# A Study on Steel Moment Resisting Frames with Setbacks: Dynamic properties

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**SUMMARY:**
Lots of buildings all over the world include irregularities in Plan or Elevation. A common type of geometrical irregularity in buildings is setback which known as an elevation irregularity. Behavior of building with setbacks still is not understood well. Consequently, to clarify Seismic behavior of buildings with this type of irregularities more researches are required. Although Seismic Design Codes provide provisions for Architectural Configurations, According to the past earthquakes, Irregular configurations either in plan or in elevation exhibited inadequate behavior. In this paper, a number of low to mid rise plane steel moment resisting frames (MRF) with various types of setbacks have been studied. All of plane steel moment resisting frames have been designed according to International Building Code (IBC2006). The major goal is to clarify the effects of different types of setbacks with different conditions on dynamic properties of frames. Results show dynamic properties of frames, i.e. Natural period, Modal participating Mass Ratio, mode shapes are strongly affected by different types of setbacks. Variation of above mentioned properties have been presented & some logical procedure seen between different types of setbacks.

*Keywords: Setbacks, Vertical irregularity, Dynamic properties, Modal Analysis, Natural period*

## 1. INTRODUCTION

Nowadays modern urban construction has a tendency to employ irregular configurations for buildings to satisfy aesthetics sense of human societies. Although irregular buildings may create more attractive urban landscapes, consequences should not be ignored.

Having a glimpse to the earthquake loses, damages are mostly due to architectural design [Harmankaya & Soyluk, 2012]. Seismic design codes have proposed some provisions called “architectural Considerations” to reduce vulnerability of irregular buildings, nevertheless the experiences from past earthquakes have shown that the irregular buildings either in plan or elevation do not sustain earthquake shocks satisfactorily. Seismic design codes categorized irregular buildings to two groups; irregular buildings in plan and irregular buildings in elevation.

A common type of irregular building in elevation is setback. The increasing number of damage statistics after seismic events has provided strong evidence that setback buildings exhibit inadequate behavior though they were designed according to the current state of knowledge existing in existing in seismic codes [Karavasilisa et al., 2008]. Setback buildings are characterized by staggered abrupt Reductions in floor area along the height of the building which result in drops in mass, strength and stiffness along height [Sarkar et al., 2010]. Although some researches performed on setback buildings, on the contrary according to the results, seismic behavior of setback frames is a rather controversial issue since some works indicate adequate seismic performance, while some others show the opposite for those frames [Karavasilisa et al., 2008]. A comprehensive literature review could be find on the reference “Seismic response of plane steel MRF with setbacks: Estimation of inelastic deformation demand”.

Having complicated structural behavior, different behavior factor of irregular buildings i.e. P-Delta effects, inelastic responses, behavior factor, dynamic behavior and etc. should be studied. A number of 5 and 10 story moment resisting frames (MRF) with various types of setbacks which have been designed according to IBC2006 [International Building Code, 2006]. Major Goal of this paper is to find out how the dynamic behavior of buildings affect by setbacks. The results which extracted form modal analysis and response spectrum analysis presented in the following sections.

## 2. A GLANCE AT DESIGN CODES

Seismic design codes have presented a definition for irregular buildings in elevation according to geometry, distribution of mass and stiffness along height and strength. Table 1 shows the brief overview of provisions which related to definition of irregular building in elevation for the considered Seismic design codes which are ASECE7-05, Euro Code 8 (EC8) and Iranian National Building Code [ASCE, 2005; Eurocode 8, 2003; Iranian National Building Code]

**Table 1.** Definition of irregular building in elevation according Seismic Design Codes

<table>
<tr><th></th><th>ASCE7-05</th><th>EC8</th><th>Iranian Building Code</th></tr>
<tr><td>Stiffness</td><td>There is a story in which the lateral stiffness is less 70% of that in the story above or less than 80% of the average stiffness of the three stories above.</td><td rowspan="2">Both the lateral stiffness and the mass of the individual stories shall remain constant or reduce gradually, without abrupt changes, from the base to the top of a particular building.</td><td>There is a story in which the lateral stiffness is less 70% of that in the story above or less than 80% of the average stiffness of the three stories above.</td></tr>
<tr><td>Mass</td><td>Effective mass of any story is more than 150% of effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.</td><td>distribution of mass along height should be almost constant and effective mass of any story should not vary more 50% of adjacent stories, otherwise it is irregular in elevation</td></tr>
<tr><td>Strength</td><td>The story lateral strength less than 80% of that in the story above.</td><td>—</td><td>Same as ASCE7-05</td></tr>
<tr><td>Geometry</td><td>In-Plane Discontinuity in Vertical Lateral Force-Resisting Element Irregularity is defined to exist where an in-plane offset of the lateral force-resisting elements is greater than the length of those elements or there exists a reduction in stiffness of the resisting element in the story below.</td><td>When setbacks are present, building is regular if:<br>a) for setbacks preserving axial symmetry, the setback at any floor shall be < 20 % of the previous plan dimension in the direction of the setback (Figure 1.a and 1.b).<br>b) for a single setback within the lower 15 % of the total height of the main structural system, the setback shall be< 50 % of the previous plan dimension (Figure 1.c).<br>c) For setbacks do not preserve symmetry, in each face the sum of the setbacks at all stories shall be <30 % of the plan dimension and the individual setbacks shall be < 10 % of the previous plan dimension (Figure 1.d).</td><td>–</td></tr>
</table>

According to the Table 1, despite EC8 take into account setback buildings more clearly, Two other codes did not pointed setback buildings directly. Furthermore EC8 decrease behaviour factor for irregular buildings to 80% of Corresponding regular building.

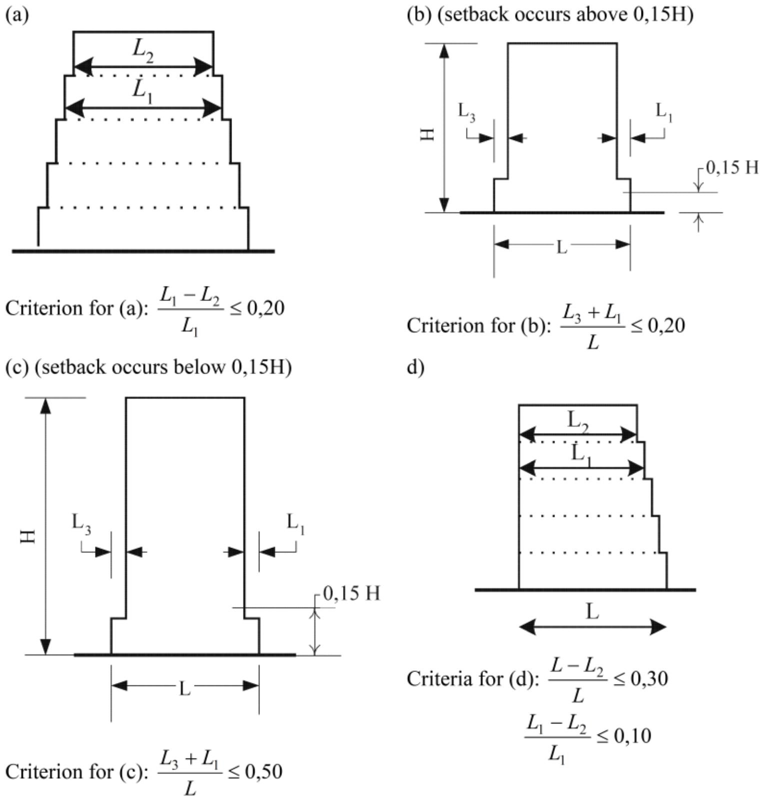


**Figure 1.** Criteria for regularity of buildings with setbacks according to EC8 [Eurocode 8, 2003]

The codes recommend dynamic analysis (Response Spectrum Analysis) for the design of all buildings with irregular form. The codes also require the base shear obtained in the dynamic to be scaled up to the base shear corresponding to the fundamental period as per the code specified empirical formula [Sarkar et al., 2010]. Empirical fundamental natural period of vibration is given by:

$$T = C_t H^x \tag{1}$$

Where, T is fundamental period of vibration (in Seconds) and H is the height of the building (in meter). $C_t$ And x are related to structural system which may differ by different building codes. Table 2 shows the suggested values by each Design code. This empirical equation (Eq.1) does not account irregularities in elevation or plan and is a function of Height and lateral bearing system.

**Table 2.** Parameters of empirical formula for calculation of fundamental period of vibration

| | ASCE7-05 | EC8 | IRNBC |
|---|---|---|---|
| Ct | 0.0724 | 0.085 | 0.08 |
| x | 0.8 | 0.75 | 0.75 |

## 3. STEEL MOMENT RESISTIG FRAMES USED IN THIS STUDY

The study is based on 34 steel frames which are categorized in two groups of 5 and 10 stories and with story heights and bay widths equal to 3.3 and 5.0 meter respectively (**Figure 2**). Numbers of bays are constant and equal to 5 bays for all frames and various types of setbacks considered in models. The first and the eleventh frames are regular in elevation with 5 and 10 stories respectively. Other models are irregular in elevation due to different types of setbacks. Response spectrum method hired for analysis of these frames and minimum required modes considered. Modal combination implemented using CQC method. As mentioned above all of 34 models have been designed according to IBC2006.

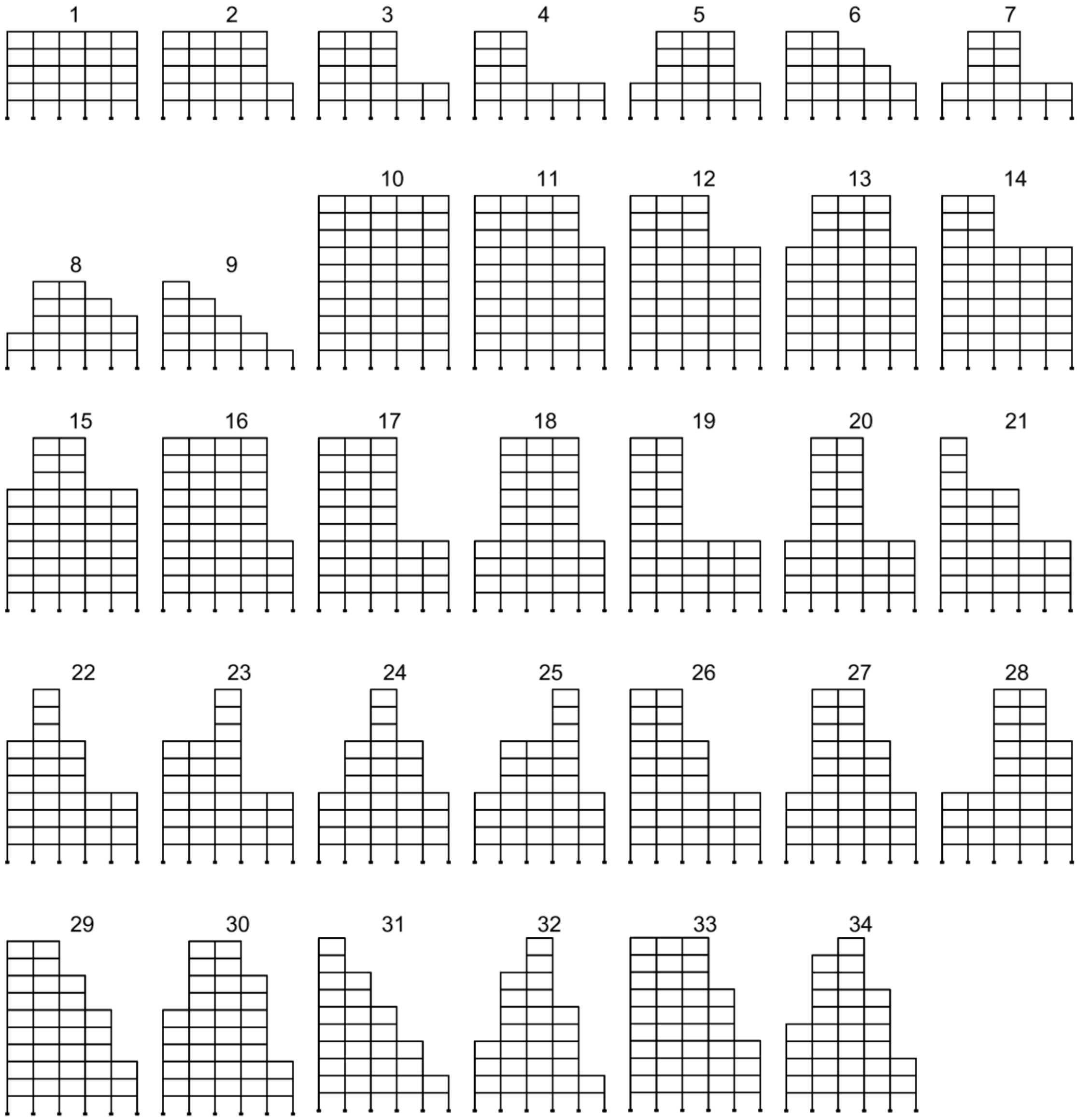


**Figure 2.** Geometries of the setback steel MRF considered in this study

## 4. ANALYSIS OF STEEL MOMENT RESISTIG FRAMES

Design codes recommend dynamic analysis (Response Spectrum analysis) for irregular buildings with the base shear scaled up to the value corresponding to the fundamental period as per the code specified empirical formulas.

**Table 3**. Fundamental Period of Vibration obtained by Empirical equation

| Model | H (m) | T (s) | | |
|---|---|---|---|---|
| | | ASCE7-05 | EC8 | IRNBC |
| 5 Story | 16.5 | 0.68 | 0.70 | 0.65 |
| 10 Story | 33 | 1.19 | 1.17 | 1.10 |

As mentioned in section two, the empirical equation of fundamental period of vibration (Eq.1) does not account irregularities in elevation or plan and is only a function of Height and structural system which means frames with same height and structural system should have same fundamental period of vibration (Table.3) while Modal analysis results proved that the fundamental period of vibration is not only a function of height.

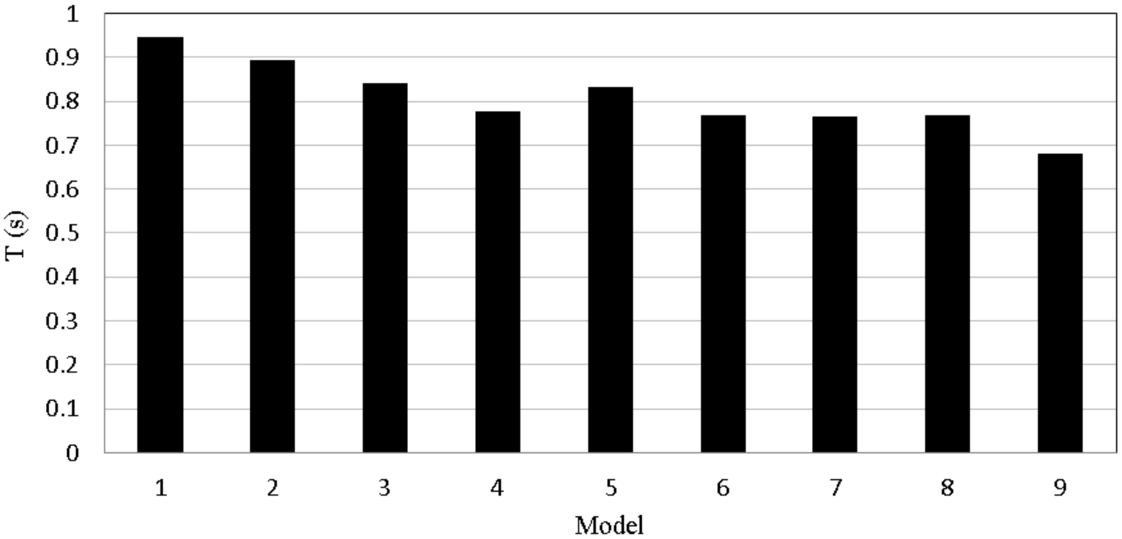


**Figure 3.** Fundamental period of vibration for 5 Story models obtained by Modal analysis

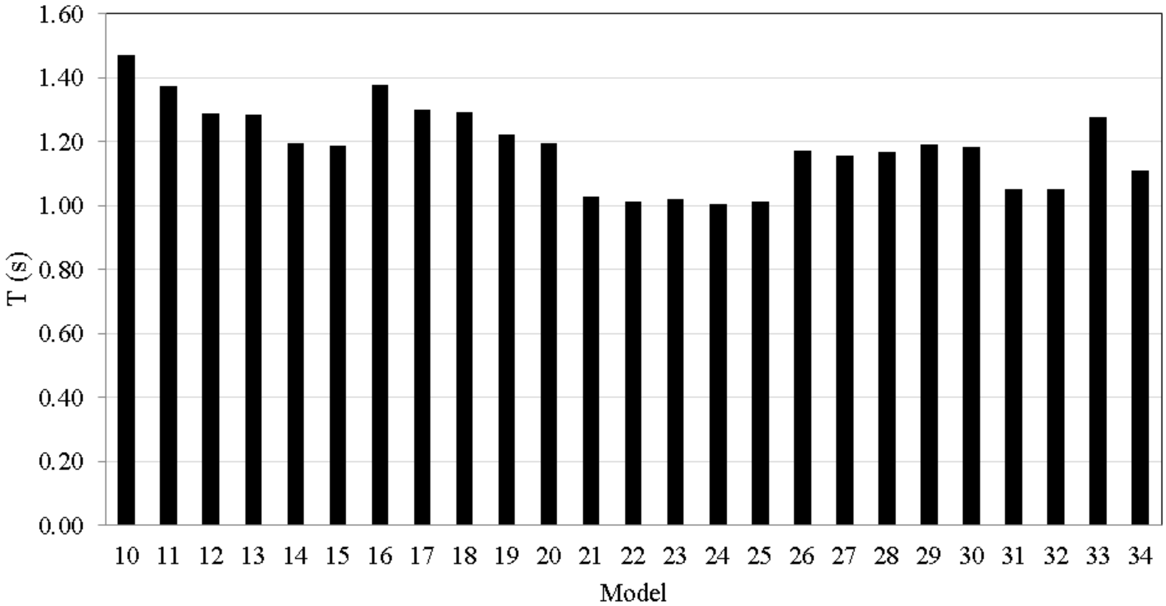


**Figure 4.** Fundamental period of vibration for 10 Story models obtained by Modal analysis

**Figure 3** and **Figure 4** show the fundamental period of vibration obtained by modal analysis (analytical value for fundamental Period of vibration) for 5 and 10 story frames respectively. Coefficient of variation (CV) for fundamental period of vibration are 10% and 11% for both groups of 5 and 10 story steel MRF respectively. Variations of fundamental periods of vibrations for both 5 and 10 story frames are considerable which means in addition to height and structural system, another factor affects the fundamental period of vibration. Therefore, the empirical equation of fundamental period (Eq.1) has to be modified to include effects of setbacks. Sarkar et. al. [Sarkar et al., 2010] proposed a method to Estimation of fundamental period of vibration for stepped buildings which considers effect of irregularities.

Effective modal mass is another factor which describes dynamic properties of a structure. Regular and low rise buildings tend to behave on their first mode of vibration while irregular and high rise buildings behave on a combination of their modes of vibration. **Figure 5** and **Figure 6** show the effective modal masses for the first three modes of vibrations of 5 and 10 story frames respectively. Variations of Effective modal mass for different models indicate the effect of geometrical configuration on dynamic behaviour of buildings.

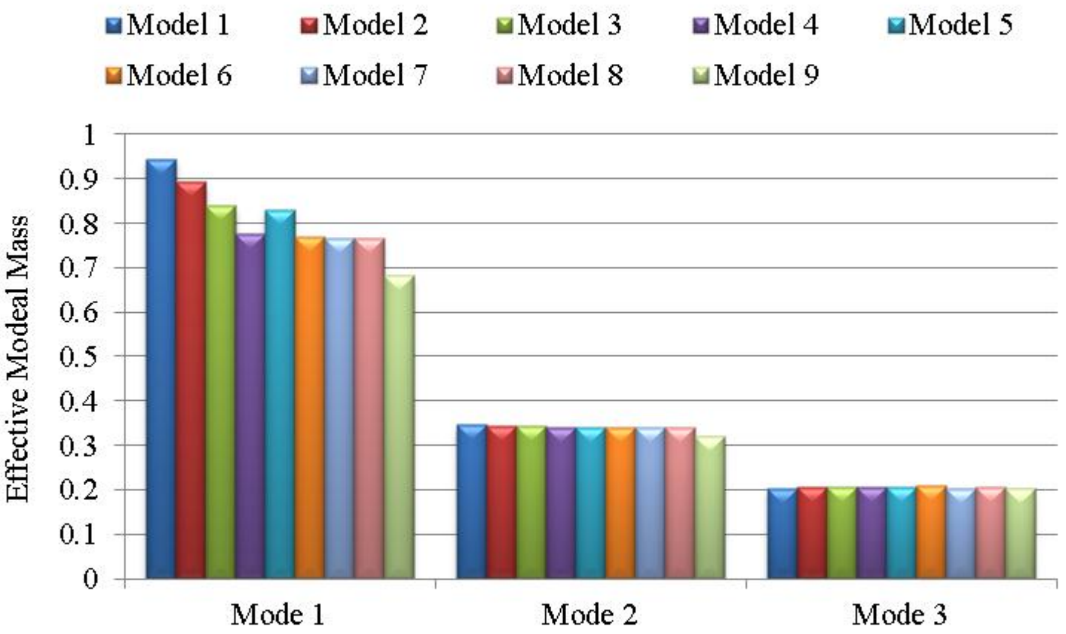


**Figure 5.** Effective modal mass for the first three modes of vibration of 5 story frames

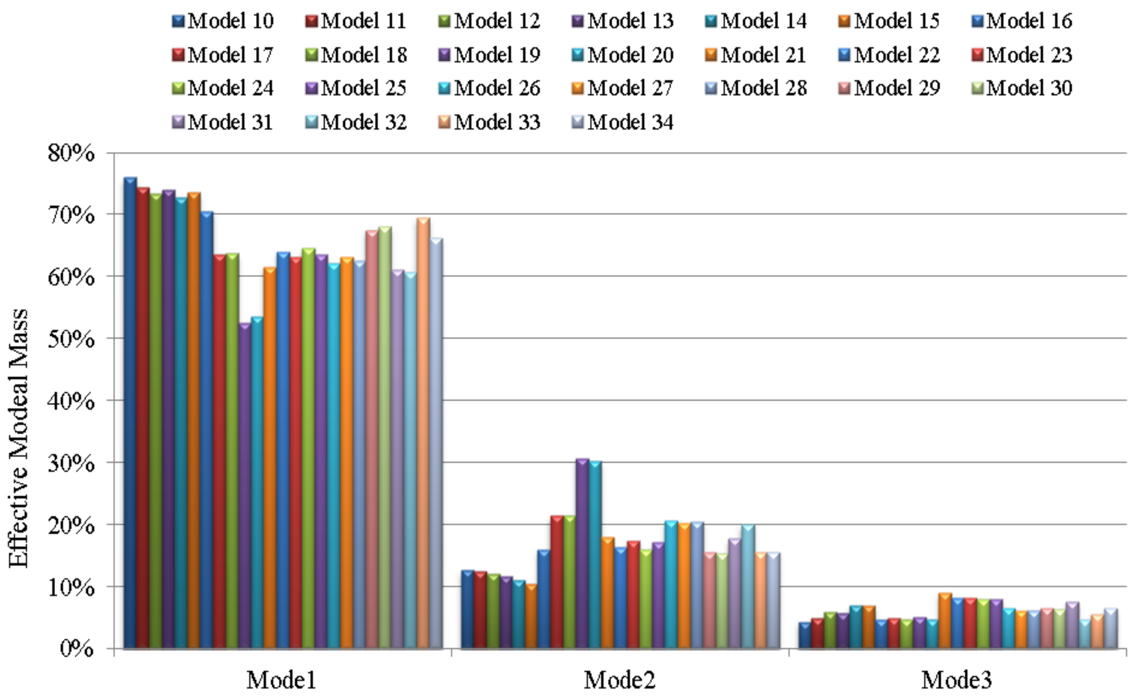


**Figure 6.** Effective modal mass for the first three modes of vibration of 10 story frames

Vertical distribution of seismic force is another factor that strongly depends on dynamic behaviour of building. **Figure 7** and **Figure 8** show normalized pattern for vertical distribution of seismic force for some of the 5 and 10 story frames which obtained from Response spectrum analysis. Various forms of patterns of vertical distribution of seismic force imply that shape modes of vibration are strongly depending on geometry of frames. Irregular models experience higher story forces and base shear which caused by decreasing fundamental period and participation of higher modes in addition to first mode. Furthermore participation of higher modes result in considerable variation of distribution of seismic force in elevation. Symmetric models experience lowest base shear and story forces while increase of asymmetry effects the base shear and story forces adversely.

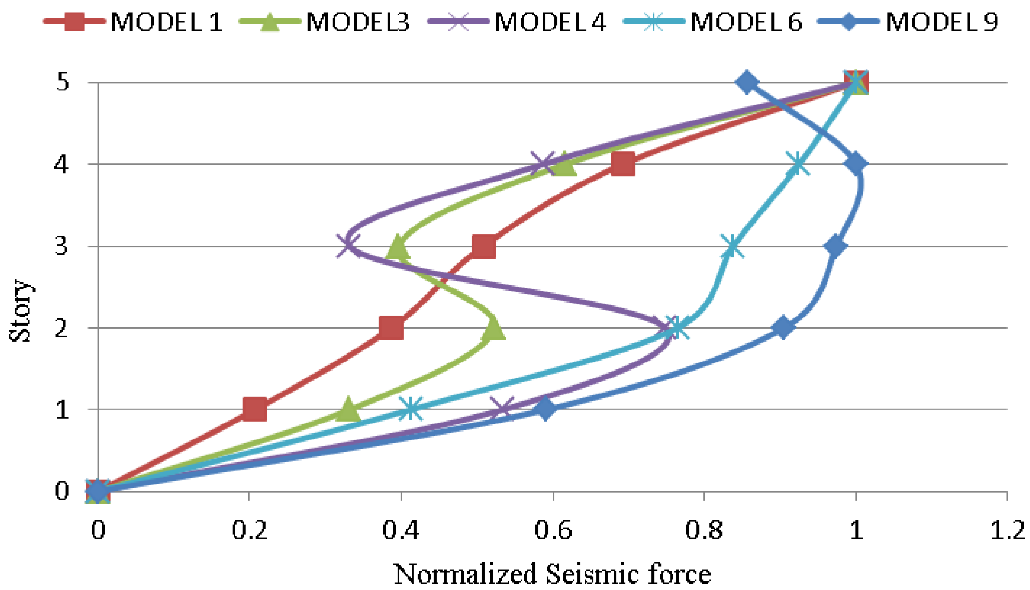


**Figure 7.** Normalized vertical distribution of seismic force for 5 story frames

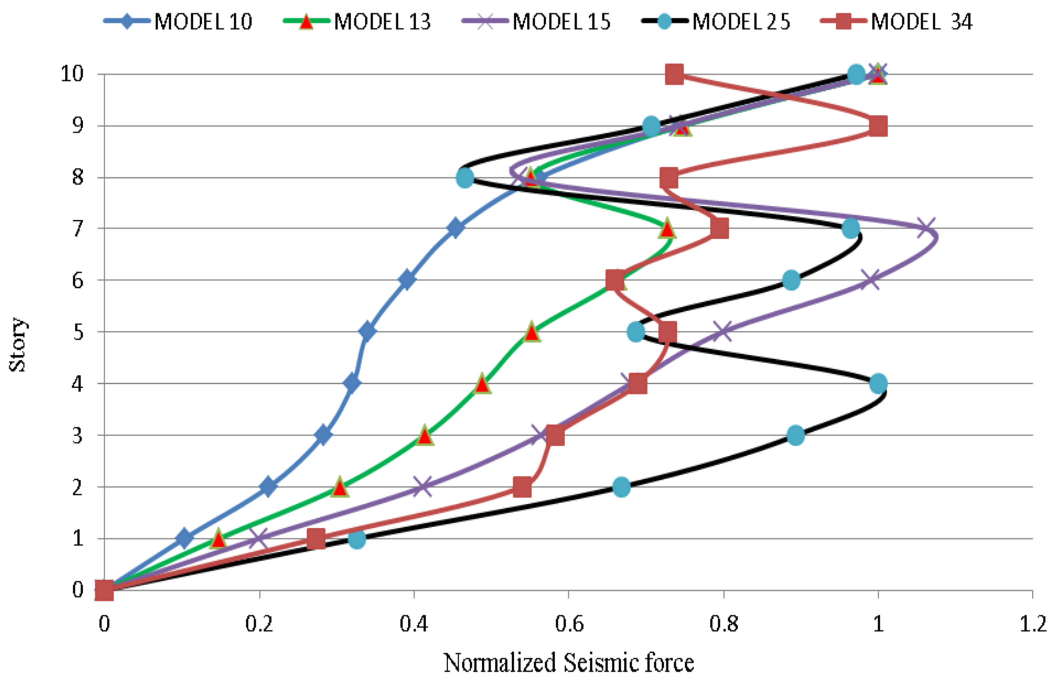


**Figure 8.** Normalized vertical distribution of seismic force for 10 story frames

## 5. CONCLUSION

In this paper a number of 5 and 10 story steel moment resisting frames with various types of setbacks, which was designed according to IBC2006, have been studied. Response spectrum and modal analysis performed using the well-known software SAP2000. Experiences of past earthquakes have shown the vulnerability of irregular buildings specially buildings with setbacks. As a result, The codes recommend dynamic analysis (Response Spectrum Analysis) for the design of all buildings with irregular form and the base shear have to be scaled up to the value corresponding to the fundamental period calculated by empirical formula which is only a function of height and lateral bearing system.

Fundamental period for all frames calculated by both empirical formula and analytical method. The fundamental periods of vibration obtained by modal analysis show that setbacks affect the fundamental period of Steel MRF and this effect is considerable which means Seismic design codes have to consider these effects which is ignored currently.

In addition to fundamental period, effective modal masses for different types of setbacks vary considerably, which is due to changes of distribution of mass and stiffness along height. Furthermore, setbacks strongly affect vertical distribution of seismic forces and base shear. Increase of asymmetry result in more story forces and base shear.  Moreover, results show that, the equivalent static methods are not qualified for analysis of setback buildings at all, which have mentioned by seismic design codes. Although EC8 has some points for setback buildings, ASCE7 and Iranian National Building Code have not pointed setback buildings directly.

To sum up, irregular buildings especially setback buildings need to be design more carefully to avoid seismic loses and codes have to improve provisions related to these buildings. In addition, procedures have to be designated for rehabilitation of existing setback buildings.

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