EARTHQUAKE INDUCED AMPLIFIED LOADS IN STEEL INVERTED V-TYPE CONCENTRICALLY BRACED FRAMES

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ABSTRACT

This study focuses on exploring the seismic axial loads for columns in steel inverted V-type concentrically braced frames (INV-V) under strong ground motions. For this purpose, the increases in axial loads are investigated for specified earthquake. Two types of low and medium-rise inverted V-type concentrically braced frame are designed according to the seismic design requirement in ASCE 7-10 and AISC 341-10 . Two sets of ground motions representing moderate and severe having 10% and 2% probability of exceedance are used in nonlinear first mode incremental dynamic time history analyses. The results are presented in terms of axial load amplification factors (Ω_0) in braced by columns, drift rations and first story column capacities under the selected ground motions and axial load-moment levels in columns.

KEYWORDS: Amplification Factor, Seismic Design, Concentrically Braced Frame

1. INTRODUCTION

During the last two decades, many steel structures with modern steel concentrically braced frames (SCBF) suffered from unexpected structural damages which ended up with changes in steel building design. One of the major innovations in design code is to consider amplified earthquake effects on steel building design. The amplification factor Ω_o, is used to estimate for the lateral strength of a steel building. It varies from 2.0 to 3.0 and based on structural system. Lateral strength of a structure can be defined as the maximum lateral force that the building can resist during a strong ground motion. In earthquake resisting systems, (shear walls, moment frames, braced frames) strength of the columns under axial compression and tension are determined by using load combinations including amplified seismic load. [1]. The requirements in the specification are mostly based on engineering judgement and a comprehensive analytical investigation is urgently needed to justify these requirements. Seismic codes require that column stability should be checked under amplified seismic loads.

Seismic design procedure introduced in ASCE 7-10 (2010) defines some coefficients such as response modification factor (R values), deflection amplification factors (C_d values), and system overstrength factors (Ω_o values). ASCE 7-10 (2010) acknowledges that structures will be loaded beyond their elastic range during strong ground motions. R is related to the ductility and can be calculated by the cross product of overstrength factor and ductility reduction factor, which is the ratio of the story drift if the structure remained entirely elastic for design earthquake ground motion to the story drift corresponding to actual strength [2]. C_d is defined as the ratio of the inelastic story drift corresponding to design earthquake ground motion divided by the design displacement; i.e. C_d is a fraction of R. Ωo is the ratio of actual strength (V_{max}) divided by the design strength (V) (Fig. 1). Conceptually, the columns and connections should be designed for forces corresponding to V, but stability of the columns should be maintained under V_{max}.

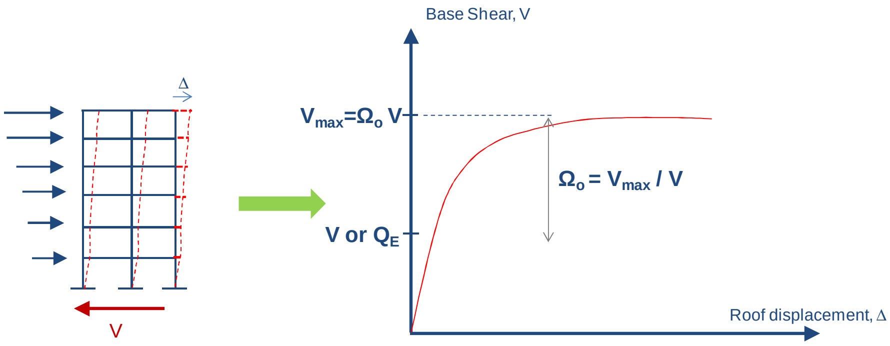

Figure 1. Schematic illustration of amplified seismic load, Ωo.

This study focuses on exploring the seismic axial loads for columns in steel inverted V-type concentrically braced frames (INV-V) under strong ground motions. For this purpose, the increases in axial loads are investigated at the maximum lateral load level and the corresponding lateral displacement. The results are presented in terms of drift ratios, amplification factors (Ω_0) of braced by columns under the selected ground motions and axial load-moment levels in columns. Two steel inverted V-type concentrically braced frames with 4- and 8-stories having a same lateral span length representing typical low and medium rise steel buildings are designed based on the seismic design requirement in ASCE 7-10 and AISC 341-10 . An ensemble of ground motions range from moderate to severe are selected to identify the seismic response of each frames. Two sets of ground motions corresponding to 10% and 2% probability of exceedance are used in nonlinear first mode incremental dynamic time history analyses.

2. AMPLIFIED SEISMIC LOADS IN ASCE PROVISIONS

ASCE 7-10 (2010) Seismic Provisions is required to be applied for structures in Seismic Design Categories D, E, and F and Seismic Design Categories A, B, and C when using R > 3. Seismic Design Category is based on a classification assigned to a structure based on its occupancy or use. Basic LRFD load combinations including earthquake-induced forces (horizontal and vertical), “E”, are given in ASCE 7-10 (2010) as follows:

$$1.2D + 1.0E + 0.5L + 0.2S \quad (1)$$

$$0.9D + 1.0E \quad (2)$$

For load combinations in Eq. 1 and Eq. 2, E is given in Eq. 3 as:

$$E = \rho Q_E \pm 0.2S_{DS}\, D \quad (3)$$

ρQ_E in Eq. (3) takes account for the effects of horizontal earthquake forces, whereas $0.2S_{DS}$ D is simply intended to account for the effects of vertical ground accelerations. Q_E is the effect of horizontal earthquake-induced forces; S_{DS} is the design spectral acceleration at short periods; D is the dead load effect; L is the live load effect; S is the snow load effect; ρ is the redundancy factor that depends on extent of redundancy in the seismic lateral resisting system (≈1.0~1.5). Replacing E in Eq. (3) with Eq. 1 and Eq. 2 results in:

$$(1.2 + 0.2S_{DS})D + 1.0\rho Q_E + 0.5L + 0.2S \tag{4}$$

$$(0.9 - 0.2S_{DS})D + 1.0\,\rho Q_E \tag{5}$$

Note that the $0.2S_{DS}$ term in Eq. 4 and Eq. 5 simply modifies the dead load factor. Amplified seismic loads are defined by multiplying the horizontal portion of E by Ω_o. Thus, E in Eq. 3 becomes:

$$E = \Omega_o Q_E \pm 0.2S_{DS}\,D \tag{6}$$

$$(0.9 - 0.2S_{DS})D + \Omega_o Q_E \tag{7}$$

It is important to note that the amplified seismic load is only used where called for in the Seismic Provisions [1]. The magnitude of Ω_o depends on the structural system and is given in Table 1 [3]. $\Omega_o Q_e$, is intended to provide approximately lateral strength of a frame (Fig. 1). The maximum lateral force that a structure will experience during the earthquake is defined by the structure's lateral strength. Thus, $\Omega_o Q_e$ provides an estimate of the lateral strength of a structure.

Table 1. Overstrength Factors, Ωo, in ASCE 7-10 (2010)

Structural System	t_o
Moment Frames (special moment frames, intermediate moment frames, ordinary	3
Concentrically Braced Frames (special concentrically braced frames, ordinary concentrically braced	2
Eccentrically Braced Frames	2
Special Plate Shear Walls	2
Buckling Restrained Braced Frame	2/2.5

3. ANALYTICAL STUDY FOR AMPLIFIED SEISMIC LOAD EFFECTS

2.1 Description of the Buildings

Two typical steel inverted V-Type braced frames with 4- and 8stories, representing typical low - and medium-rise steel buildings were designed based on the seismic design requirements for Concentrically Braced Frame (CBFs) in accordance with ASCE 7-10 , AISC 360-10 , AISC 341-10. The plan dimensions of buildings are (width) 45 m and (depth) 45m with constant span length of 9.0 m (five equal spans) for all stories.

The typical story height for the 4- and 8- stories frame is 4.0 m and the height of ground for the 8-story frame is 5.0 m in Fig. 1, 2, 3, and 4. For the 8- story building, concrete foundation walls and surrounding soil are assumed to prevent any significant horizontal displacement of the structure at the ground level, i.e. the seismic base is assumed to be at the ground level. The linear analysis of buildings are applied by using Load and Resistance Factor Design (LRFD) specification in accordance with AISC 360-10 standard. Dead loads including self-weight of the members and live load used in the study are 5.0 kN/m^2 and 2.4 kN/m^2 in except at the roof level, where it is 4.0 kN/m^2 and 1.4 kN/ m^2, respectively European wide flange profiles are preferred with quality of S355. The yield stress of braces in the building are preferred with quality of S275. The structural system for each building consists of steel perimeter inverted V-TYPE braced frames and interior simply-connected framing for gravity, i.e. lateral loads are carried by perimeter frames and interior frames are not explicitly designed to resist seismic loads in the direction of the earthquake.

Shear wave velocity (V_s) of site class is between value of 300 m/s and 770 m/s. These ground motions were scaled to comply with the response spectra given in Fig. 5. The acceleration time histories are given in Fig.s 6, and 7. Design response spectrum curve are developed in accordance with ASCE 7-10 as indicated in Fig. 5. Modal Response Spectrum Analysis are used in seismic design based on the structure's seismic design category D. Also, Equivalent Lateral Load Procedure are calculated to compare the base shears and if needed, forces are scaled.

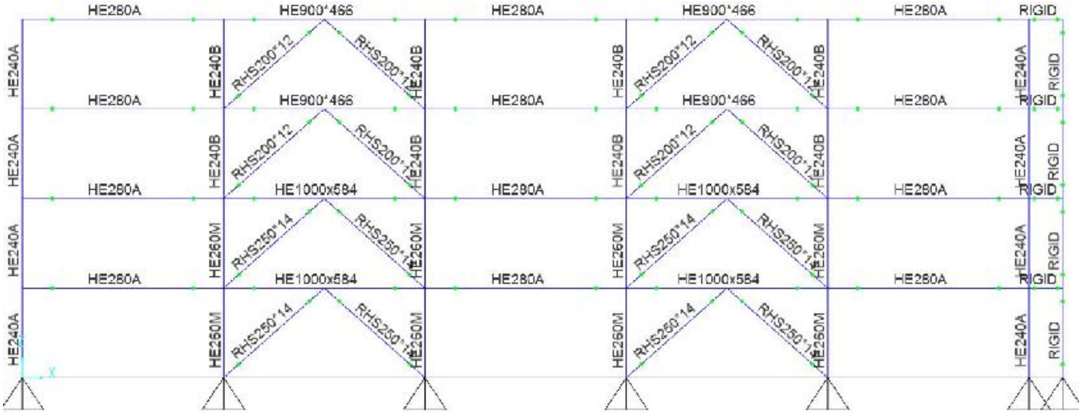

Figure 2. Elevation of the 4-story frame

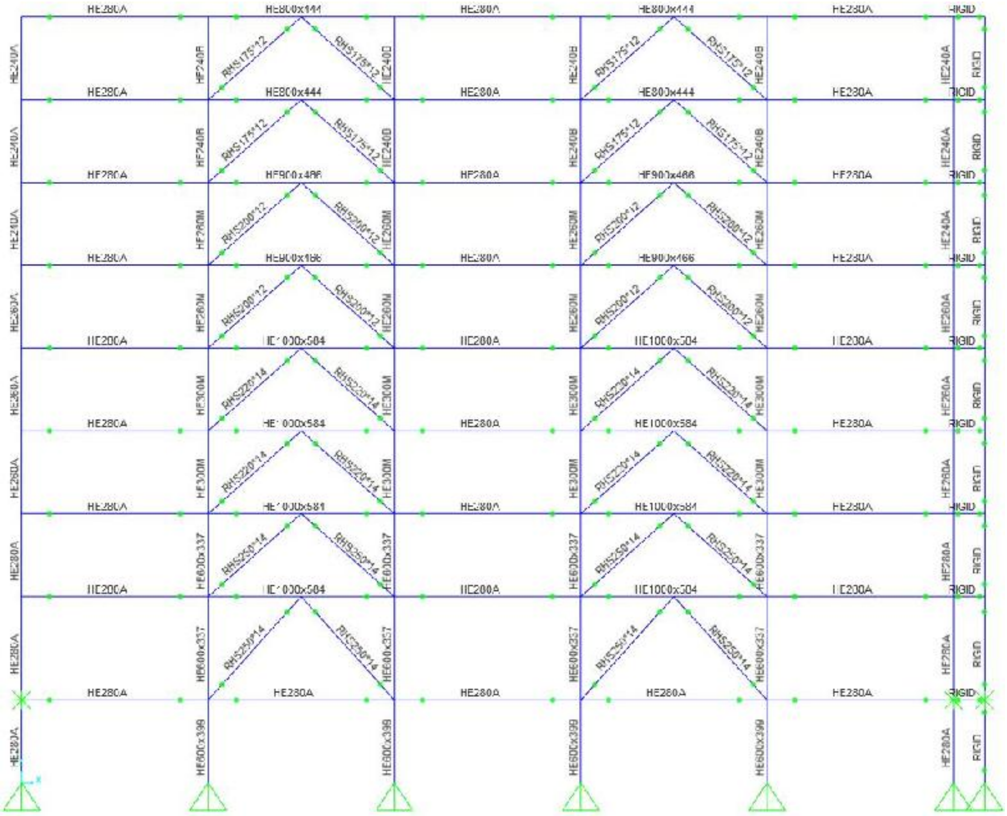

Figure 3. Elevation of the 8-story frame

The calculated fundamental period of the structure (T) are checked with the approximate fundamental period (T_a) and coefficient of upper limit (C_u) . Where the calculated fundamental period (T) exceeds C_uTa , C_uT_a is used instead of T in accordance with ASCE 7-10. Structural system is checked by using amplified seismic load effect including overstrength factor. The fundamental periods of vibration, the equivalent lateral force procedure base shear (V), the base shear from the required modal combination (V_t) for the frames are given in Table 2.

Table 2. Fundamental periods and base shears for the braced frames

Story	**T (sec)**	**T_a (sec)**	**C_u**	**C_uT_a (sec)**	**T_{used} (sec)**	**Total Mass (kN.sec^2/m)**	**V (kN)**	**V_t (kN)**
4-STORY	0.5022	0.390	1.4	0.549	0.931	2173	4337	4364
8-STORY	1.376	0.656	1.4	0.918	1.662	4485	5322	4946

The floor system of the buildings is assumed to provide diaphragm action and to be rigid in the horizontal plane. In design of steel inverted V-TYPE braced frames, the appropriate response modification coefficient (R= 6) , overstrength factor (Ω_o=2), and the deflection amplification factor (C_d=5), are used in determining the base shear, element design forces, and design story drift.

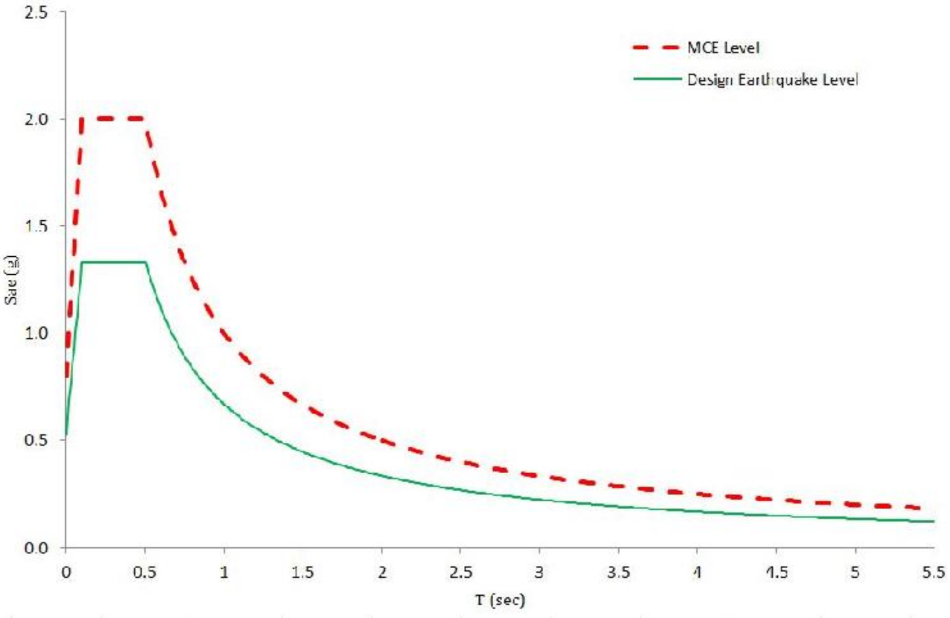

Figure 6. Response Spectra for Design Earthquake and MCE levels

The buildings were designed for a site where S_S is 2.0g and S_1 is 1.0g. Seismic parameters for design spectrum are S_{DS} =1.333 (g), S_{D1}= 0.666 (g) and long-period transition period, T_L = 12.0s. Two sets of ground motion records were selected from PEER Strong Ground Motion Database corresponding to 10% and 2% probability of exceedance. Each set consists of 3 records.
The frames were designed by selecting an assumed 2% target drift in ASCE7-10. The columns of the buildings are assumed to be simply connected to the foundation.

2.2 Analyses Results

The Incremental Dynamic Analysis (IDA) approach was employed to investigate the amplified seismic load effects on the 4-, 8- story frames. The frames were subjected to two sets of ground motions (a total of 6 ground motions) .Table 3 lists the detailed information of these ground motions. Two sets of ground motions corresponding to 10% and 2% probability of exceedance are used in IDA analyses. As specified in in Fig. 7 and Fig. 8, ground motions corresponding to 10% probability of exceedance are presented as GM 1, GM 2 and GM 3 that cause moderate structural damage and ground motions corresponding to 2% probability of exceedance are presented as GM 4, GM 5 and GM 6 that cause heavy structural damage. Fig. 9 and Fig. 10 summarize the elastic response spectra of the ground motions. In The Incremental Dynamic Analysis (IDA)**,** selected ground motions are scaled corresponding to their first period spectral acceleration. The scale factor (SF) was determined in such a way that the ground motion intensity with a scale factor of SF would have a spectral acceleration, Sa, equal to (SF) g. For example, a scale factor of 1.00 means that the scaled ground motion has a 1.00g spectral acceleration at the fundamental period. In each step from 0.1g to 2.5g, 0.1g scale factor increment is used for both 4- and 8- stories frames. Fig. 8 and Fig. 9 also show spectral accelerations values of selected ground motions for fundamental periods of 4-story, 8 story frames.

Column, beams and braces are modeled by PERFORM 3D a nonlinear analysis and performance assessment software. Braces were modeled as an “Inelastic Steel Bar”. Beams in braced by are modeled as a column element because of the unbalanced force caused by braces. In beams, connection near columns has pinned connection. PMM releases were modeled for defining nonlinear behavior at the center of the beam where braces are connected. Beams were modeled as two half beam. One half of the beam is composed of linear moment release (columns side), linear beam part and nonlinear PMM release (brace connection side). To define nonlinear behavior Columns adjacent to braced bay were modeled as FEMA Column. P-Δ effects were always included in the time-history analyses.

Table 3. Earthquake Ground Motion Characteristics from PEER Database

	NGA#	Record	Scale Factor	Duration (sec)	PGA (cm/sec^2)
GM 1 (%10)	1612	Düzce	3.5588	41.0	531.89
GM 2 (%10)	4284	Basso,Tirreno	3.9035	29.00	572.00
GM 3 (%10)	587	New Zealand	1.451	50.00	404.17
GM 4 (%2)	1111	Kobe	1.3103	41.00	620.973
GM 5 (%2)	4099	Park Field	2.2397	21.00	1047.708
GM 6 (%2)	4481	L’Aquila	1.7551	61.00	828.945

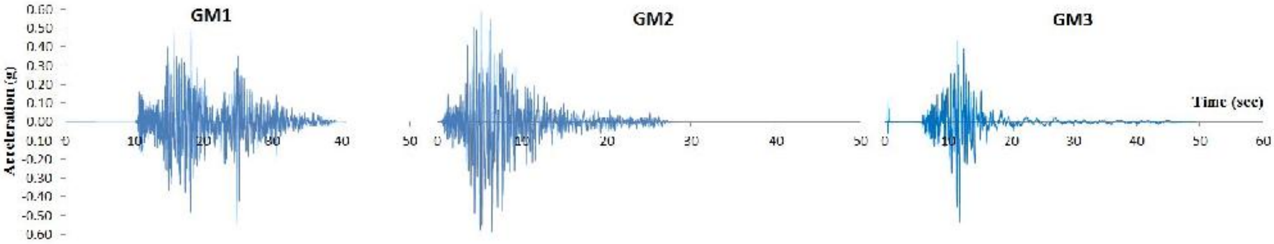

Figure 7. Time histories of the ground motions corresponding to 10% probability of exceedance

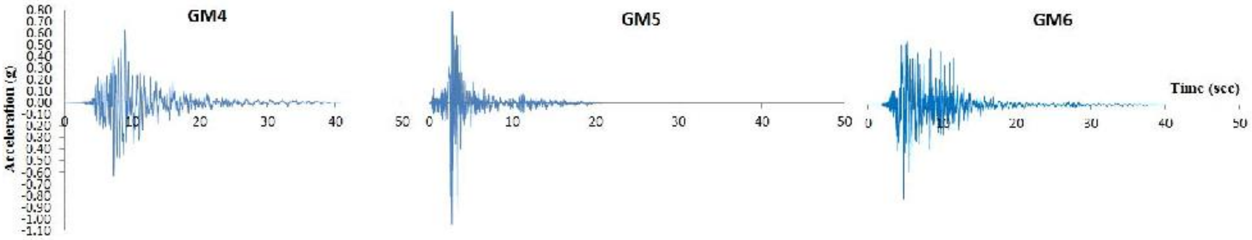

Figure 8.Time histories of the ground motions corresponding to 2% probability of exceedance

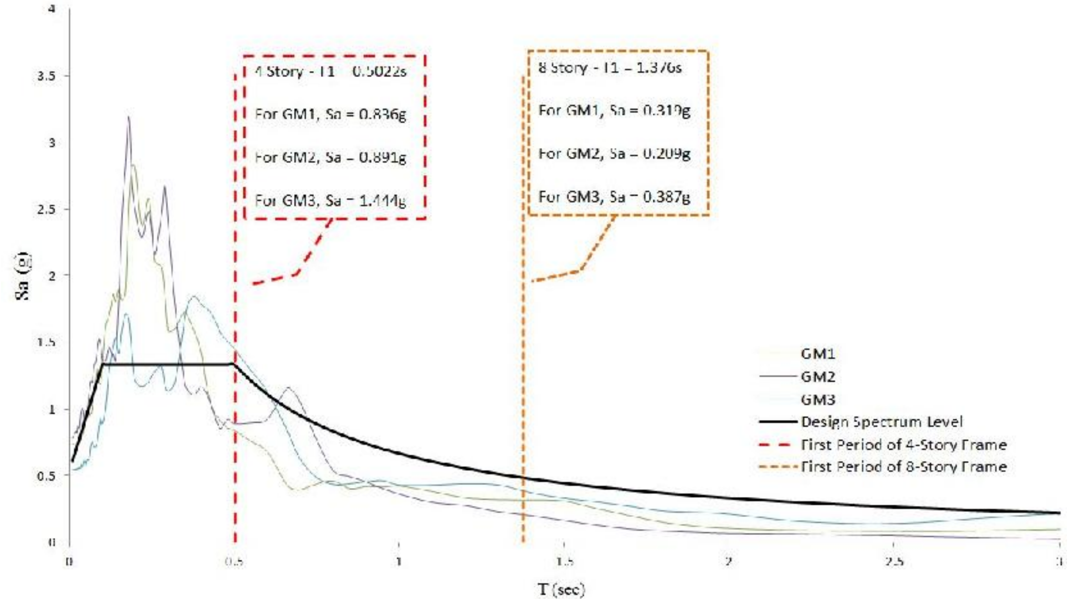

Figure 9. Response Spectra of the ground motions (GM 1, GM 2, GTM 3) selected from PEER database for design earthquake level corresponding to 10% probability of exceedance

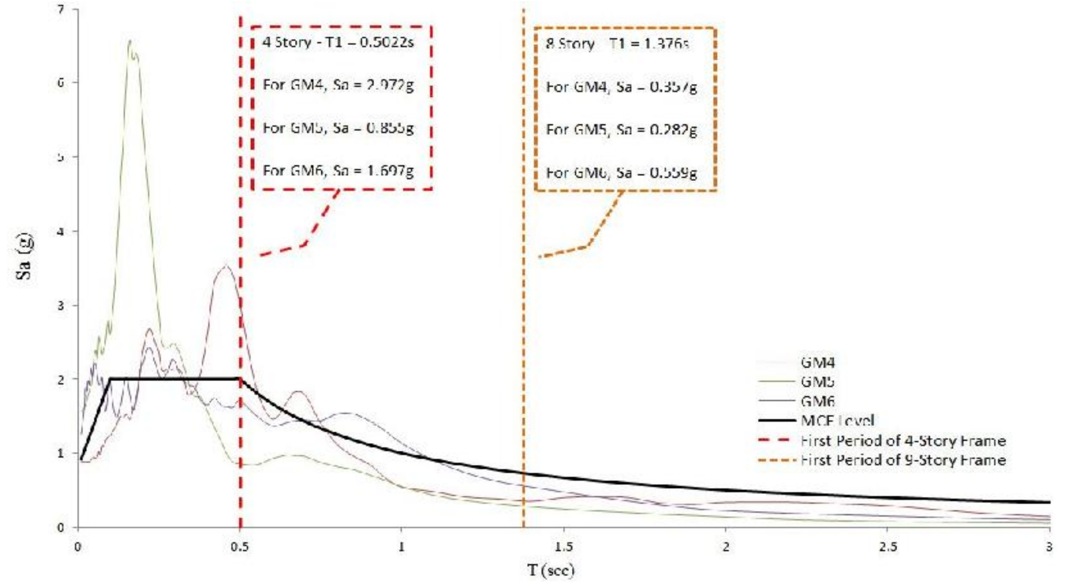

Figure 10. Response Spectra of the ground motions (GM 4, GM 5, GTM 6) selected from PEER database for MCE level corresponding to 2% probability of exceedance

Maximum drift ratios in frames for each steps under selected ground motions are given in Fig.11. The amplification factors Ω_o for axial compression in braced by columns in each stories, the capacity level of the first story braced by column in each frame and the drift ratios are given under S_a=2.00g and S_a=1.00g for 4- and 8- stories frames in Figs. 11 through 14 .

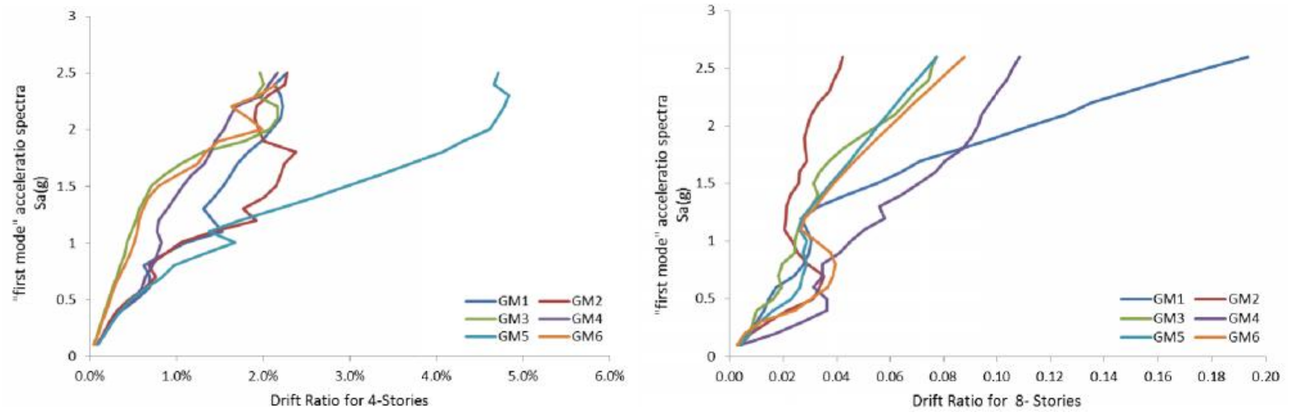

Figure 11. Peak drift ratio development of frames subject selected ground motions

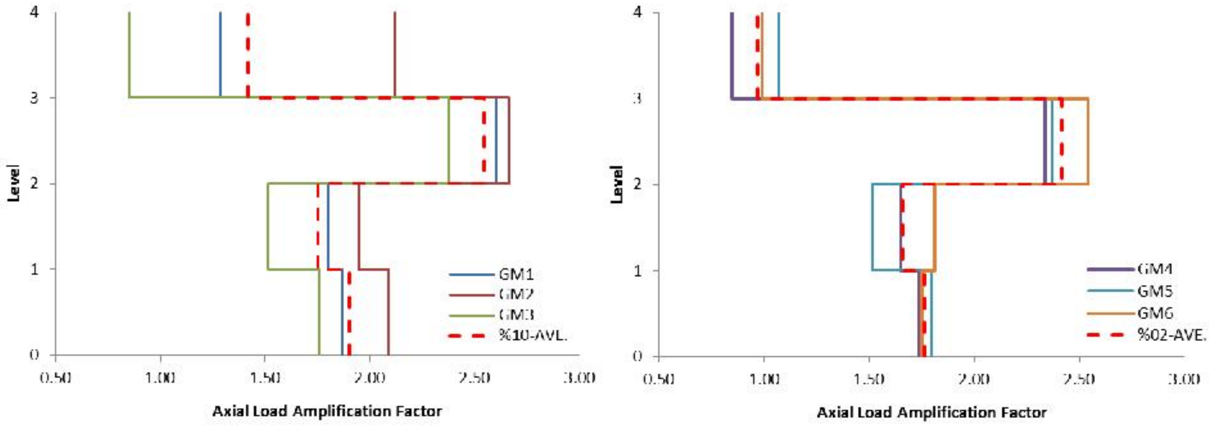

Figure 12. Amplification factor for axial compression load in 4- story frame under Sa=2.00g

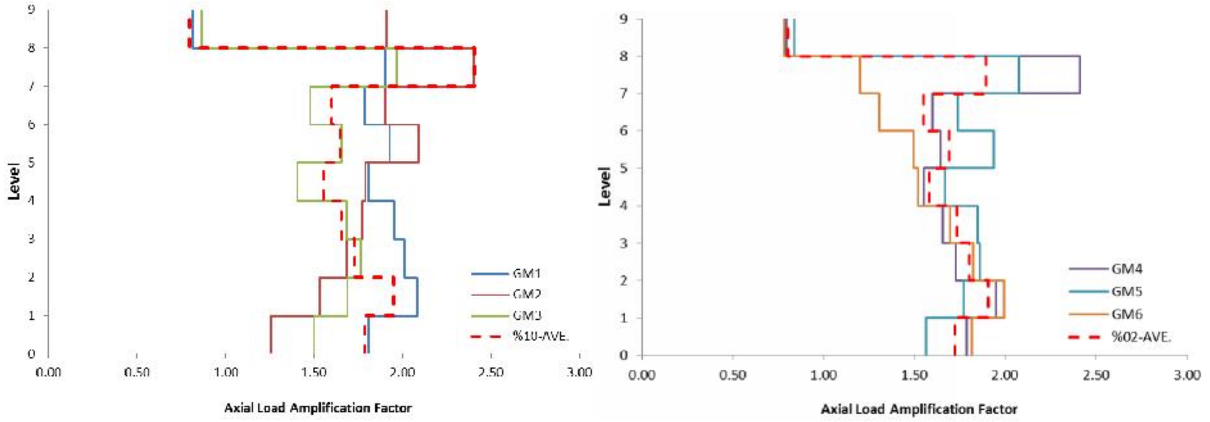

Figure 13. Amplification factor for axial compression load in 8- story frame under Sa=1.00g

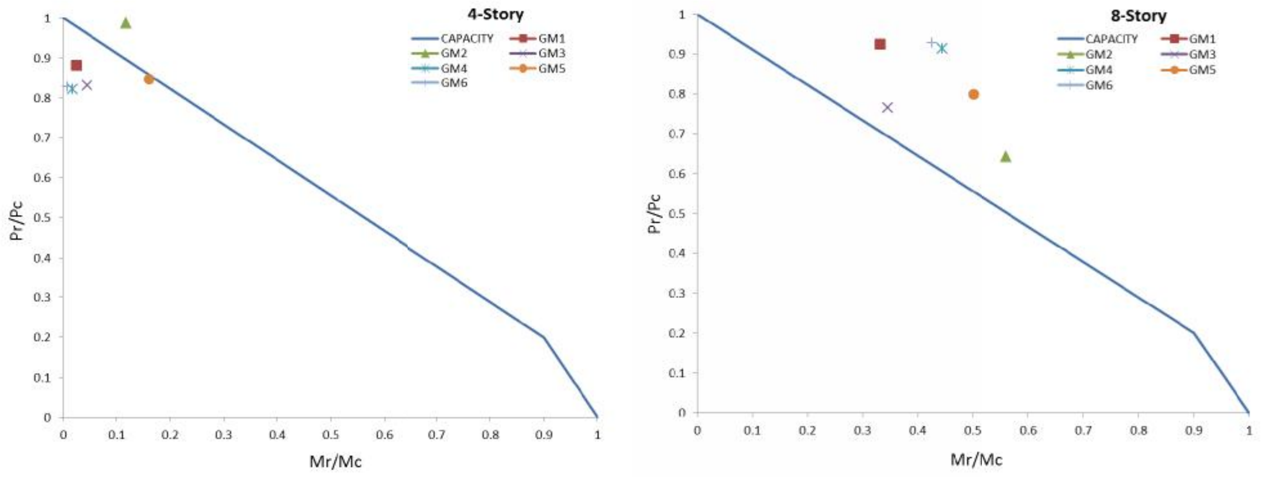

Figure 14. Capacity level of the first story braced by column in 4- and 8-story frame under Sa=2.00g and Sa=1.00g

4. CONCLUSION

Typical 4- and 8-story buildings using inverted V-braced frames were subjected to a set of ground motions corresponding to 10% and 2% probability of exceedance and incremental dynamic analysis (IDA) approach was employed to investigate the amplified seismic load effects. Major conclusions are drawn as follows:

- The 4-story frame reach its 2% design drift ratioapproximately at spectral accelerations, Sa of 2.0g for ground motions having 10% probability of exceedance and Sa of 1.70g for ground motions having 02% probability of exceedance, respectively.
- The 8-story frame reach its 2% design drift ratioapproximately at spectral accelerations, Sa of 0.5g for ground motions having 10% probability of exceedance and Sa of 0.35g for ground motions having 02% probability of exceedance, respectively.
- The maximum amplification factor in four story frame varies between 0.85 and 2.39 under selected ground motions for Sa 2.0g.
- The maximum amplification factor in eight story frame varies between 0.78 and 2.41 under selected ground motions for Sa 1.0g.
- P/Pn + M/Mn levels in four story frame vary between 0.83 and 1.10 under selected ground motions for Sa 2.0g.
- P/Pn + M/Mn levels in eight story frame vary between 1.10 and 1.36 under selected ground motions for Sa 1.0g. Capacity of braced bay column in first story acceeds limits in all ground motions.

Acknowledgement

The authors gratefully acknowledge The Scientific and Technological Research Council of Turkey (TUBITAK) for supporting this research (Grant # 114R044). However, the views expressed in this paper belong to the authors alone and do not necessarily represent the position of any other organization or person.

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