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Seismic Performance of Semi-Rigid Connected Prefabricated Structures

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Abstract

Prefabricated structures are constructed by bolted connections of separated members. The design and analysis of these structures are generally performed by defining fully hinges for the connection of separated members at the joint of junction. In practice, these connections are not fully hinged. Therefore, the usage of assumption of semi-rigid connections (restrained or partially fixity) instead of fully hinge connection in the design and analysis of these structures is a more realistic approach for bolted connections used in the combination of prefabricated elements. The aim of this study is to investigate the effects of semi-rigid connections on seismic performance of prefabricated structures. To this aim, nonlinear static analysis (pushover analysis) of a selected RC prefabricated structure is performed with SAP2000 structural analysis program by considering various partially fixity percentages for bolted connections. The target values of roof displacements obtained from the analyses according to ATC-40, FEMA-356, FEMA-440 and TEC-2007 codes are compared each other. The numerical results are given in tables and figures comparatively and discussed.

Key words: Prefabricated Structures, Semi-rigid Connections, Nonlinear Static (Pushover) Analysis

1. Introduction

As a result of earthquakes in the recent years, many damages in the prefabricated structures have occurred due to their weakness in construction such as week column-beam connections, uncertainties in the design of the junction points, insufficient cross section of structural elements as a result of major earthquakes in the recent years. Especially, significant economic and goods losses occurred after the major earthquakes such as 1989 Loma Prieta and 1994 Northridge earthquakes in United States of America; 1995 Kobe earthquakes in Japan; 1992 Erzincan, 1999 Marmara and Duzce earthquakes in Turkey due to damaged and collapsed prefabricated structures [1]. For this reason, the seismic safety of prefabricated structures presents very common a subject for investigation in worldwide.

The semi-rigid assumptions are not considered in desing and evaluation of prefabricated structures and truss system. Therefore, damages in such structures are generally derived from connections of separated members at the joint of junction [2-3]. However, these structures are structure that with neither fully hinged connections nor fully rigid connections. For this reason, the supposition of semi-rigid connection instead of fully hinge and fully rigid connection is a more factual approach for bolted connection used in the combination of prefabricated elements and truss systems.

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In this study, the effects of semi-rigid connections on seismic performance of prefabricated structures are investigated. To this aim, the target roof displacements and pushover curves of a RC prefabricated structure are obtained by considering the connection percentage of 0% (fully hinged), 25%, 50%, 75% and 100% (fully rigid) for bolted connections. The displacements and curves are attained by using pushover analysis which are performed with SAP2000 structural analysis program [4]. The target roof displacements obtained from the analyses according to ATC-40, FEMA-356, FEMA-440 and TEC-2007 [5-8] codes are compared each other. The numerical results are given in tables and figures comparatively and discussed.

2. Semi-rigid Connections

The connection flexibility at the ends of structural elements can be represented by rotational springs [9]. The stiffness terms of the rotational springs may be obtained by using Young's modulus (*E*), moment of inertia (*I*) and length (*L*) of related beam element. This approach is very effective and useful for introducing the connection flexibility [10]. The stiffness matrix of the beam element with rotational springs at both ends in local coordinate system can be written in the following [11];

$$[k] = \frac{EI}{L^3}\begin{bmatrix} 12\theta_1 & 6L\theta_2 & -12\theta_1 & 6L\theta_3 \\ 6L\theta_2 & 4L^2\theta_4 & -6L\theta_2 & 2L^2\theta_5 \\ -12\theta_1 & -6L\theta_2 & 12\theta_1 & -6L\theta_3 \\ 6L\theta_3 & 2L^2\theta_5 & -6L\theta_3 & 4L^2\theta_6 \end{bmatrix} \tag{1}$$

The coefficients of θ_1, θ_2, θ_3, θ_4, θ_5 and θ_6 in Eq. (1) are defined as follows

$$\theta_1 = \frac{\alpha_i + \alpha_j + \alpha_i\alpha_j}{4(3+\alpha_j)+\alpha_i(4+\alpha_j)} \tag{2-a}$$

$$\theta_2 = \frac{\alpha_i(2+\alpha_j)}{4(3+\alpha_j)+\alpha_i(4+\alpha_j)} \tag{2-b}$$

$$\theta_3 = \frac{\alpha_j(2+\alpha_i)}{4(3+\alpha_j)+\alpha_i(4+\alpha_j)} \tag{2-c}$$

$$\theta_4 = \frac{\alpha_i(3+\alpha_j)}{4(3+\alpha_i)+\alpha_j(4+\alpha_i)} \tag{2-d}$$

$$\theta_5 = \frac{\alpha_i\alpha_j}{4(3+\alpha_i)+\alpha_j(4+\alpha_i)} \tag{2-e}$$

$$\theta_6 = \frac{\alpha_j(3+\alpha_i)}{4(3+\alpha_i)+\alpha_j(4+\alpha_i)} \tag{2-f}$$

In which α_i and α_j are the stiffness indexes and they can be used to obtain the rotational spring stiffness terms at *i* and *j* end of the beam element as follows

$$k_i = \alpha_i \frac{EI}{L} \tag{3-a}$$

$$k_j = \alpha_j \frac{EI}{L} \tag{3-b}$$

where k_i and k_j are the rotational spring stiffness terms, respectively. These parameters can change from 0 to ∞.

The coefficients in Eq. (2) given for semi-rigid connections may also be identified by connection percentages and may be represented as follows [10, 12]

$$\theta_1 = \frac{r_i + r_j + r_{ij}}{3} \tag{4-a}$$

$$\theta_2 = \frac{2r_i + r_{ij}}{3} \tag{4-b}$$

$$\theta_3 = \frac{2r_j + r_{ij}}{3} \tag{4-c}$$

$$\theta_4 = r_i \tag{4-d}$$

$$\theta_5 = r_{ij} \tag{4-e}$$

$$\theta_6 = r_j \tag{4-f}$$

where, r_i, r_j and r_{ij} are the correction factors, and described as follows

$$r_i = \frac{3v_i}{4 - v_i v_j} \tag{5-a}$$

$$r_j = \frac{3v_j}{4 - v_i v_j} \tag{5-b}$$

$$r_{ij} = \frac{3v_i v_j}{4 - v_i v_j} \tag{5-c}$$

where v_i and v_j are the fixity factors, and represent the semi-rigid connections defined as percentages. If the Eqs. (2) and (4) are equated, a relationship between the rotational spring stiffness and the connection percentage is obtained as follows [13,14]

$$k_{i,j} = \frac{3EIv_{i,j}}{(1 - v_{i,j})L} \tag{6}$$

3. Numerical Application

3.1. Details of selected prefabricated structure

A plan view of the selected RC prefabricated structure is shown in Figure 1. The structure has two bays in the x-direction with 20,7m. The height of the structure is 8,10m. The system has six bays in the y-direction. Total area covered by the structure is 1876,66m^2.

The RC prefabricated structure is constructed in city of Kayseri in Turkey. The city is located in Earthquake Zone 3. This structure was built on soil class Z3. According to TEC-2007, the design ground acceleration of the zone is 0,2g, and the characteristic periods (T_A and T_B) for soil class Z3 are 0,15 and 0,60 seconds. All frame elements in the prefabricated structure were designed according to the requirements of TEC-2007. The concrete and reinforcing steel classes are considered as C30 (f_{ck}=30MPa) and S420 (f_{yk}=420MPa), respectively. The Young's modulus and the weight per unit volume of concrete is 32×10^{6}kN/m^2 and 25kN/m^3, respectively.

Three-dimensional finite element model of the selected RC prefabricated structure is performed with SAP2000 structural analysis program by considering various partially fixity percentages for bolted connections. The percentages for bolted connections of the selected RC prefabricated structure and the equivalent rotational spring stiffness calculated by Eq. (6). Furthermore, gravity loads are included in structural model, and were applied to compute mode shape, frequencies, and pushover analysis. Moreover, P-Δ effects were considered in the structural model.

The cross-section dimension of the column is 40×50cm. Longitudinal bars in all columns are 12Φ16. The confinement bars are 64Φ8. The columns are considered as non-linear frame elements due to hinged distributions of prefabricated structures, while the beams are modeled as linear frame elements. It is assumed that plastic hinges occur only at the lower end of columns of the prefabricated structure by taking into account the damages occurred in the prefabricated buildings during earthquakes previously. For this reasons, the columns are modeled non-linear frame elements.

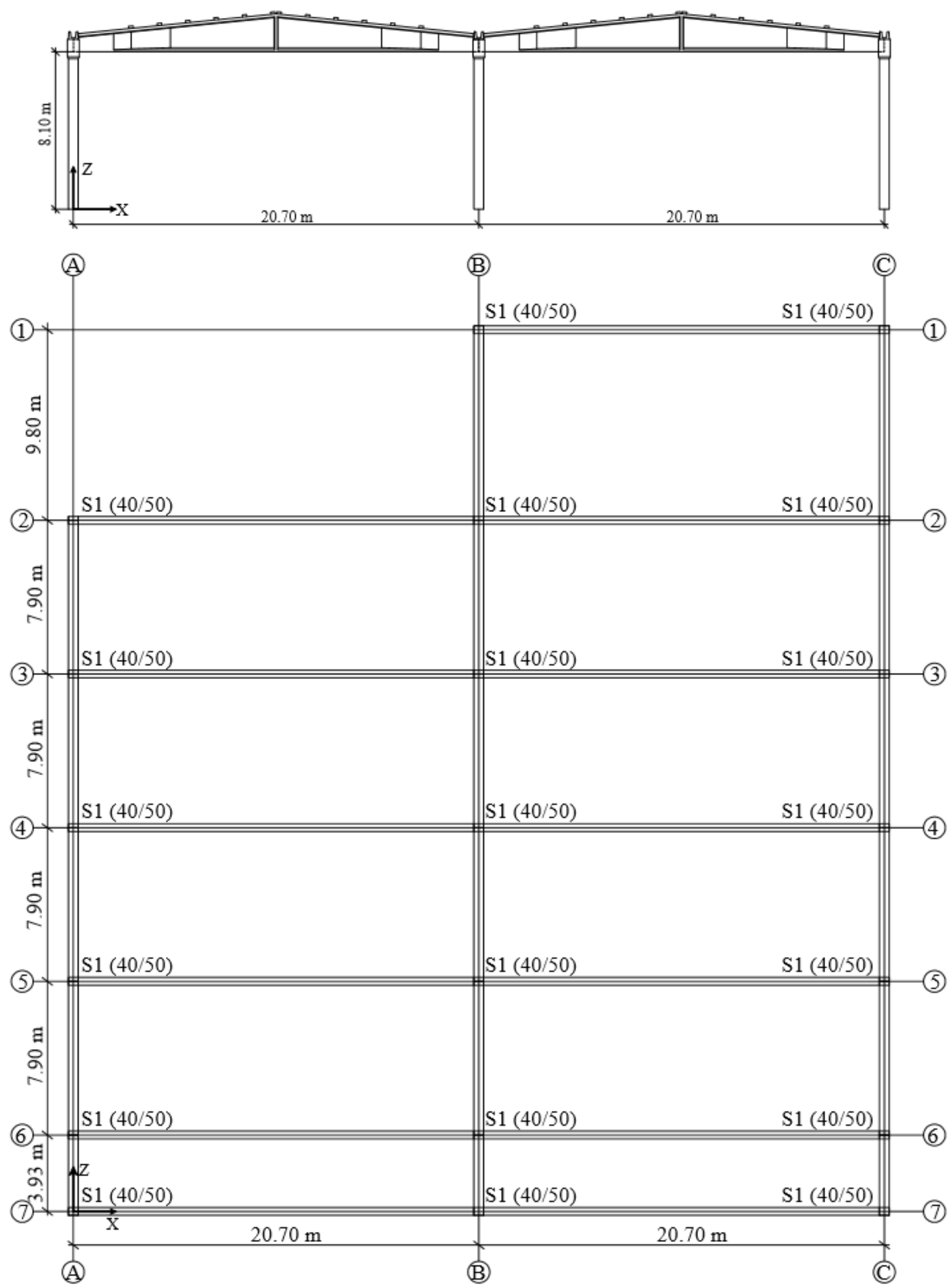


Figure 1. Plan view of the selected RC prefabricated structure

Initial effective bending stiffnesses (EI)e of the cracked sections has been calculated for the nonlinear static analysis. The calculated values are assigned at the related column elements. Thus, the reduction at the stiffness of the frame sections due to plastic deformations and cracking of concrete is taken into account in the nonlinear analysis. The fundamental periods of the selected RC prefabricated structure with uncracked and cracked sections are obtained for x and y-directions, and given in Table 1.

Table 1. Fundamental periods of the selected RC prefabricated structure with uncracked and cracked sections

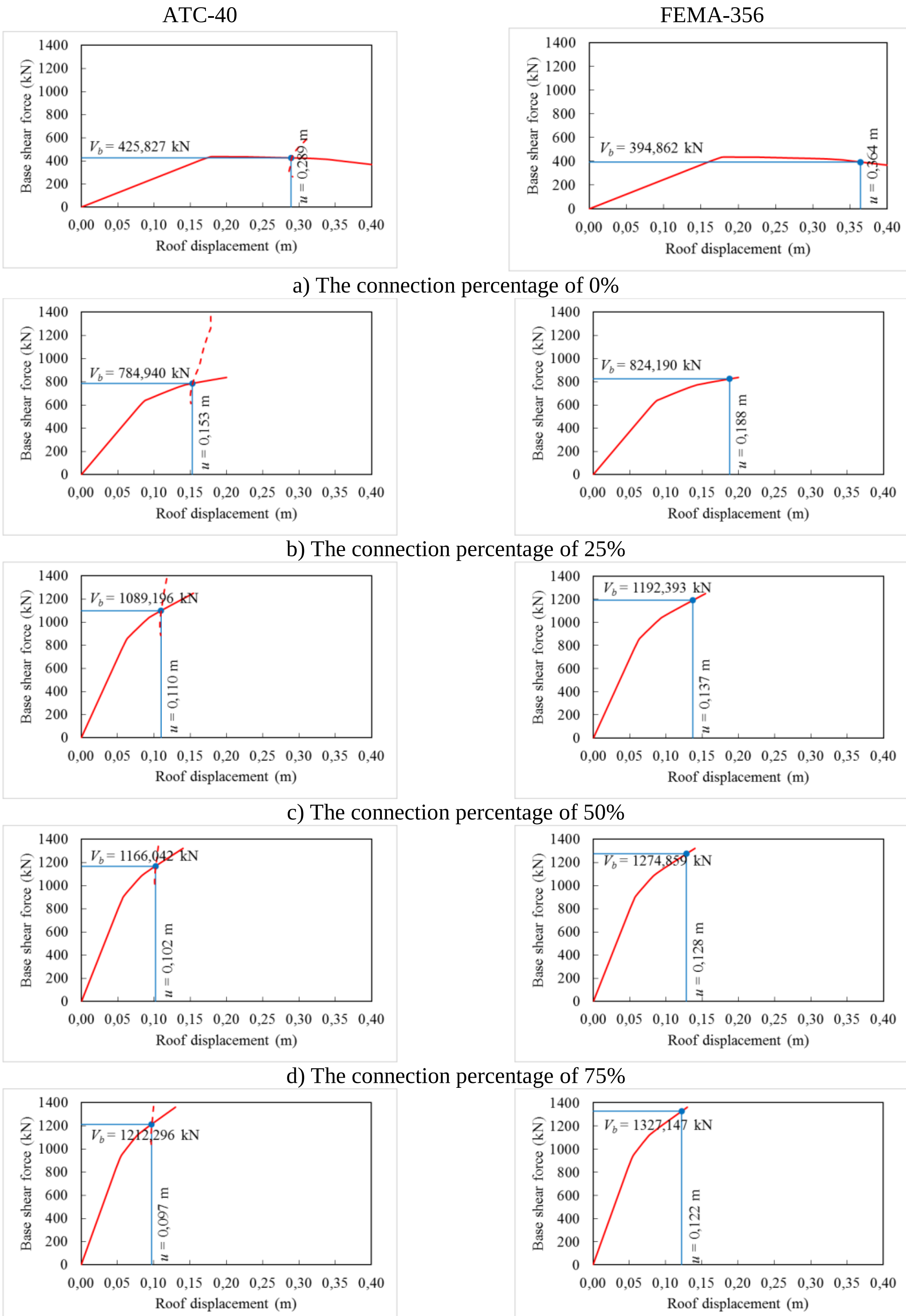
Connection Percentage (%)	**Fundamental Periods (sec)**			
	x-direction		*y*-direction	
	Uncracked Section	Cracked Section	Uncracked Section	Cracked Section
0	1,0494	1,6457	2,5189	3,0801
25	0,9219	1,2866	1,6622	1,9956
50	0,8964	1,2435	1,3660	1,5778
75	0,8900	1,2363	1,2480	1,4580
100	0,8844	1,2298	1,1427	1,3612

3.2. Response Results

In this section, the effects of semi-rigid connections on target roof displacements and base shear forces of the selected prefabricated structure are investigated. ATC-40, FEMA-356, FEMA-440, and TEC-2007 are used for the calculations. The obtained displacements and shear force are given on the pushover curves for each codes and fixity percentages. The pushover curves have been obtained for dead loads and a unit seismic load by considering the connection percentages of 0% (hinged connection), 25%, 50%, 75% and 100% (rigid connection) for bolted connections of the selected RC prefabricated structure.

It is shown from Figs. 1 and 2 that the target roof displacements decrease from 0,289m to 0,097m for ATC-40, from 0,364m to 0,122m for FEMA-356, from 0,304m to 0,102m for FEMA-440, and from 0,320m to 0,119m for TEC-2007 with the connection percentages increasing from 0% to 100%. The target roof displacements obtained from the selected RC prefabricated structure with fully hinged connections are greater than those from the selected RC prefabricated structure with semi-rigid connections. Therefore, the selected RC prefabricated structure with fully hinged connections behaves more flexible than that with semi-rigid connections. In fact, the prefabricated structures have semi-rigid connections, and they cannot be as flexible as the hinged connected structures.

In contrast to the target roof displacements, the base shear forces increase from 425,827kN to 1212,296kN for ATC-40, from 394,862kN to 1327,147kN for FEMA-356, from 423,631kN to 1236,206kN for FEMA-440, and from 418,717kN to 1319,574kN for TEC-2007 with the connection percentages increasing from 0% to 100%. The increase in the base shear forces can be seen by comparison of Figs. 9 and 10, and also from Table 5. In addition, according to Table 5, for the smallest connection percentage (25%), the base shear forces increase 84% for ATC-40, 109% for FEMA-356, 87% for FEMA-440, and 97% for TEC-2007 compared to fully hinged connection (0%). All comparisons are concluded that the base shear forces obtained from the selected RC prefabricated structure with fully hinged connections are significantly smaller than those from the structure with semi-rigid connections. This situation points out that unexpected damages due to the earthquakes may be occurred at intersections of the column-foundation.



a) The connection percentage of 0%

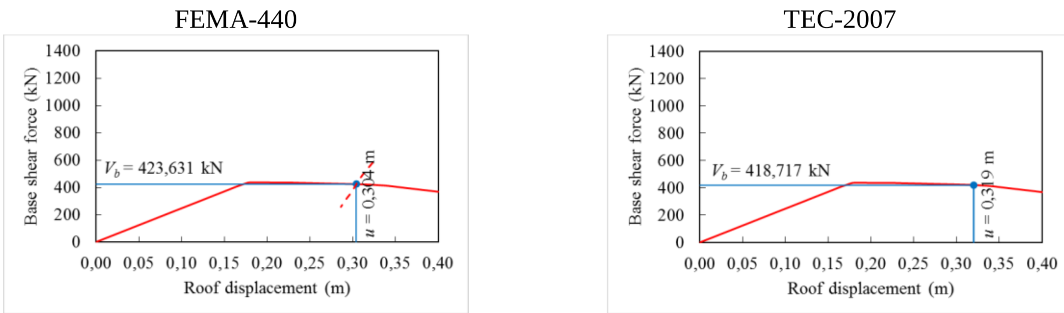
b) The connection percentage of 25%

c) The connection percentage of 50%

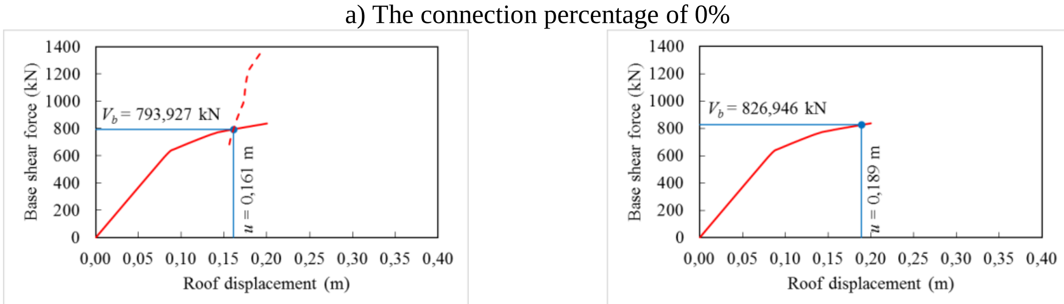
d) The connection percentage of 75%

e) The connection percentage of 100%

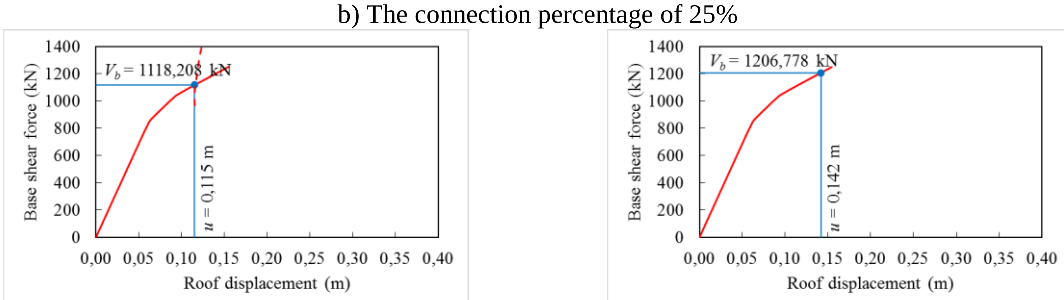
Figure 2. Pushover curves for ATC–40 and FEMA–356



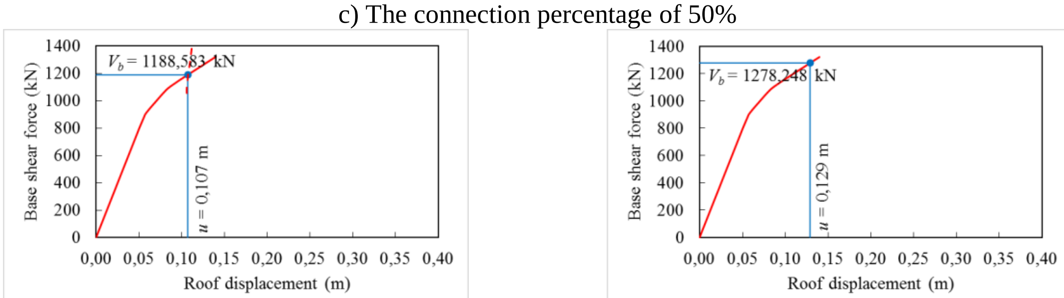
a) The connection percentage of 0%



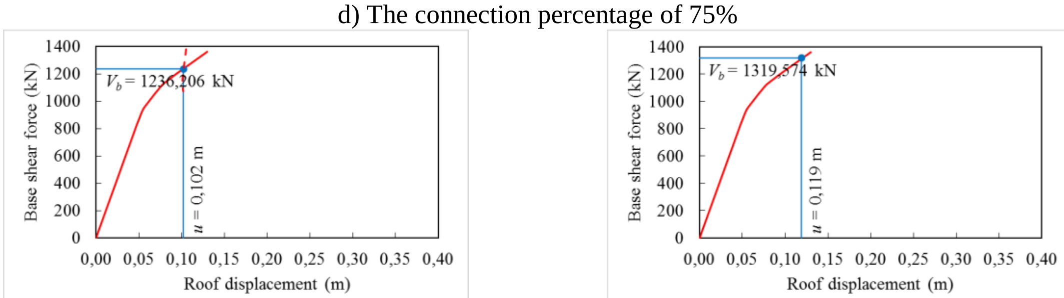
b) The connection percentage of 25%



c) The connection percentage of 50%



d) The connection percentage of 75%



e) The connection percentage of 100%

Figure 3. Pushover curves for FEMA–440 and TEC–2007

Conclusions

In this study, the effects of semi-rigid connections on seismic performance of prefabricated structures are investigated. Nonlinear static analyses (pushover analysis) of a selected RC prefabricated structure are performed with SAP2000 structural analysis program by considering various connection percentages (0%, 25%, 50%, 75%, and 100%) for bolted connections. Pushover curves of the selected RC prefabricated structure with the connection percentages are obtained from the nonlinear static analysis. The target roof displacements and the base shear forces obtained from the pushover curves according to ATC-40, FEMA-356, FEMA-440, and TEC-2007 codes are compared each other. It can be reached the following conclusions:

- The prefabricated structures cannot be as flexible as the hinged connected structures since they have semi-rigid connections, in fact.
- All comparisons show that the base shear forces obtained from the selected RC prefabricated structure with hinged connections are significantly smaller than those from the structure with semi-rigid connections. This situation points out that unexpected damages due to the earthquakes can be occurred at the column-foundation intersections.
- It is seen that the prefabricated structures are subject to higher base shear forces. Therefore, the hinged-connection assumption may not be suitable for the prefabricated structures.

Finally, the effects of semi-rigid connections should be considered in design and analysis of the prefabricated structures.

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