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A Numerical Investigation of the Influence of Semi-Rigid Composite Connections on the Seismic Behavior of a Building with Steel Concentrically Braced Frames

Ömer Yönev[*1], Ahmet Necati Yelgin[2]

ABSTRACT

Semi-rigid composite connections are connections which have a certain rotational stiffness and bending strength by means of the slab and its reinforcement. The use of these connections can lead to economic and structurally efficient solutions such as selecting smaller beam sections, reducing deflection and vibration problems. Additionally, they are permitted to use as a secondary lateral resisting system in regions of high seismicity. Therefore, in this study, two investigations were made in terms of seismic behavior evaluation: the influence of semi-rigid composite beam-column connections on interior frames and the influence of shear tab connections. Firstly, a 6-story building with steel special concentrically braced frames is designed according to current seismic design codes. Secondly, 3 models are created using the designed building. In Model 1, all beam-column shear tab connections are assumed as pinned connections. Model 2 and Model 1 are identical except that In Model 2, shear tab connections used in Model 1 are not assumed as pinned connections and their actual behavior is determined and included to the model. In Model 3, all beam-column connections on the interior frames are designed as semi-rigid composite connections. The interior frame sections are reselected and the exterior beam-column connections except for the ones on the braced bays are assumed the same as in Model 2. Lastly, nonlinear static analysis (pushover) is carried out and some comparisons are made with respect to the following aspects: lateral displacement and story drifts under same lateral force and lateral force under the same lateral displacement. As a result, Model 1 and Model 2 showed similar behavior due to the shear tab connections acting almost as pinned while Model 3 showed that using semi-rigid composite connections can increase the base shear capacity by %48 and decrease peak displacements and story drifts by %65.

Keywords: semi-rigid composite connections, concentrically braced frames, nonlinear static analysis, pushover.

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1. INTRODUCTION

In steel structures, beam-column connections are traditionally assumed either pinned connections or rigid connections to simplify calculations and reduce the complexity of analyses. In analyses, it is assumed that pinned connections have no rotational stiffness and cannot transfer moment while rigid ones have infinite rotational stiffness and can transfer moment. However, in practice all connections have some rotational stiffness and can transfer moment. This behavior, which is called semi-rigid, falls between pinned and rigid behavior.

Semi-rigid connections have been permitted by the AISC Specifications since 1949 but haven't been used widely due to the complexity of analysis required and lack of reliable information of determining moment-rotation characteristics of the connections [1]. However, the moment-rotation characteristics of these connections can be easily achieved thanks to the equations obtained as a result of the studies carried out for many years and various software using finite element analysis method.

Semi-rigid connections that take into account the slab reinforcements in determining of strength and stiffness of connections are called "semi-rigid composite connections" [2]. These connections mostly consist of slab reinforcements which form the top portion of the connection, seat angle for the bottom portion and web angles for shear resistance (Figure 1) [1].

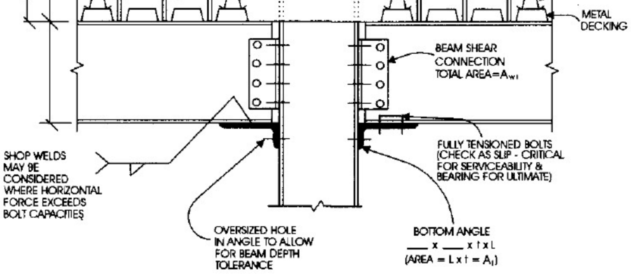

Figure 1 Semi-rigid composite connection [1]

The use of semi-rigid composite connections has many advantages in terms of economy and application. Economically, they can lead to smaller and lighter beam sections. In site, they help reducing erection time and cost when bolted angle connection types are used due to requiring no welding [3].

Apart from these advantages, the structural benefits of the use of these connections are more significant than the ones mentioned above. They help reduces deflection and vibration problems which are an important part of composite beam design [1]. They provide additional strength to structures by having some rotational stiffness and moment capacity [4]. Most importantly, as Leon stated, "they improve the ability of the structure of redistribute loads and survive accidental overloads" [3, p.160].

1.1. Literature Review

In this section, the studies on the influence of semi-rigid connections of seismic behavior of steel structures are mentioned.

Reyes-Salazar et al. [5] investigated the seismic behavior of steel buildings with perimeter moment resisting frames (PMRF) and interior gravity frames (GF). Three steel building models that represent low-, medium- and high-rise buildings were investigated for two cases. The interior connections are assumed as perfectly pinned for Case 1 and then semi-rigid for Case 2. Results show that inter-story shears and inter-story displacement at PMRF reduced for Case 2. It is observed that inter-story shears decreased up to 20, 46 and 11% while the reductions for inter-story displacements are about 14, 44 and 15% for low-, medium- and high-rise buildings, respectively. In conclusion, it was stated that semi-rigid connections have larger stiffness than pinned connections do, and actual behavior of pinned connections should not be neglected in analyses.

Zhang [6] studied the influence of shear tab connections of the behavior of moment frames. Two prototype buildings were designed; one with pinned connections and the other one with semi-rigid composite connections. Then some comparisons were made in terms of lateral displacement under the same lateral force, lateral force under the same lateral displacement, moment in moment frames and moment in gravity frames. As a result, the building with semi-rigid composite connections showed larger stiffness, moment in moment frames were decreased and it was stated that shear tab connections which are mostly modeled as pinned connections could be used as semi-rigid for providing additional lateral resistance to buildings.

Maison et al. [7] investigated the seismic performance of partially restrained (PR) connections (also known as semi-rigid connections). For this purpose, two buildings (3 and 9 stories) having partially restrained moment frame lateral-force-resisting systems in two different seismic zone were studied. In conclusion, it was stated that PR buildings could be used in regions of moderate and high seismicity.

1.2. Objectives

In the recent researches, there are not many studies which investigate the seismic behavior of semi-rigid composite connections with steel special concentrically frames. Most of the studies have focused on semi-rigid composite connections as a replacement to moment connections or together with moment connections.

In this paper, a 6-story steel office building is designed in compliance with the current seismic design code [8] for three different cases. In the first case (Model 1), all beam-column connections (shear tab connections) are assumed as pinned connections. In the second case (Model 2), the actual behavior of the shear tab connections represented with moment-rotation curves are included to the analyses. In the third case (Model 3), all beam-column connections on the interior frames are designed as semi-rigid composite connections, the interior frame sections are reselected, and the exterior beam-column connections are assumed the same as Model 2. Then nonlinear static analysis (pushover) are carried out in x direction and some comparisons are made with respect to the following aspects: lateral displacement and story drifts under same lateral force and lateral force under the same lateral displacement.

To sum up, the main purpose of this study is to investigate whether replacing pinned connections with semi-rigid composite ones could improve the seismic behavior of structures with steel special concentrically braced frames. The other purpose is to observe the influence of shear tab connections which are assumed as pinned connections in analyses.

1.3. Scope of the Study

Within the scope of this study, some assumptions made in order to simplify the calculations and focus the main variables are listed as follows:

1. Nonlinear properties of the elements are determined according to ASCE 41-13 [9]

2. P-Δ effects are considered in the analyses.

3. Composite decks are assumed to act as rigid diaphragm.

4. All column-base connections are assumed as pinned connections.

5. All beam-beam and brace-column connections are assumed as pinned connections.

6. Element lengths are determined using centerline to centerline dimensioning.

2. BUILDING MODELS

In this chapter, the properties of the designed building are described, and three models are defined briefly.

2.1. Definition of the Building

The building in this paper is assumed to be a 6-story steel office building which has 5 bays in x direction and 4 in y direction. The bay lengths are equal in each direction and 8 m. in x direction and 7 m. in y direction (Figure 3). The story heights are selected 3,5 m for each story and the height of the building is 21 m. (Figure 4 and Figure 5). The concentrically braces are placed on the perimeter bays of the building and two-story x-braces are selected (Figure 2 and Figure 4).

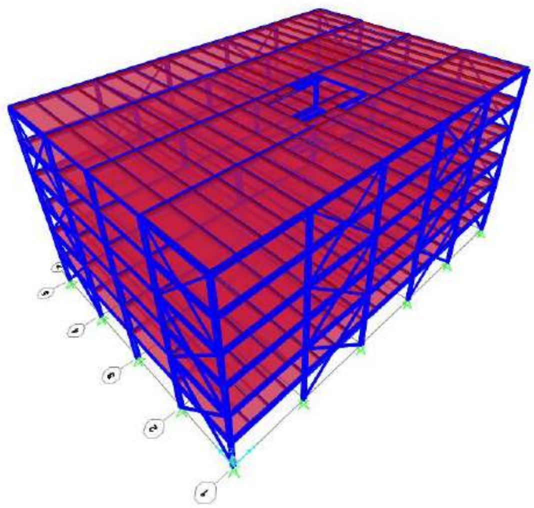

Figure 2 3D view of the building

In the design phase, LRFD method is used and S235 steel grade is selected for all steel structural components except for the steel decking. For secondary beams IPE220 sections are used. For primary beams and columns in braced and unbraced bays different sections are used (Table 1). Column splices are located at 12,00 m. height but are assumed as at 3rd story level in the analyses.

Table 1 Column and beam sections in x direction

Story	Columns		Beams	
	Braced bays	Unbraced bays	Braced bays	Unbraced bays
6	HE320B	HE300B	IPE450	IPE450
5	HE320B	HE300B	HE400B	IPE450
4	HE320B	HE300B	IPE450	IPE450
3	HE300M	HE400B	HE400B	IPE450
2	HE300M	HE400B	IPE450	IPE450
1	HE300M	HE400B	HE400B	IPE450

For determining the earthquake loads Equivalent Lateral Force (EQL) Analysis is performed. Site class ZC is selected and the spectral acceleration parameters used in EQL Analysis are selected as follows; $S_s = 0,759$, $S_1 = 0,217$, $S_{DS} = 0,911$ and $S_{D1} = 0,325$.

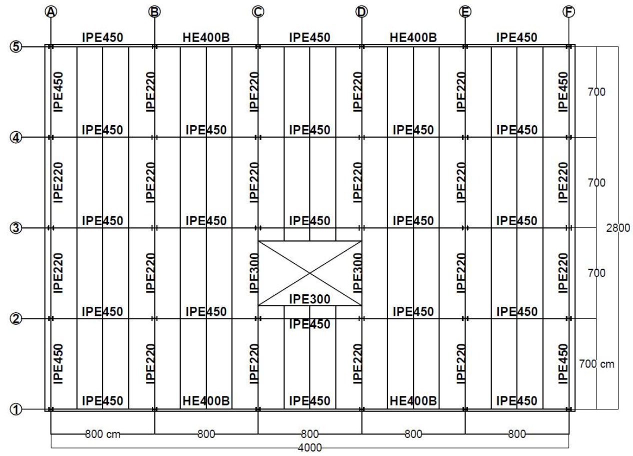

Figure 3 Typical plan view

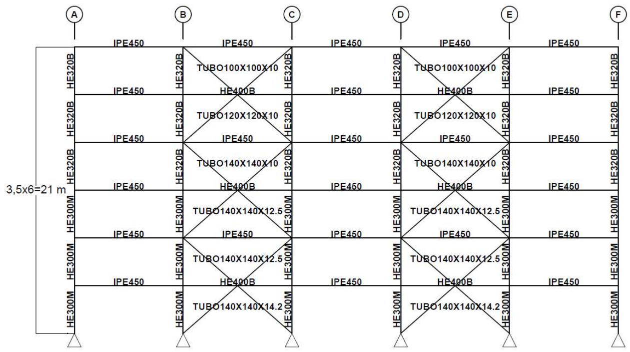

Figure 4 Elevation of the exterior frames (x direction)

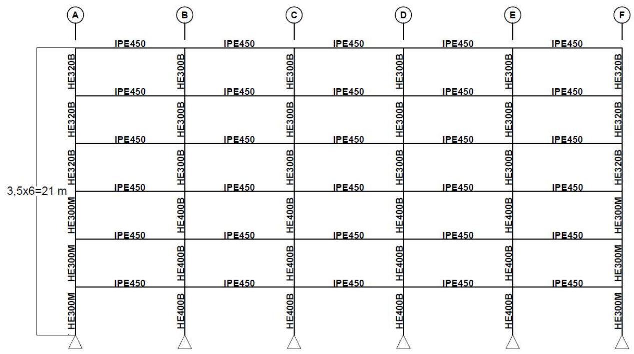

Figure 5 Elevation of the interior frames (x direction)

2.2. Models Used in the Analyses

There are three models used in the analyses. All of them have the same column, brace and secondary beam sections. The only difference between Model 1 and Model 2 is that while beam-column connections are assumed as pinned connections in Model 1, their actual behavior represented by moment-rotation curves is determined in compliance with Astaneh-asl's study [10] is included in the analysis. The differences between Model 2 and Model 3 are as follows; the interior frame sections are selected IPE400 in Model 3 and the interior connections are designed as semi-rigid composite connections according to American Design Guide 8 [1].

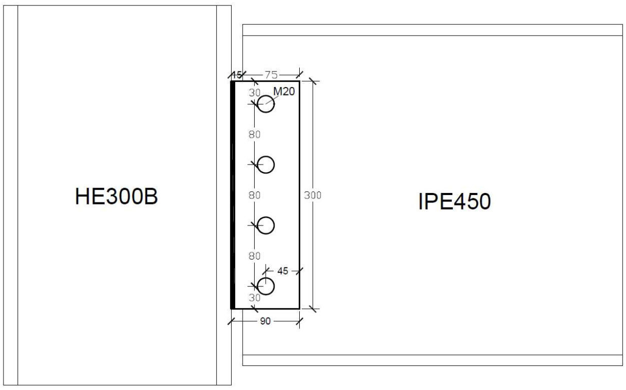

Figure 6 Typical shear tab connection details

There are two types of shear tab connections which have the same configuration and details but different moment capacities. Figure 6 shows typical shear tab connection details and Figure 7 shows moment-rotation behaviors of the connections.

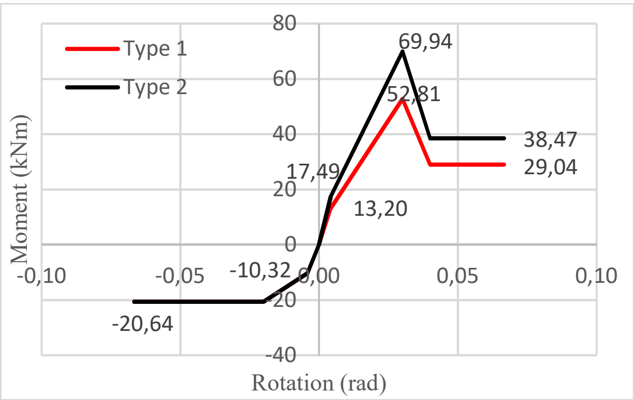

Figure 7 Moment-rotation behavior of the shear tab connections

There is only one type of semi-rigid composite connection used in Model 3 (Figure 8) and its moment-rotation behavior is represented by trilinear model in compliance with Malek's study [11] (Figure9).

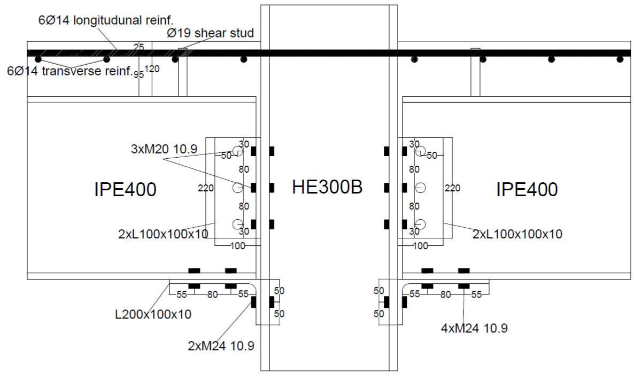

Figure 8 Typical semi-rigid composite connection details

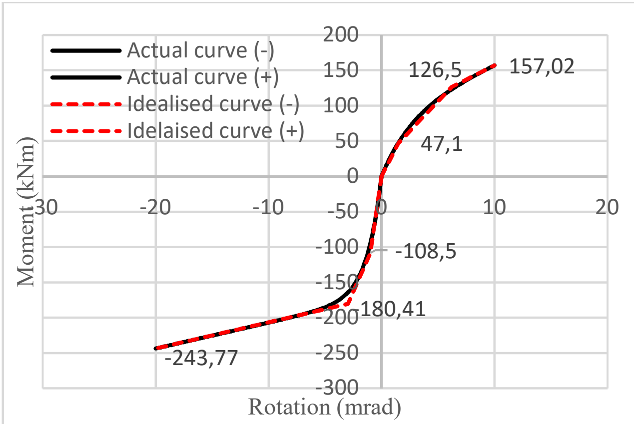

Figure 9 Moment-rotation curve and trilinear idealization of semi-rigid composite connections

3. NUMERICAL ANALYSES OF THE MODELS

In nonlinear static analyses, Sap2000 [12] is used for determining the seismic behavior of the models. Nonlinear moment-rotation behavior of the connections used in Model 2 and Model 3 are represented using nonlinear elastic link elements. These link elements are modeled as 10 cm long (Figure 10) and their properties are defined as seen in Figure 11. Normally the behavior of semi-rigid composite connections are determined for 20 mrad rotation in negative moment, 10 mrad rotation in positive moment and their strength degradation behavior aren't determined but according to ASCE 41-13 [9], strength degradation properties must be included in analyses. Therefore nonlinear link elements for semi-rigid composite connections are modeled with strength degradation properties (Figure 11), which are determined using nonlinear modeling parameters suggested in ASCE 41-13 [9].

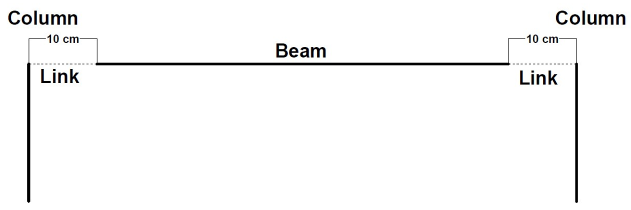

Figure 10 Modeling of nonlinear elastic link elements

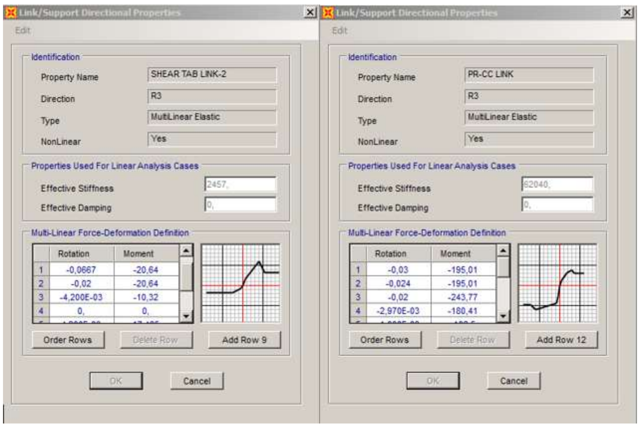

Figure 11 Defining the properties of nonlinear elastic link elements in Sap2000 [12]

Lateral load-bearing system elements are assigned plastic hinges at appropriate locations and the properties of plastic hinges are calculated according to ASCE 41-13 [9]. The types of plastic hinges can be seen on Table 2.

Table 2 Types of plastic hinges assigned

The elements that can go beyond elastic behavior	**Types of plastic hinges**
Braces	P
The columns in the braced bays	P
The beams that intersect the braces	P-M3
The columns linked to the semi-rigid composite connections	P-M3

For determining the seismic behavior of the models, all models are pushed until 50 cm top displacement. Using the pushover curves (Figure 12) base shear and top displacement points are selected for the comparisons (Table 3). Then the models are investigated when they reach the target points.

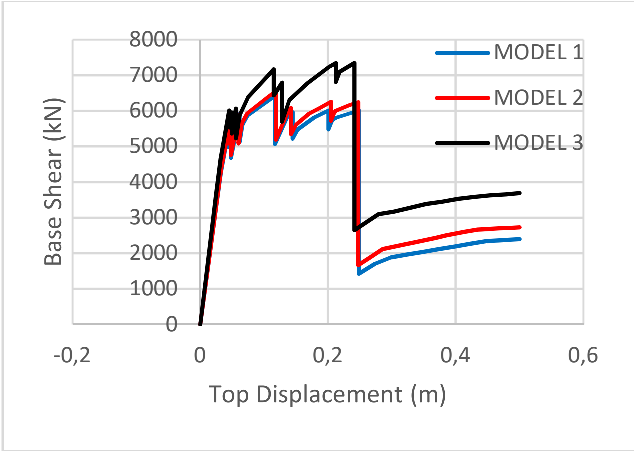

Figure 12 Pushover curves

Table 3 Selected base shear and top displacement values

Base shears (kN)	Top displacements (m)
3000	0,05
4000	0,1
5000	0,15
6000	0,2
6400	0,3

First the models are pushed until target top displacements and base shear capacities are compared. It is observed in Figure 13 that Model 1 and Model 2 have almost the same base shear capacities at the target displacements except that at 0,30 m top displacement Model 2 have larger base shear capacity by 15%. Model 3 have larger base shear capacity than Model 2 at every target displacement. The largest difference between them is 48% at 0,30 m top displacement.

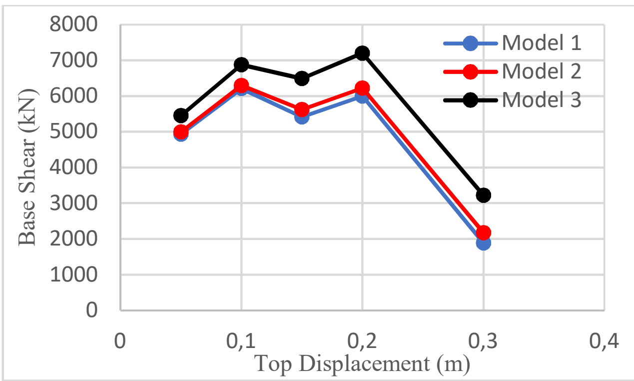

Figure 13 Base shear capacities at the target displacements

Table 4 Top displacements under same lateral force

	Top Displacement (m)				
Base Shear Force (kN)	3000	4000	5000	6000	6400
Model 1	0,023	0,030	0,039	0,083	0,117
Model 2	0,023	0,030	0,039	0,080	0,108
Model 3	0,020	0,027	0,035	0,045	0,076
Model 2/Model 1	0,983	0,980	0,985	0,964	0,922
Model 3/Model 2	0,907	0,919	0,899	0,566	0,704

Under same lateral forces top displacements are close to each other for Model 1 and Model 2. The largest fall in top displacement is observed at 6400 kN lateral force by 8%. On the other hand, Model 3 has smaller top displacements in all cases ranging from %8 to 43% (Table 4).

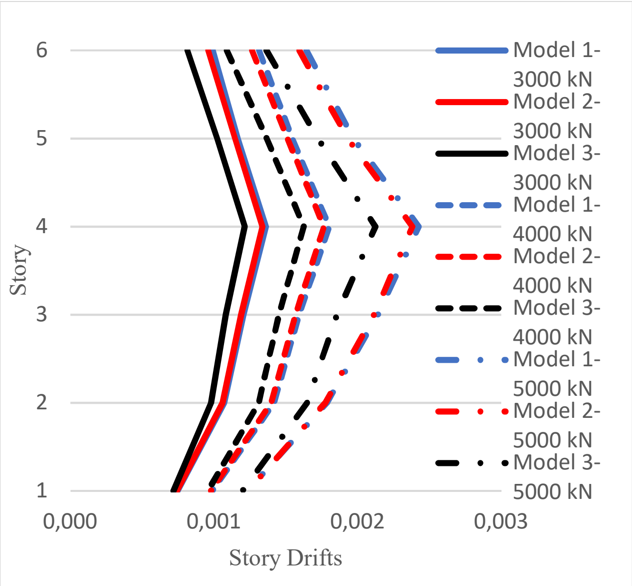

Figure 14 Story drifts under same base shear forces (a)

It is observed from Figure 14 that under 3000, 4000 and 5000 kN base shear forces Model 1 and Model 2 have similar story drifts. The most significant difference between them is that in Model 2 story drifts has decreased by 4%. However, the behavior of Model 2 and Model 3 are explicitly different. Although at first story levels similar results are observed, Model 3 has decreased story drifts by 10% to 15%.

Under 6000 and 6400 kN base shear force while Model 1 and Model 2 has similar story drifts, Model 2 and Model 3 have great differences. Model 2 has smaller story drifts than Model 1 by %10 to 15% and Model 3 has smaller drifts than Model 2 by 20% to 65% (Figure 15). In other words, due to having additional stiffness because of semi-rigid composite connections, Model 3 have smaller story drifts which is the major parameter evaluating the seismic performance of buildings.

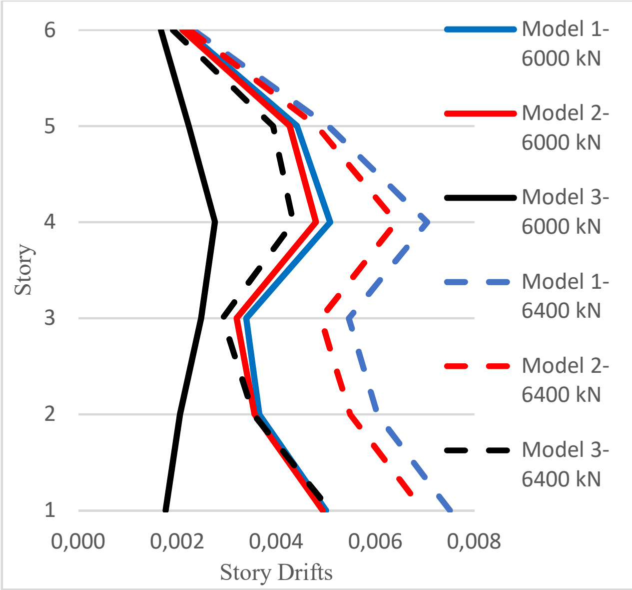

Figure 15 Story drifts under same base shear forces (b)

4. CONCLUSIONS AND FUTURE RECOMMENDATIONS

From the results obtained in this study, the following conclusions can be made:

1. Model 1 and Model 2 showed similar behavior that neglecting actual behavior of shear tab connections doesn't cause significant errors.

2. In every cases Model 3 showed superior performance than Model 2 did in terms of base shear capacity, top displacement and story drifts.

3. The study shows that the use of semi rigid composite connections could lead to better seismic performance and they might be used as an alternative to pinned connections in buildings with steel special concentrically frames.

To obtain more accurate and realistic results, these recommendations can be made for future researches:

1. Target building performance levels could be evaluated and compared.

2. Plastic deformations in braced frames at target displacement could be investigated.

3. Semi-rigid connections having different strength and rotational capacities might be used and compared.

3. Different types of buildings might be selected in terms of story levels, widths, lengths, regularity etc.

4. Nonlinear time history analysis could be used for more accurate structural behavior.

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