric irregularities in plan and height as well as mixing these two mentioned ones. Irregularities in plan were defined in one direction and with two values of low and high. Irregularity at height was created through recession on one direction of building in two stairs. In addition, some buildings were taken into account with mixed irregularities in plan and height in low and high forms. Defined irregular buildings were designed by three types of systems including special steel flexure frame, special steel flexure frame with special converged bracing, and special steel flexure frame with special concrete sheer wall by using ninth and tenth sections of national regulations. After designing mentioned buildings in PERFORM 3D, non-linear static analysis was performed in both directions.

Keywords: seismic behavior, geometric irregularity in plan, non-linear static analysis

Introduction

Irregular buildings form a large part of modern urban infrastructure. Many people are involved in structure construction including owners, architects, structure engineers, contractors, and urban planners and collaborate to design the map, select structural system (structural configuration) which might lead to irregularity distribution in mass, stiffness and resistance in structure height. When such structures are located in regions with high seismicity, the role of structure engineers is highlighted. Thus, structure engineer needs to have a comprehensive understanding of seismic response in irregular structures (Al-Ali, & Krawinkler, 1998). Nowadays, seismic Building Codes regarding irregular buildings are being revised and reviewed due to increased usage of different types of irregularities in structures as a result of architectural measures and particular structure use. 2800 Standard is sued as the main reference of seismic design of structures in Iran (ASCE, 2010).

Analytical methods fall into two categories including linear and non-linear. Each of these methods is performed by two ways of static and dynamic. Generally, speaking, performance behavior and estimation of a structure need to be studied by non-linear dynamic analysis and according to certain and proportional acceleration mappings. However, non-linear dynamic analyses have been limited to some certain projects due to complexity, strong hardware computer requirement, time-taking, costly analyses, and difficulties to justify and interpret the results. Therefore, a simpler and more applicable method such as Pushover analysis which is a non-linear static analysis can meet many mentioned problems. In fact, Pushover analysis is the analysis of step-by-step yield process in structure critical points which has received the noticeable attention of researchers and engineers in order to study the real behavior of structure under earthquake in the last few decades (Romão, Costa, Delgado, 2004).

By using Pushover analysis, we are able to determine yield sequence, ductility capacity, and structure lateral resistance and predict structure weaknesses and introduce treatment methods to

improve structure performance. In Pushover analysis, the structure is analyzed under step-by-step rising lateral load. Equation 1 shows a sample of Pushover diagram for a structure (PERFORM 3D, PERFORM, 2011)

In terms of behavior, we can simulate and compare the behavior of soft ground floor with a base isolation. In building with soft story, ground story columns act similar to base isolators and their base sheer carrying capacity of building (V0max) is equally limited to flexural strength:

$$V_{0max} = \frac{\sum M_y}{\frac{H}{2}} \quad (1)$$

In addition, various earthquake experiences show that, like buildings with base isolation in upper stories of soft ground floor (equal base isolator), no damage is created in these buildings. The big problem in these buildings is the creation of large defamations in soft story which is greater than ductility capacity of flexural columns of the story which lead to the creation of large plastic rotations and destruction in joints where the maximum moment occurs. Plastic joint rotation is accessible at the end of soft story columns through the following equation:

$$\theta^0_{max} = \frac{\delta^0_{max}}{H} \quad (2)$$

According to above equations, behavior of buildings with soft ground floor under lateral loads can be displayed by base sheer diagram against lateral displacement as Figure 1.

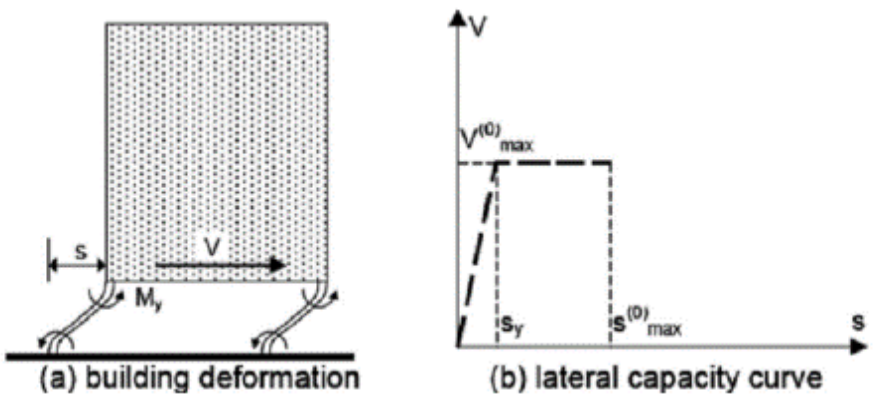

Figure 1: Soft story lateral displacement and structure capacity diagram

In order to study the seismic behavior of structures with soft story as well as the seismic effect of building infill on behavior of such structures, a 5-story building was taken into account with lateral seismic resistant system of steel flexural frame but various configurations concern presence or absence of infill. The story height of structure was reported 3 meters in both models. Also, structure, in the first model, had infill in all stories except for the first floor (Humar, & Wright, 1977). The second model specifications are similar to those of the second structure. The only difference was in absence of building infill in this model and the structure was modeled without infill. Designing frames was performed according to the third version of Iran 2800 Standard and Iran Steel Code. A view of Plan, infill layout, and structure configuration are presented in Figure 1.

Background of study

Farhani and Parvari (2009) studied the seismic behavior of special steel flexural frames with irregular mass distribution at height (PERFORM 3D, PERFORM, 2011).

This assessment was performed with linear and non-linear structure analysis, static, and dynamic methods. To this end, as many as 28 frames were studied in 2-D form and frames had the following properties: the number of stories were reported 6, 12, 18, and 24; irregular story locations

were first, middle, and roof; and irregular story mass to neighboring story ratio (50% and 100%) were considered as variables. The result indicates the fact that story mass rise leads to relative displacement increase of stories and plastic joint rise in irregular story and in particular in irregularity of the last story. That is why beams and columns of irregular stories and the surrounding need to be strengthened and mass rise in roof floor should be avoided.

Another research conducted by Akbar Pour, Javari, and Torabi who studied the behavior of irregular metal system in terms of stiffness at height for flexural steel frames with coaxial bracing (ASCE, 2010).

In this paper, we used equivalent static and spectral dynamic analysis methods to analyze structures against earthquake equivalent force. Also, dynamic parameters of structure including modes, effective weight of mode, etc. were compared to regular and irregular structures.

In this paper, different steel buildings with medium flexural frames and mixed system of medium flexural frame with coaxial bracing in three heights of 3, 6, 9, and 12 stories and three 4-meter spans were modeled and analyzed. Story height was considered constant (3 meters) in all models. All sections were considered for IPB and IPE for columns and beams respectively (Chintanapakdee, & Chopra, 2004).

Chintanapakdee and Chopra (2004) studied the effect of irregularities in stiffness distribution and resistance along with the structure height in order to evaluate story drift demand (relative story displacement) and displacement responses of stories (ETABS HELP, 2010). To this end, they considered 48 2-D frames in which all were 21 stories and they were designed with the philosophy of strong columns and weak beam (joint model in beam). Three types of irregularity were reported in specification distribution of frames along the structure height:

- Stiffness irregularity
- Resistance irregularity
- Mixed hardness and resistance irregularity

Statement of Problem

Center of mass and center of stiffness do not sometimes coincide due to architectural reasons and application method of building and the structure is considered irregular. The asymmetry of the structure occurs due to unbalanced distribution of stiffness due to the asymmetric posture of wind braces in plan and sometimes due to unbalanced distribution of mass. Both states lead to creation of eccentricity and accordingly, torsion in structure. The failures in common Codes in terms of performance evaluation of steel structures against earthquake have led to the fact that performance-based design or Capacity Spectrum Method (CSM) are taken into account in order to raise a building with predictable performance against various earthquakes. Miri and Maramaee conducted a research on 5-story steel building with various percentages of symmetry along x and y due to stiffness change in structure. Buildings were initially designed and then non-linear static analysis was performed. Finally, performance level of structures was obtained (Applied Technology Council, 1996).

Generally, it is concluded that, in 6-story models, non-linear behavior of structure declines by cornice percentage rise up to 19% as well as critical joint percentage; however, non-linear behavior of structure improves by irregularity rise in structure and critical joint percentage declines for values more than 19% of cornice. Thus, L models do not generally have clear behavior (Applied Technology Council, 1996).

While determining horizontal and height configuration, allowed Code range along with common design size need to be taken into account. For steel flexural frames, the number and length of frame span as well as story height are the main physical features for model configuration. In this

study, the height was considered 2.3 meters for all heights. Models had 10 floors. Also, 4 spans were considered in each direction and span length was considered 6 meters in both directions like Figure 2.

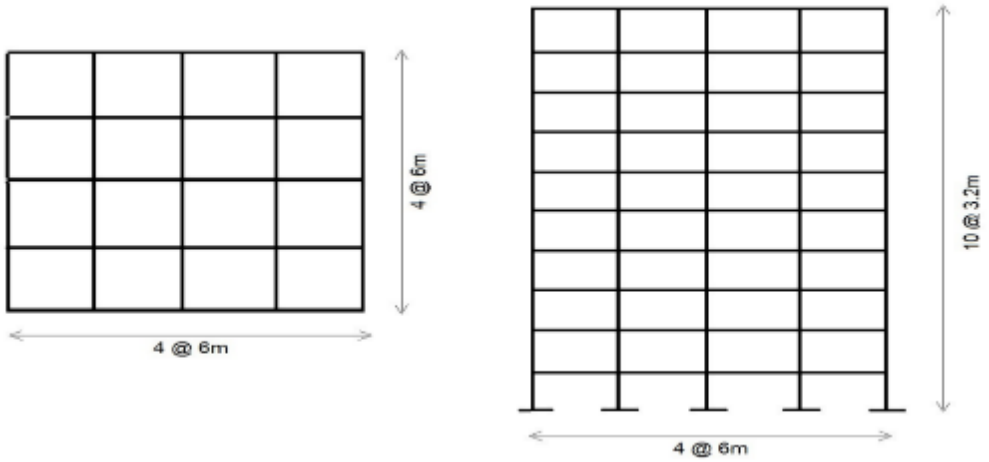

Figure 2: The number and length of frame span

Elements in models should well reflect lateral resistant structural system. Like for instance, sections of beams and columns along with type and sections of bracings are regarded in brace frames. In this study, IPE was considered for beam sections and flexural connection for beam and column link. Box-shaped sections were used for sections of columns. Face-to-face double channel sections were used which form a box. The introduced sections were selected based on Table 1. Since the objective of this study was to compare the design results by non-linear methods and common type methods which are used for beams and columns, sections will be used in type form after story or span-based floors (Federal Emergency Management Agency, 2000).

After selecting and introducing different patterns in Table 1, we need to design the patterns optimally and logically in order to clarify frame sections. Since the most important section of design is loading patterns, loading pattern is explained. To perform analyses, semi-dynamic or spectral method was used. First, design spectrums are drawn and then sheer base and internal forces are obtained through these spectrums. In this study, the effect of 30% earthquake load was also taken into account along vertical direction (Chintanapakdee, & Chopra, 2004).

Structure importance coefficient (I):

Building use: residential Degree of importance: Medium I=1

Base acceleration of project (A):

Construction location: Shiraz

Seismicity: High relative risk zone A=0.3

Structure behavior coefficient (R):

Each of buildings will take advantage of a resistant system in both directions against earthquake force. According to the type of building system, this coefficient is different and it will be calculated through Table 1 (Chintanapakdee, & Chopra, 2004).

Table 1. Behavior coefficient of frames in different directions

Building system	Rx , Ry
Special Moment Frame	8
Special Moment Frame + Special Concentrically Braced Frame	7
Special Moment Frame + Shear Wall Frame	7

Designing models

In this section, each of configuration of samples (patterns) are modeled, analyzed, and designed by principles and assumptions in previous sections and AISC Code through LRFD method in ETABS software. Here, a random pattern of SMSC-PH+HH was selected for accurate evaluation. All patterns were designed and evaluated. First, the frame was modeled in ETABS software. Then, the analysis was performed by imposing pre-determined loads. After that, frame element was finalized by controlled resistance criteria and after multiple trial and error cycles, one of the most optimum possible and applied design was used as the sample model. Figure 3. shows a view of 3-D modeling of this frame in the program.

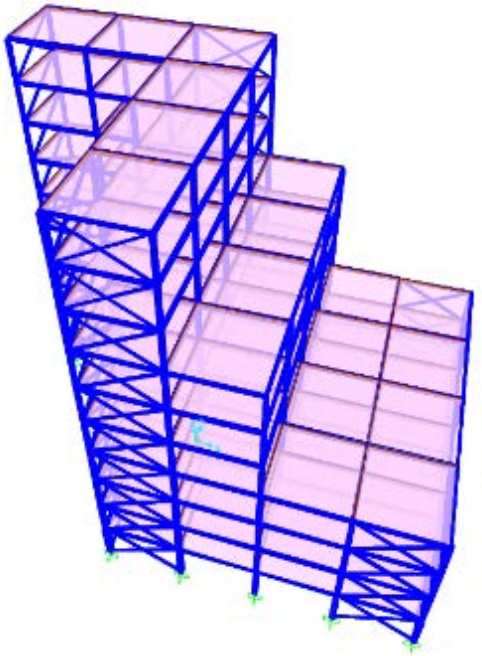

Figure 3: A view of SMSC-PH+HH building modeling in ETABS

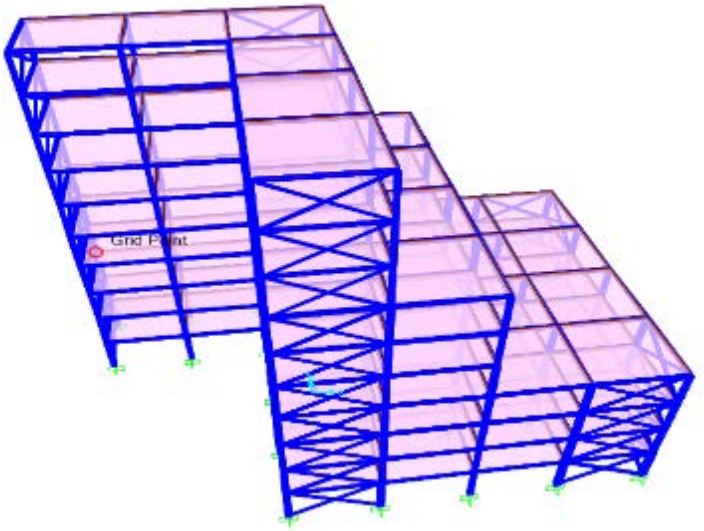

Figure 4: A view of SMSC-PH+HH building modeling in ETABS

After building modeling and complete loading, a set of buildings were analyzed completely according to the given spectrum. First, it is necessary to calculate coordinate coefficient and multiplied by spectrums. Then, final analysis was performed. Thus, the coordination was studied according to 2800 Standard.

Calculation of building base sheer by static method:

$W = DL + 0.2\ LL = 3196.8\ ton$

$V_{static} = C_{x\ or\ y} * W = 0.083 * 3196.8 = 265.33\ ton$

$V_{static,,min} = 0.12 * A * I * W = 0.12 * 0.3 * 1 * 3196.8 = 115.1\ ton$

Column-to-beam resistance ratio control from seismic criteria

The ratio of frame columns to its beams is one of important parameters in building frame performance against vigorous shaking of the earthquake and the forces. The studies show that frames with stronger columns and weaker beams (compared to columns) display better behavior. This is mainly because strong columns enjoy higher ability to make various parts of beams for flexural yield. Accordingly, they lead to frame energy damping power rise. In other words, the section of beams- in which they lose more energy compared to columns in earthquakes- needs to be increased up to capacity limit of weak beam to strong column. Then we increase dimensions of column section. Controlling these criteria is essential for special steel flexural frames and floors except for the roof. This is mainly because of expecting up to 4% drift tolerance in these frames which creates the necessary base for occurrence of extensive plastic deformations in frame. According to seismic Code, the following equations show plastic resistant moment of columns to beams in each joint. Figure 5. also shows the mentioned relationships .

$$\frac{\sum M_{pc}^{*}}{\sum M_{pb}^{*}} \geqslant 1.0$$

$$\sum M_{pc}^{*} = \sum Z_c (F_{yc} - \frac{p_{uc}}{A_g}),,,,, \sum M_{pb}^{*} = \sum (1.1 R_y F_{yb} Z_b + M_{uV})$$

$$\sum M_{pb}^{*} = \sum (1.1 R_y F_{yb} Z_b + M_{uV})$$

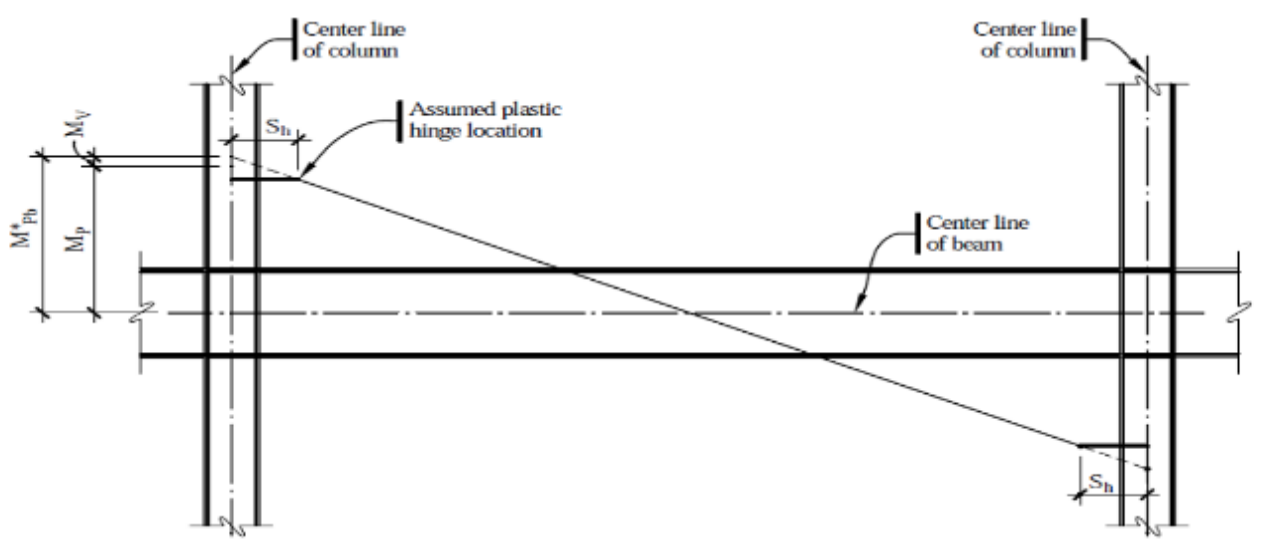

Figure 5: Details of calculating weak beam of strong column

The criteria of weak beam of strong column were calculated for all patterns. Columns were selected in a way that they met this criteria.

Conclusion

In all steel flexural buildings with any types of irregularity, there is at least one element which has reached immediate occupancy performance level of beam, beam safety, beam collapse threshold, and column immediate occupancy performance level before reaching building to targeted drift.

In irregular buildings with steel flexural frame, the maximum base sheer along X axis is considerably more than Y axis, showing overestimated design of elements along irregularity direction (X) compared to other directions.

In all designed buildings with steel flexural frame system, over-strength factor is more in irregular direction (X) than other directions. Over-Strength Factor has been declined for buildings with high and low irregularities in plan compared to Code limit along X (direction of imposing irregularities) and Y. Over-Strength Factor is more in buildings with low and high irregularities at height and high mixed irregularity rather than others.

Push behavior of designed buildings according to steel flexural dual frame and bracing is in a way that buildings have softer resistance loss after reaching the maximum resistance (base sheer) and diagram slope after maximum point is less in buildings with dual systems compared to buildings with steel flexural frames.

In columns of steel flexural buildings, we observe the greatest number of yield in buildings with high irregularities in plan and height. In these buildings, we see high torsion due to the great distance between mass center of floors and stiffness center. Torsion is the reason for great number of yielded columns in these buildings.

Recommendations

Based on the results of this study, the following recommendations can be raised:

- It is stated that beams should be designed for bigger forces in the lower half of floors (first to 5th) or designed beams need to be strengthened according to common Iran Codes in these buildings.
- In buildings with special steel flexural dual frames along with steel convergent bracing, it is essential that the beams in second and third floors and bracings in lower half of building (first to fifth) to be designed with greater coefficient of safety or to be strengthened along the orthogonal direction of imposing irregularities.
- Designed walls in the first and second floors of buildings with special steel flexural frame as well as special sheer concrete wall, and irregularity in plan according to Iran Code have not met performance objectives (safety) and it is necessary that these walls are designed for bigger loads or resistance is improved by common strengthening methods.

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