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DYNAMIC ANALYSIS OF FOLDED CANTILEVER SHEAR STRUCTURE AND BASE ISOLATED STRUCTURE

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ABSTRACT

Seismic isolation is the most important in earthquake resistant structural design. Many isolation techniques have been developed to reduce the impact of earthquake. The seismic responses of eleven-storey models of folded cantilever shear structure as a proposed structure have been studied numerically. Folded cantilever shear structure (FCSS) consist of fixed-movable-fixed supported shear sub-frames and connection rigid sub-frame which connect their sub-frames at the top. The movable sub-frame is supported by roller bearings and additional viscous damper are attached laterally between beams. In order to evaluate the efficiency of the seismic isolation system and the effect of earthquake ground motions, different structures as fixed base, rubber bearing system, and folded cantilever shear structure were analyzed. The analyses were carried out under some ground motions namely El-Centro 1940, Hachinohe 1968, and Taft 1952 earthquakes. The maximum acceleration and displacement responses for the seismic isolation were reduced generally. The main objective here is to make a comparison between the seismic isolation and fixed based structure, rather than comparing the seismic isolation within themselves. The earthquake responses are compared and results are discussed.

Keywords: Seismic Isolation, Folded Cantilever Shear Structure, Viscous Damper, Damping Ratio, Seismic Response.

I. INTRODUCTION

The purpose of earthquake prevention of buildings is to provide the structural safety and comfort by controlling the internal forces and displacement within the particular limits. Many methods have been developed for protecting the building structures against earthquake. Seismic isolation and energy dissipating systems are some of design strategies applied to increase the earthquake resistance of the structures. The seismic isolation device is installed in building structure to decrease the responses shown to the impacts such as earthquake. Recently, various kinds of device are used in the buildings for the purpose of seismic isolation. The principal of seismic isolation was studied by N. Torunbalci [1]. The characteristics of response forces can be controlled, by changing stiffness of the building. When stiffness of the building is decreased, the response acceleration also decreases and displacements increase. On the other hand, response of acceleration and displacement can be decreased, by increasing the damping effect of the building. Various kinds of dampers and their combinations can be placed in the building. Controlling and arranging the seismic forces that affect the building can be achieved by isolating the building from the ground. The most extensively used ones are the ones which belong to elastic systems class such as Rubber Bearing, High Damping Natural Rubber Bearing and Steel Laminated Rubber Bearing, the ones belonging to elasto-plastic systems class such as Lead Rubber Bearing and the ones belonging to kinematic systems class and friction pendulum systems class such as Friction Pendulum Bearing. Seismic base isolation systems have been studied of many researchers. Y.M Wu and B. Samali [2] investigated of five-storey benchmark model isolated with rubber bearing. Numerical analysis and shake table testing of model with and without the isolation system were studied under four different strong ground motions. The maximum floor acceleration increases with floor height and earthquake intensity. The efficiency of rubber isolators in protecting the five storey steel frame from earthquake attack is strongly dependent on the type of ground motion and for some earthquakes these isolators are in effective. N. Torunbalci and G. Ozpalanlar [3] also studied earthquake responses of building with various seismic isolation techniques. The model building is analyzed in the nonlinear time domain both for fixed base situation and also by using various seismic isolation and earthquake protection alternatives such us rubber bearing, friction pendulum bearing, additional isolated story and viscous damper. It shows that acceleration and story drift in all various alternatives, is significantly reduced especially in the fixed-base alternative. Thakare and Jaiswal [4] compared fixed base and base isolated building using seismic analysis, it was observed that the use of base isolation system provides more reduction in response compared with fixed base condition considered in the study. Base isolation helps in reducing the design parameters i.e. base shear and bending moment in structural members above the isolation interface by around 4-5 times. Besides, the others seismic isolation have been used. Panah *et al.* [5] studied the analysis of building structures equipped with energy dissipation system and subjected to strong earthquake excitation. The analysis was carried out by considering nonlinear time history, inherent damping coefficient and brace-damper dissipation system. An attempt has been made to analyze 15-storey steel rigid frame connected to viscous brace damper. In order to demonstrate the effect of dissipation system in the structures, an attempt has been made to compare its structural response in terms of inter story drift with and without dissipation devices. It was observed that structure equipped with control system devices, have the potential to improve the seismic behavior of structures. Garevski and Jovanovic [6] investigated the influence of friction pendulum system on the response of base isolated structures. The response of seismically isolated structure by FPS with different friction coefficients is also investigated and it is found that a small variation of the friction coefficient produces significant difference of the response for all earthquake excitation.

In recent years, the Friction Pendulum System (FPS) and additional viscous damper has become a widely accepted device for seismic isolation of structures besides rubber bearing. The concept is to isolate the structure from ground shaking during strong earthquake.

Folded Cantilever Shear Structure (FCSS) was proposed by Kaya *et al.* [7]. It is proposed an alternative seismic isolation approach that combines roller bearing as base isolation and viscous damper as connection between inter-stories to improve seismic performance and increase natural period. The proposed folded cantilever shear structure is designed consisting of mainly two parts, fixed shear sub-structure and movable shear sub-structure. These sub-structures are interconnected by a rigid connection beam at the top of the sub-structures. Besides, additional viscous dampers are supplemented to connect fixed and movable shear sub-structures with each other horizontally on the base of stories. The study was carried out to examine FCSS structure, also compare with ordinary cantilever shear structure (OCSS) and FCSS without additional damper numerically. From the results show the proposed model FCSS is capable of extending the natural period two times compared to ordinary structure and also can decrease the displacement responses due to earthquake. For advanced study to observe the behavior of FCSS, Kaya *et al.* [8] were conducted experimental of FCSS. To evaluate the efficiency of the additional viscous damper and effect of earthquake ground motions, free vibration and shake table testing of the model with and without the viscous damper device were carried out under some strong ground motions. The displacement responses of FCSS with damper show the decreasing than FCSS without additional damper. To continue this study, FCSS model was modified by Ming *et al.* [9]. It is modified to acquire symmetrical structural regularity. The proposed modified structure is designed consisting of fixed-movable-fixed shear sub-structures. At the top roof, rigid beam is used as a connection between fixed and movable parts. In order to observe the efficiency of the additional viscous damper and the effect of earthquake ground motion under three different strong ground motions, namely El-Centro, Hachinohe, and Taft earthquakes, shaking table test of the model with and without additional viscous damper were conducted. The maximum displacements, for top fixed floor and bottom movable floor were significantly reduced with the addition of viscous damper system of structure.

In the present study, an eleven storey structure with different seismic isolation as fixed base, rubber bearing and folded cantilever shear structure as a proposed structure were analyzed numerically. The analysis was carried out under some ground motion data waves. The numerical model and time histories analysis are simulated by used SAP2000. The main objective of obtained results is not the comparison of the seismic isolation alternatives, but their comparison with the ordinary fixed base building.

II. STRUCTURAL CONFIGURATION OF SEISMIC ISOLATION

1.1 Ordinary Building with Fixed-Base

Three dimensional model and time history analyses are carried out by using SAP2000 program. In this study, an eleven storey building model shown in Fig. 1 as an ordinary building is used for analysis. The structure model with 6 m space in the x direction and 8 m in the y direction. The height is 3.5 m, the thickness of the floor is 10 cm on all storeys. The column cross-section used in the structure is HSS 400x400x16x32 and beam cross-section H 440x300x111x18. Total mass of the structure is 5,500,000 kg. In the building standard law of Japan, the natural period of the ordinary building can be calculated by the following equation,

$$T=0.02H + 0.01\alpha \qquad (1)$$

where, T : natural period of building, h : height of the building, and α : the ratio of total height of stories of wooden or steel construction to the height of the building. In the Eq. (1), α =1 is assumed for steel frame building. The structural damping ratio is 0.02. From the analysis, the first natural period was obtained 1.16s.

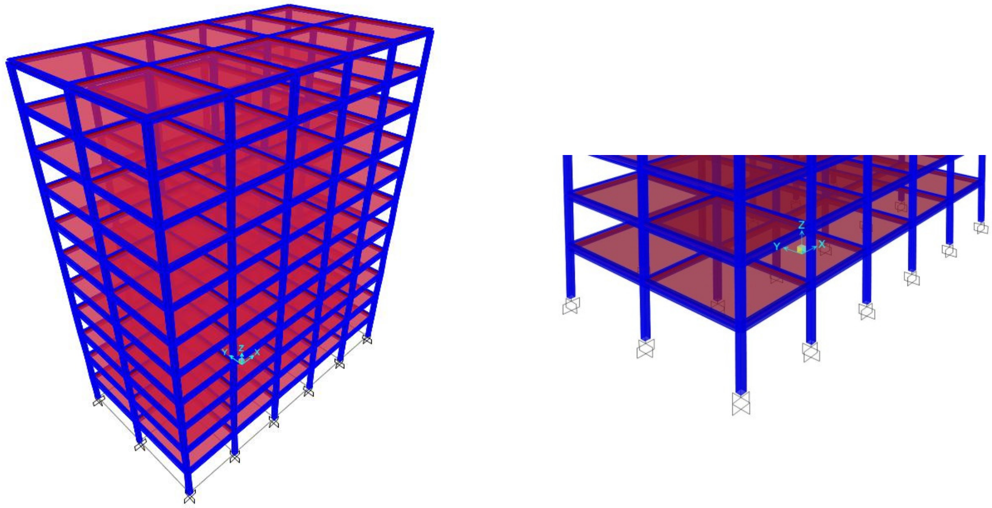


Fig.1. Model of fixed-base building as ordinary building

1.2 Folded Cantilever Shear Structure as proposed model

Model of a folded cantilever shear structure with eleven stories, with consists of a fixed shear sub-structure at both side, a movable shear sub-structure which is supported by roller bearing at middle of structure, and a connection beam which connect the top of the fixed-movable-fixed sub-structures. Besides, additional viscous dampers are supplemented between beams laterally to connect sub-frames to each other and minimize displacements to be occurred due to seismic movements and increase damping ratio as well.

Besides, the column stiffness is represented k whereas mass of beam is m and the additional damping coefficient is d. According to the main parts, m_F, m_M, m_C, are mass of beam fixed sub-frame, movable sub-frame and connection sub-frame, respectively. k_F, k_M, k_C, are column stiffness of fixed sub-frame, movable sub-frame and connection sub-frame, respectively. The equation of motion for the folded cantilever shear structure vibration model, illustrated in Fig. 1, can be expressed by the following equation in order to investigate the seismic characteristic behavior of the structure Kaya *et al.* [7],

$$\mathrm{M}\ddot{\mathrm{u}} + (\mathrm{C} + \mathrm{D})\dot{\mathrm{u}} + \mathrm{K}\mathrm{u} = -\mathrm{sgn}(\dot{\mathrm{u}}_{2\mathrm{n}})\mathrm{f}_{\mathrm{d}}\mathrm{e}_{2\mathrm{n}} - \ddot{\mathrm{z}}\mathrm{p} \qquad (2)$$

where $\boldsymbol{u} \equiv [u_1, u_2, \cdots, u_{2n}]$ is the displacement vector of size $2n$, $\dot{\boldsymbol{u}} \equiv [\dot{u}_1, \dot{u}_2, \cdots, \dot{u}_{2n}]$ is the velocity vector of size $2n$, $\ddot{\boldsymbol{u}} \equiv [\ddot{u}_1, \ddot{u}_2, \cdots, \ddot{u}_{2n}]$ is the acceleration vector of size $2n$, e_i is the unit vector of size $2n$, of which the i-th element is equal to 1, and f_d is the dynamic frictional force of the roller bearing system. The symbolsu_i, $\dot{u}_i$ and $\ddot{u}_i$ are the displacement, velocity, and acceleration of beam-i in the x direction, respectively. Then M is the diagonal mass matrix of size $2nx2n$, K is the tri-diagonal stiffness matrix of size $2nx2n$, C is the tri-diagonal structural damping matrix of size $2nx2n$, D is the additional damping matrix of size $2nx2n$. The matrices of M, K, C, and D are defined by the following formulas.

$$\mathrm{M} \equiv \text{diagonal}\,[\mathrm{m}_1, \mathrm{m}_2, \cdots, \mathrm{m}_{2\mathrm{n}-1}, \mathrm{m}_{2\mathrm{n}}] \qquad (3)$$

$$K \equiv \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2 + k_3 & -k_2 & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & -k_{2n-1} & -k_{2n-1} + k_{2n} & -k_{2n} \\ 0 & \cdots & 0 & -k_{2n} & k_{2n} \end{bmatrix} \quad (4)$$

$$C \equiv \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & \cdots & 0 \\ -c_2 & c_2 + c_3 & -c_2 & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & -c_{2n-1} & -c_{2n-1} + c_{2n} & -c_{2n} \\ 0 & \cdots & 0 & -c_{2n} & c_{2n} \end{bmatrix} \quad (5)$$

$$D \equiv d_0 e_{2n} e_{2n}^T + \sum_{i=1}^{n-1} [e_i, e_{2n-1}] \begin{bmatrix} d_i & -d_i \\ -d_i & d_i \end{bmatrix} [e_i, e_{2n-1}]^T \quad (6)$$

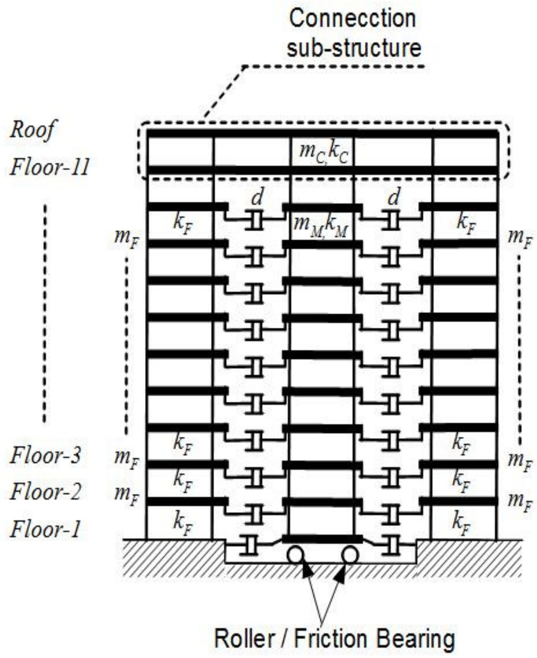


Fig.2. Model of folded cantilever shear structure

Fig.3 shows 3 dimensional model of folded cantilever shear structure in SAP2000. The story mass of fixed sub-structures is 125,000 kg, movable sub-structure is 250,000 kg and 500,000 kg for movable bottom part. Besides, the mass of connection floor to connect fixed-movable-fixed sub-structures is 500,000 kg. The total mass of fixed shear sub structure is 1,375,000 kg and movable shear sub-structure is 3,250,000 kg. Therefore, the total mass of whole structures is 6,000,000 kg. The characteristic of the isolators and dampers used are selected from the available or producible products in the light of the information obtained from the manufactures. The additional damping coefficient of viscous damper is taken as 0.37 x 10^6 Ns/m. Friction pendulum link elements in the model are oriented such that the positive local 1 axis is parallel to the positive global Z axis, the positive local 2 axis is parallel to the positive global X axis and the positive local 3 axis is parallel to the positive global Y axis. The parameters were input into properties of bearing is obtained by calculating the structure period, sliding surface radius, friction coefficient, vertical load and horizontal displacement.

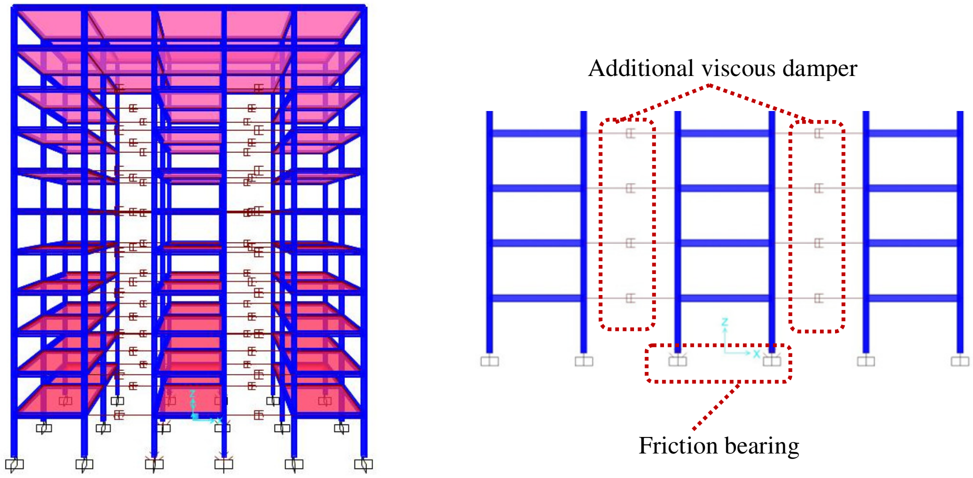


Fig.3. 3 dimensional model of folded cantilever shear structure

1.3 Base isolated structure with rubber bearing

The base isolation system that has been adopted most widely in recent years is the use of elastomeric bearing. In this approach, the building or structure is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation. Rubber bearing are most commonly used for this purpose. These bearings are widely used for the support of building. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction. Vertical rigidity assures the isolator will support the weight of the structure, while horizontal flexibility converts destructive horizontal shaking. Fig.4 shows 3 dimensional model of base isolated structure with rubber bearing in SAP2000. Total mass of the structure is 5,500,000 kg as an ordinary building. The parameters were input into properties of bearing is obtained by taking the material from available information of manufacture.

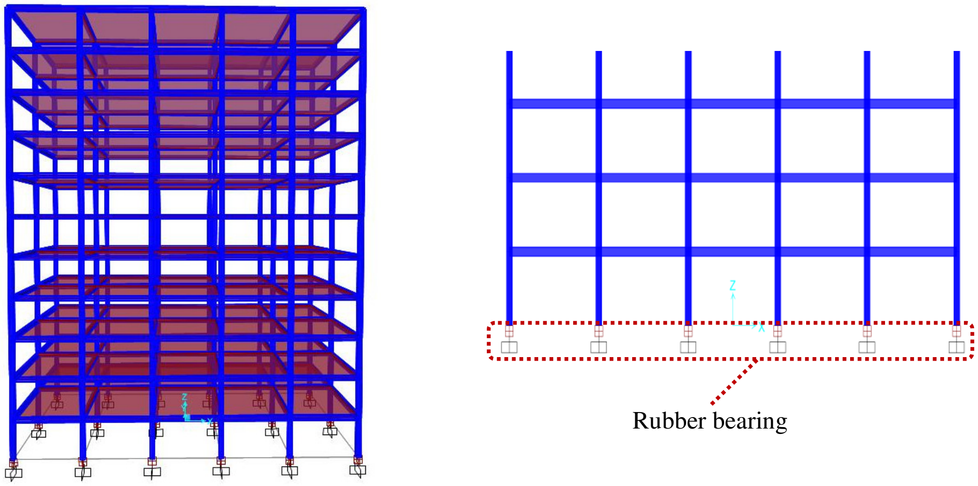


Fig.4. 3 dimensional model of base isolated structure with rubber bearing

III. NUMERICAL ANALYSIS RESULTS

1.4 Structural period

Seismic isolation is an earthquake resistant structural design approach based on the principle of decreasing the demand of the earthquake from the structure, instead of increasing the earthquake resistance capacity of the structure. The most important characteristics of the structural system, in terms of determining its response against the earthquake, is its natural period. One of the important things the seismic isolation actualizes on the structure is the prevention of coincidence with the fundamental period of the earthquake by increasing the natural period of the structure. Natural period of each model is shown in Table. 1.

Table. 1 First period of structures

Structures	Period (second)	Frequency (second^{-1})
	T_1	ω_1
Ordinary	1.167	0.857
FCSS	2.570	0.389
Rubber Bearing	4.175	0.239

The natural period of the structure being 1.167 s in fixed base situation. The folded cantilever shear structure has the natural period of approximately two times as long as the natural period of ordinary structure. It is confirm as previous study that FCSS as proposed model can increase two times of first natural period. However, the structure with rubber bearing has much influence on the natural period.

1.5 Seismic responses

To investigate the effectiveness of the control system for different structures systems, three data waves El-Centro 1940, Hachinohe 1968, and Taft 1952 earthquakes was input as dynamic analysis in SAP2000 program. The peak ground accelerations (PGA)are scaled 300g. . To set an example, only acceleration and displacement responses due to El Centro NS earthquake are given in Figure 5 and Figure 6, respectively. Then the response value results of the others are summarized graphically of bar chart in Figure 7 and Figure 8.

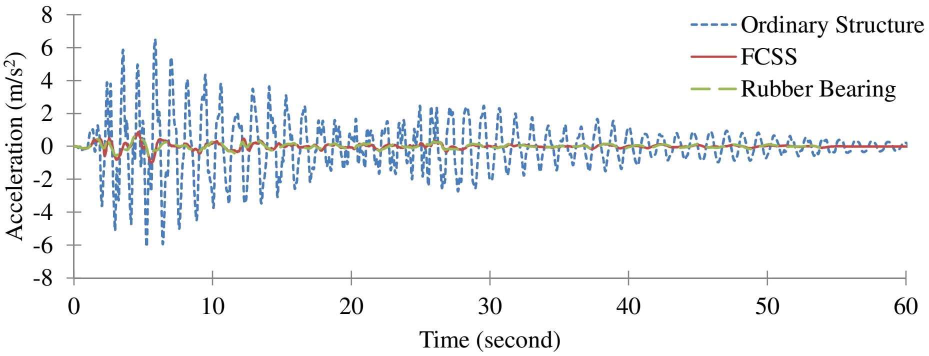


Fig.5. Time histories of acceleration responses at the top floor

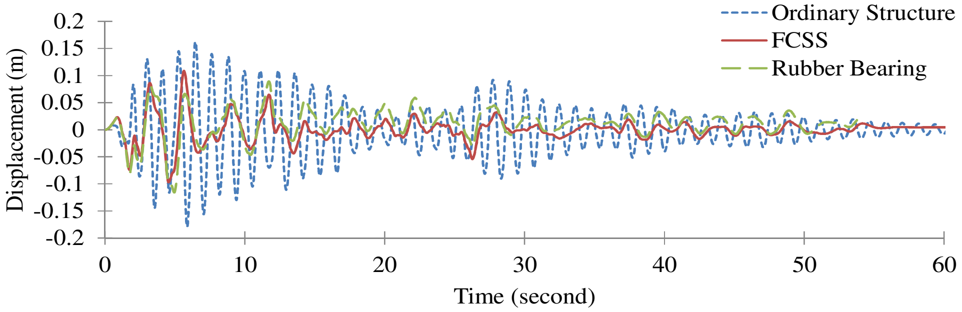


Fig.6. Time histories of displacement responses at the top floor

From Fig. 5 and 6, both of seismic isolation system as FCSS and rubber bearing can reduce the acceleration and displacement response of structure. It is seen that significant reductions in the acceleration response. FCSS model can reduce about 84.66% and rubber bearing about 89.36% of ordinary structure. In displacement the maximum responses can reduce 39.46% of FCSS and 35.41% of rubber bearing. On the other hand, it can remark that FCSS as proposed model also has capability to reduce the seismic response. Shown in Fig. 7 and Fig. 8 depict maximum acceleration and displacement responses for all earthquake data wave. In general for acceleration responses, both of the seismic isolation system can decrease the seismic response significantly. In Fig. 8 is found the seismic isolation system is not able to reduce the potential structure damage from earthquake. It can be seen at El Centro (EW) and also Hachinohe (NS) of earthquake waves.

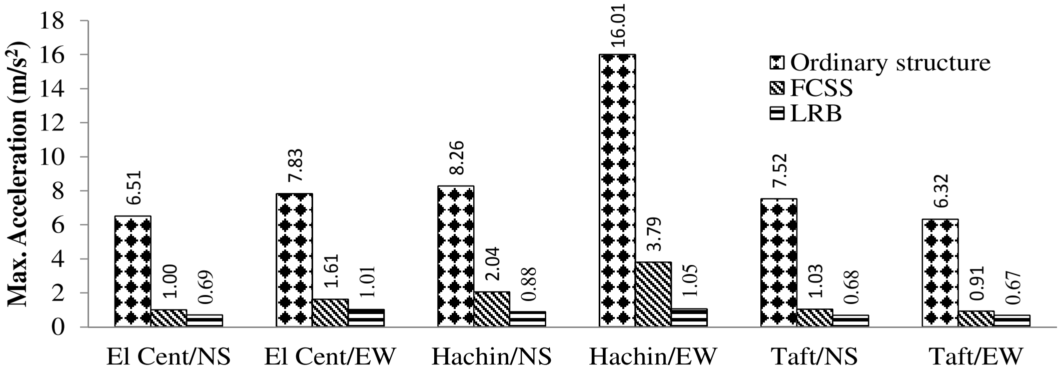


Fig.7. Maximum acceleration responses at the top floor

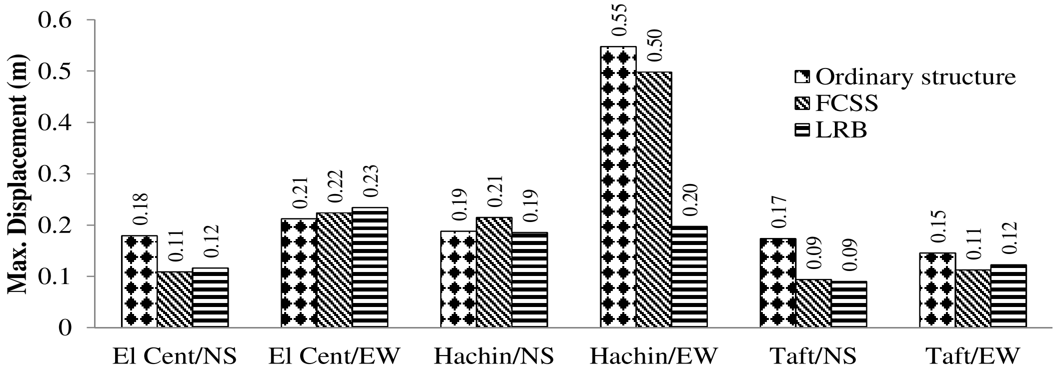


Fig.8. Maximum displacement responses at the top floor

To provide more information about the performance of the structures, plastic hinge patterns are investigated using default-hinge properties in SAP2000 which implements from FEMA-256 and ATC-40. It compare at different location of structures and at different time step.

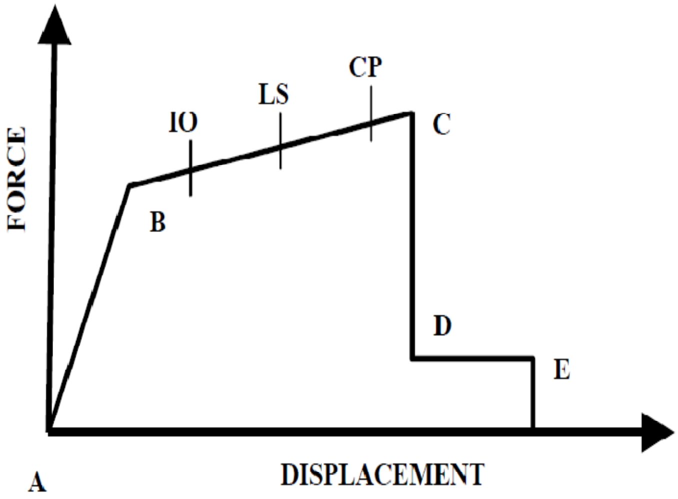
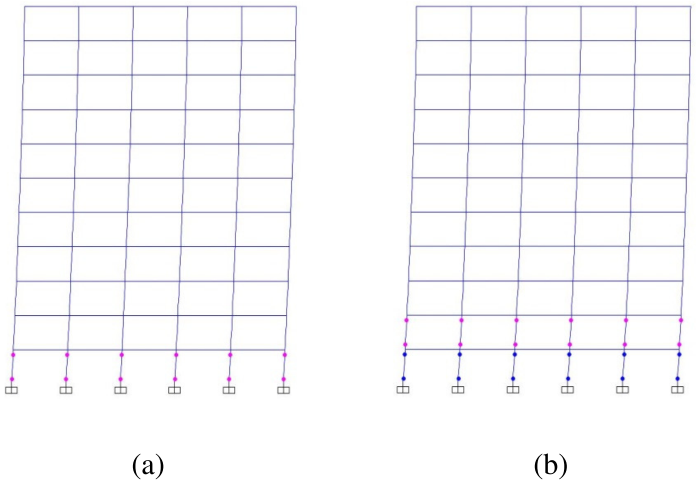


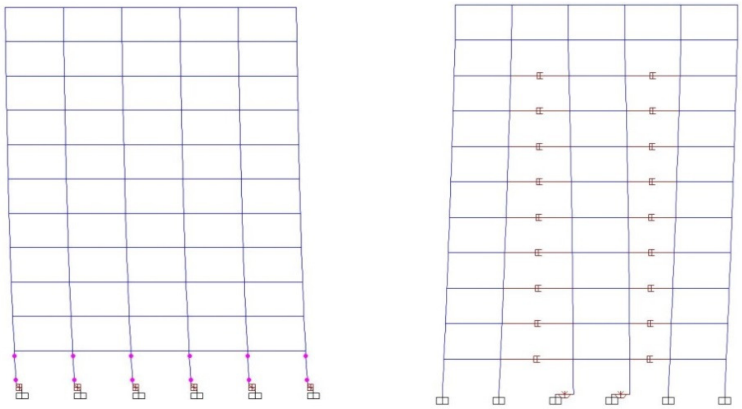
Fig.9. Force-displacement relationship of typical plastic hinges

As shown in Figure 9, five points labeled A, B, C, D, and E are used to define the force-displacement behavior of the hinge and three points labeled IO, LS, and CP are used to define the acceptance criteria for the hinge. The IO, the LS and the CP stand for Immediate Occupancy, Life Safety and Collapse Prevention, respectively. These are informational measures that are reported in the analysis results and used for performance-based design.



(a) (b)

Fig.10. Plastic hinge distribution of ordinary structure due to El Centro (NS) earthquake wave: (a) at 2.96s ; (b) at 2.97



(a) (b)

Fig.11. Plastic hinge distribution of seismic isolation structures due to El Centro (NS) earthquake wave: (a) FCSS ; (b) Rubber bearing system

For the ordinary structure shown in Fig.10, plastic hinge formation starts with column ends at the first floor, at 2.96s with Immediate Occupancy (IO) label and the hinges propagates at 2.97s with Life Safety (LS) at the first floor and Immediate Occupancy (IO) at second floor. Then it will propagate to whole structure. In Fig. 11 (a), the structure with rubber bearing as seismic isolation also will start plastic hinge formation at the first floor but it started at 7.82s with Immediate Occupancy (IO) label. The propagation of plastic hinge is slow. For the analysis of FCSS model in Fig.11 (b), it shows that there are significant differences in hinge pattern. FCSS model did not present plastic hinges formation under earthquake motion. This also can demonstrate the effectiveness of the seismic isolation system on structure.

IV. CONCLUSION

This study is carried out to investigate the FCSS model as alternative proposed structure as seismic isolation system. Three dimensional model of folded cantilever shear structure (FCSS) with fixed – movable – fixed sub frames was analyzed. To observe the performance of FCSS, the different seismic isolation system is used. The main objective of obtained results is not the comparison of the seismic isolation alternatives, but their comparison with the ordinary fixed base building. According to the numerical analysis, it is found that:

1. The proposed FCSS model is capable of increasing natural period of ordinary structure.
2. It was also observed that the efficiency of seismic isolation system both FCSS and rubber bearing in protecting the structure from earthquake is dependent on the type of ground motion and for some earthquakes the type of seismic isolation are ineffective.
3. From failure mechanism by investigated plastic hinge, it can be remarked that the FCSS model can satisfy the performance of structure under earthquake.
4. Proposed FCSS model has seismic responses stability and able to reduce seismic responses of the different earthquake ground motion generally, although rubber bearing as general seismic isolation has been used.

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