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Seismic Performance of Steel Moment Frame with Side-Plate Connections Combined with Friction Dampers

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ABSTRACT

With the gradual change in the design method of structures from resistance-based methods to performance-based methods, existing common building frames do not respond to the criteria of these methods, and if these frames are designed with new performance criteria, the design will be uneconomical. The basic problem of the existing types of frames is the imbalance between hardness and plasticity in them. A structure must have sufficient hardness in order not to be displaced in an earthquake, and it must have high ductility in order to dissipate the energy of the earthquake well. In this article, the purpose of the structure's performance in the combination of friction dampers and side-pleat joints in the steel structure of the bending frame is according to the constraints in solving the problem such as architectural, executive and design limitations and considering the uncertainties inherent in the system. This problem is solved in such a way that all three conditions are estimated, and for this purpose, three structures, 6, 10, 15 stories, have been modeled in three dimensions and have been analyzed under time history analysis. In examining the arrangement of dampers in the frames, the amount of energy in the 3x3 structures in the second frame is more than the first frame, which has increased by about 15%. But in 5x5 structures, the amount of energy when the frame damper is 3 is more than other frames. In these structures, when the damper is in the third frame, the energy of the structure has increased by about 10% compared to other states. Also, the effect of side plate connection in increasing the hardness is also important. that the above connection will reduce displacement by creating hardness at the connection point, and as a result, it will absorb more energy.

Keywords: Friction damper - side plate connection - time history analysis

INTRODUCTION

One of the methods to control structures vibrations and seismic loads effect is to make use of energy dissipation equipment or dampers. It is simply possible to make use of these equipment to design new buildings and to retrofit existing buildings. Dampers seek to dissipate seismic energy instead of increase the plasticity of structures elements. It is possible to recognize the increasing of energy absorber tools to structures or structures seismic isolation through structure control methods. Structure control has witnessed many developments during two recent decades. According to the nature of energy dissipation of earthquake, control systems have been classified into three categories: active control, semi-active control and passive control.

Friction dampers are considered a part of passive systems and are increasingly used in moment frames. Many projects are conducted in the world related to these dampers. It is worth to note that the semi-active systems have been recently produced that are used both as a brace and as a separator. The performance of passive friction dampers has been studied in different researches and new algorithms have been provided for analysis of structures with these type dampers. All of these researches confirmed the satisfactory performance of these dampers to decrease seismic responses of structures. Such dampers are classified as hysteresis damper and they dissipate the energy through displacement and their slip load. In fact, all existing friction dampers act in the same way, so that one part is fixed and another part slip on dynamically.

Slippage occurs at a certain level of power in which no movement occurs until such level is reached. However, the slippage and movement start after such level. The movement occurs based on Coulomb friction law and these dampers create stable loops usually. Rotational friction dampers are considered as a special type of passive friction dampers. They was provided by Mola for the first time in 2002 in his Ph.D. thesis and they are called new friction damper in literature. They could be used in different brace systems.

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Reliability of a structure is dependent to control of errors sources and to decrease them. Errors are deviation of acceptable process, the inseparable section of human being activities leading to significant uncertainties in the process of designing and structuring. In fact, literature shows that human errors are considered as the dominant reasons of structure failures in buildings and bridges. It is therefore so important to identify and control such errors to be able to improve and increase the reliability and certainty of structures. In other hand, we could classify the existing uncertainties in construction process based on their sources. Two main sources of uncertainty are: natural events and human being events. Natural events come from natural issues including wind, earthquake, temperature inhomogeneity, and snow load or ice accumulation. The normal changes include building materials features (e.g. resistance of elastic module and its dimensions), loads such as individuals and materials weight or vehicle load on bridges.

Human events could be classified into two groups:

- Events occurred during construction process including innovations, unique structures, making use of new materials and structures and errors arising from deviation of known methods.

- External vents including fire, explosion, accidents and the similar cases.

Objective

This study aimed to consider the performance of structure in the combination of friction dampers and side-plate connections in steel moment frame structure considering to existing constraints in problem-solving including architecture, functionality and designing limitations and considering potential uncertainties in system. This problem should be solved in a way that all three conditions should be met certainly. Three conditions are: (1) the given location should be suitable for design earthquake and it satisfy suitable performance level, (2) reliability coefficient in optimal condition should have the least difference with design reliability coefficient, and (3) the structure cost should be decreased to the least level which is has direct relationship with the used sections and the weight of consumed materials.

Review of Related Literature

The method of fragility curves production using capacity spectrum was provided in 2015. Researchers plotted fragility curves using nonlinear static analysis method for displacement between floors. Mostafa (2018) calculated fragility curves for nonstructural systems for the first time, in which a 40 ton water resource was studied on the roof of a 20-floors hospital as a real condition. In that study, the hospital was subjected to different stimulations in terms of PGA and the seismic response of roof was considered as input in the stimulation of secondary system of water resource. The difference between fragility curves of this study with literature was that horizontal axis was partial displacement diagram of drift stories. In 2013, Pangi from Washington University provided a damage model for parts of old reinforced concrete. He introduced 12 damage states for components including initial cracking, beam-column commons, crack in concrete parts with a width of 5 mm to fracture and crushing of concrete. Pangi grouped the 12 damage states into two categories including concrete cracking and concrete crushing. Then, he determined the best distribution between normal, log-normal, weibuill and beta distributions using maximum likelihood method.

In 2004, fragility curves to retrofit structures was provided in Istanbul. To this end, researchers provided four models with concrete stories. They made use of different models including wind bracing and shear wall in their retrofitting design. Furthermore, they made use of nonlinear dynamic method to analyze fragility curves and plotted fragility curves for between-stories displacement in different levels of PGA.

In 2006, Arizaga plotted fragility curves for steel moment frame structures using PERFORM software and nonlinear dynamic analyses for frames of 2, 3, 4, 6, 8 and 10 stories. He produced fragility curves using FEMA regulation and based on PGA and inter-floors displacement. Baker Ozer et al. (2006) studied buildings of the Turkey and attempted to develop the seismic failure curve for buildings with 3, 5, 7 and 9 floors which were designed based on given regulations. In their work, structures systems were concrete moment frame and the model of structures was two-dimensionally designed using SAP2000 software and evaluated and analyzed using IDARC-2D software. The structures frame was classified into two categories including weak category (2 with poor quality) and excellent category (3 with suitable quality) considering certain features of construction process and observed performance after big earthquakes in Turkey. Then, failure curves were plotted in different classifications with regard to dominant effective parameters on seismic performance. These parameters included the number of floors and structural deficiencies that were created in the designing and construction stages. It seems that number of floors was considered as an important parameter for buildings seismic vulnerability.

Passive energy dissipation systems including dampers are new technology that is able to optimize the responses of structures or to increase damping. Recently, literature attend to control of structure response against earthquake using passive energy dissipation in which the effect of distribution or dampers displacement on structure behavior was studied in detail that we mention some of them here.

Various methods were suggested for dampers displacement and damping suitable distribution in the height of structure so far. Some researchers including Constantine and Tajbakhsh (1983), Ashour and Hansen (1987), Girgouse and Moler (1992), Han et.al. (1992) studied these issues. In a study, Constantine and Tajbakhsh [5] calculated the optimal damping coefficient for viscous damper that was located at the first floor. In this research, the hypothesis was based on shear behavior of building.

Jang and Song (1992) provided step-by-step search algorithm to find optimal location for dampers as ordinal where their effects were maximum level. The base of such dampers displacement method was the basic of control index in floors. Firstly, the system response was calculated without considering dampers. Then, values were considered as optimal situation indexes. The biggest drift square index between floors is calculated which shows the optimal situation of the first damper. The second damper is located in the floor that the modified optimal index is the maximum. This process continues until all dampers are placed exactly. Size of all dampers is assumed to be the same. Since all dampers have the same size, SSA have the most practical method, because it could provide the numbers of possible options in spite of equations related to shape and size. For example, if the size of dampers is limited, we could calculate the size simply. Effect of two dampers with the same size that are located in the same floor is equal with the effect of a damper with twice the size of primary dampers located in the same floor. Therefore, we could control the numbers of different sizes of dampers through constraining the number of dampers in a floor. The only complication of this method is related to calculation of optimal situation indexes [6].

In 1999, Sing and Morichi studied the application of genetic algorithms to optimal design of viscous dampers to be able to decrease structure response [9]. Furthermore, Bagheri and Fallah [3], in another study, provided a genetic algorithm to determine the number and optimal layout of viscous dampers to control seismic vibrations of buildings. In this study, shear model of a building with 10 floors was evaluated in two controlled state with viscous dampers and uncontrolled state under three earthquakes. Results showed the optimal performance of this algorithm with uniform distribution of dampers.

Evolution of sequential method provided by Jang and Song is simple sequential search algorithm (SSSA) that was provided by Lopez Garcia in 2016. It seeks to more simplify the method for displacement of passive systems using computational reduction of optimal situation indexes and simulated movements of earth. Related to structures with viscous linear dampers, this method will have more effect than to complicated methods such as displacement method in Tikwaki and Klag works based on drifts between floors [11]. In this method, all dampers are sequentially located in the maximum speed location between floors through determination of a damping coefficient for all dampers. This operations continuous until all dampers located optimally. To evaluate reflection and efficiency of this method, the obtained displacement responses of this method compared with existing displacement methods response and results showed that reflection and efficiency of obtained displacements are equal with the efficiency of old complicated method.

2. Project Features

The given structure in this paper are three structures including 3, 10 and 15 floors which have been modeled in three dimensions (3D). Each of them have two different states. One in the form of 3 openings in 5 meter in both directions and the another have 5 openings in 5 meter in both directions of X and Y.

3. Modeling

Three models are considered and are modeled using ETABS software. This software is a finite element software and have the ability to analyze linear and nonlinear static and dynamic analyses.

3.1 Designing of Friction Damper based on Seismic Performance Index (Amola Method)

The most accurate method to determine optimal slip load is to make use of sum of nonlinear time history analyses. It means that we should analyze the nonlinear time history of the structure for sum of slip loads. Then, structure responses including partial displacement of floors, base shear, floors acceleration and etc. should be registered in detail. At last, optimal load of slip will be equal with the load that minimize our desired response. The optimal minimum response could be equal with structure displacement, base shear, floors acceleration and or input energy on structure. Mola (2002) provided an index as SPI that was a combination of other executive indexes in which the slip load that could minimize this index will be determined as optimal slip load. In the following formula, Rf, Re and Rd refer to maximum displacement of the roof, base shear and structure dissipated energy with friction damper to initial structure without damper. Therefore, we should model the damper in the structure and then analyze multiple time history and structure responses.

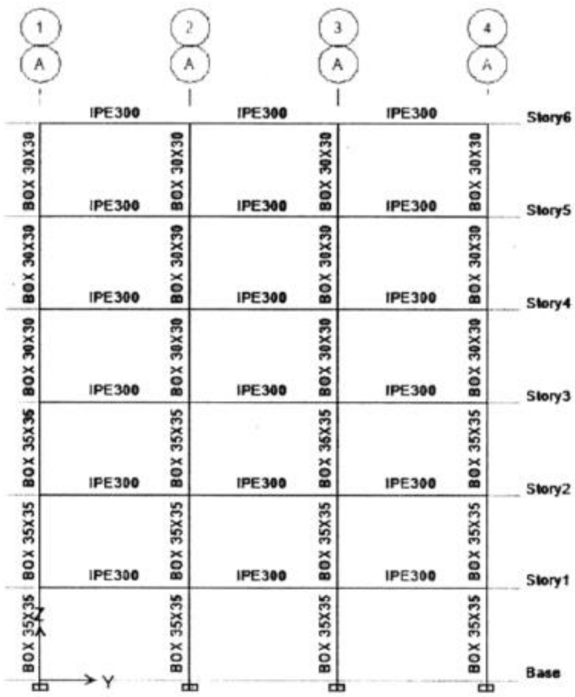

Figure 1. The features of structure with 6 floors and 3 openings

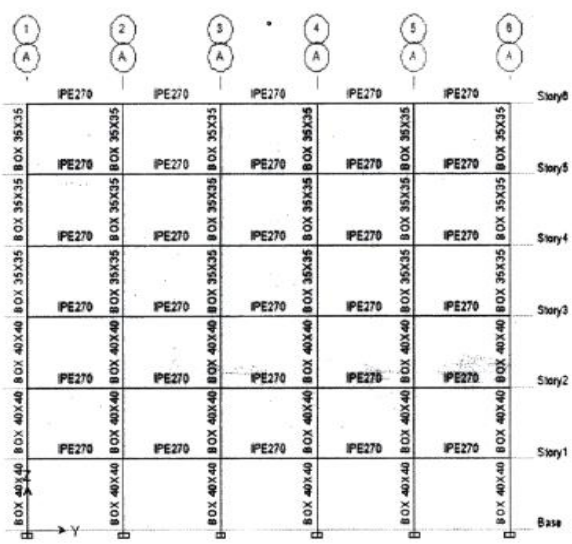

Fig 2. The features of structure with 6 floors and 5 openings

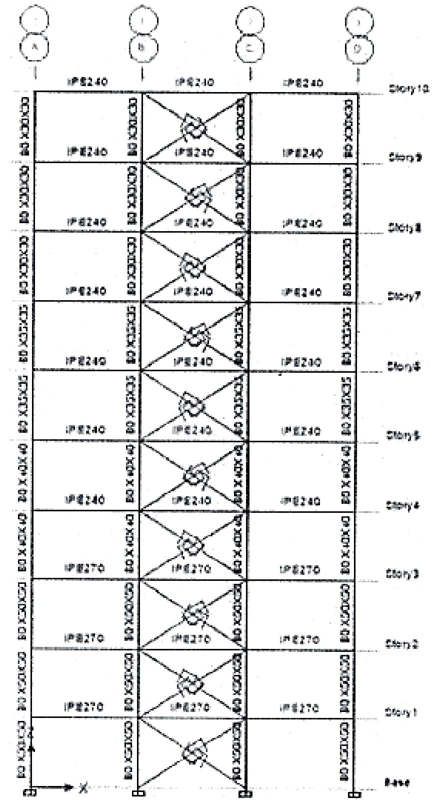

Fig 3. The frame of structure with 10 floors and through damper

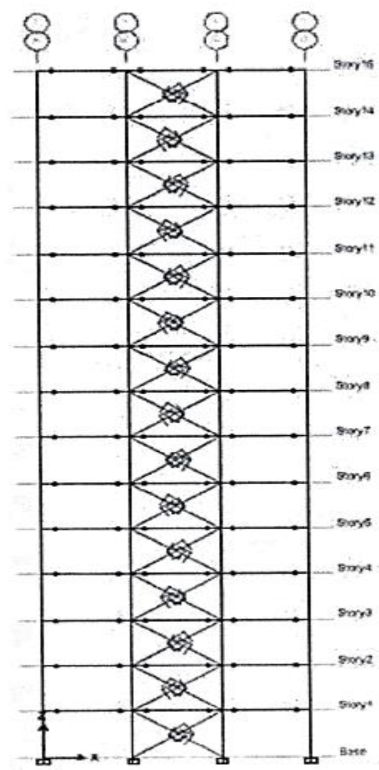

Fig 4. The frame of structure with 15 floors and through damper

Response reduction factor

This factor is a structure equipped with friction damper with elastic parts response to initial moment frame of the structure with elastic parts.

$$R_d = \frac{D_f}{D_p}$$

In which, D_f refers to structure displacement equipped with friction damper and D_p refers to initial moment frame structure displacement.

Base shear reduction factor

This factor refers to base shear equipped with friction damper with elastic parts to base shear of initial moment frame structure with elastic parts. Base shear factor is considered as a factor to elasticize the structure.

$$R_P = \frac{D_F}{D_P}$$

In which, V_f is base shear equipped with friction damper and V_p is base shear of initial moment frame of the structure.

Energy dissipation factor of Damper

This factor is defined as the ratio of the remaining energy share in the form of the difference between the total energy and the energy dissipated by the damper to the total energy for a structure equipped with a friction damper with elastic parts.

$$R_d = (E_i - E_h)/E_i$$

In which, E_i shows the input energy to structure equipped with friction damper and E_h is dissipated hysteretic energy by the damper.

Efficiency index of damper (seismic performance)

This index is a hybrid index including three previous factors that was applied by Mola for rotational friction dampers.

$$SPI = \sqrt{R_d^{\text{٢}} + R_f^{\text{٢}} + R_e^{\text{٢}}}$$

This index, in fact, is an optimizing index and the design engineer could make use of weight coefficient related to each factor based on their importance:

$$SPI = \sqrt{W_d^{\text{٢}} R_d^{\text{٢}} + W_f^{\text{٢}} R_f^{\text{٢}} + W_e^{\text{٢}} R_e^{\text{٢}}}$$

In which, W_d refers to base shear reduction factor and W_e shows the energy dissipation factor of the damper.

We made use of Multi Linear Plastic element to model the friction damper. Computation related to each of models are provided as follows:

$$T_g = 0.474\,Sec, \quad a_g = 0.32g \;, T_u = 1.94$$

$$M_3 = 25026 kg.s^2/m \;, M_9 = 75080 kg.s^2/m$$

$$M_{20} = 111304 kg.s^2/m$$

$$V_0/(m.a_g) = 1.9(Tu/Tg) = 0.4636$$

$$V_0 = 0.4636 * 0.32 * 9.81 * Mi$$

$$V_{si} = V_0/n$$

$$2 * Pi * \cos a = V_{si}$$

3.2. Nonlinear Dynamic Analysis

In the nonlinear dynamic analysis, the structure response is computed based on material' nonlinear behavior and considering geometric structure' nonlinear behavior. In this method, we assume that the hardness and damping matrix could change step-by-step, however, it is stable during each time step. Then, the model response under earthquake acceleration is computed to numeric methods and for each time step.

3.3 Dynamic Analysis of Time History

In this method, structure' dynamic is analyzed through applying earth acceleration as a time function in the base level of building and making use of common computations of structures' dynamics. The earthquake acceleration is determined according to conditions of accelerograms. Each pair of accelerograms are influenced in two directions perpendicular to each other in the main stretches of the structure simultaneously. In this method, we could make use of seven pairs' accelerograms instead of three pairs given accelerograms and then we could consider the average value of the reflections obtained from them as final reflection.

Analysis of Nonlinear Time History

Nonlinear features of structure parts used in the model should be compatible with the laboratory data or analytical models in terms of resistance, hardness and plasticity. Damping ratio should be determined based on structure' nonlinear features. If there is not sufficient data, we could take damping ratio as 5%. Time history analysis-based designed structure should be approved by qualified private person or an independent legal entity in which the following conditions should be met preciously:

- The accelerograms used in whole analysis
- Compatibility of structure’ specifications with data used in whole analysis
- Compatibility of capacity of structure parts with the obtained results of the analysis

Nonlinear Analysis of Time History

To determine the probable performance of structure under a specified earthquake, we could compare our results with the obtained data through experiments on the samples of structure components directly. In this method, we determine the total displacement maximum applied by certain accelerogram and it is not required to estimate this parameter based on the theoretically-experimental relations. It is a complicate method, however, is the most accurate method to evaluate the structure’ inelastic demands under effect of accelerograms of earth movements. Through time history analysis, the effect of higher modes and changes in the inertial load model are considered automatically because of softening of the structure.

RESULTS

4.1 Evaluation of the Roof displacement History

In this section, history level of roof point displacement is considered in the structure. The structures in states 3*3 and 5*5 are studied without brace and also with the change of brace location. According to the fig 5, 6 and 7, we could see that displacement history is higher in all systems without damper compared with the states with damper. However, displacement history in 3*3 structures in which time frame is in the second frame is less than damper presence in the first frame and almost 20% has been decreased in the second frame. According to results, in structure of 5*5, the displacement history in the first frame was less than other frames and the displacement level has been decreased 10% approximately. As well as, we observed displacement decrease in other states, however, the behavior of the system without damper and with damper had no significant different in some sections of floors and the decrease of displacement history in maximum point in some systems was 3 to 5 percent approximately.

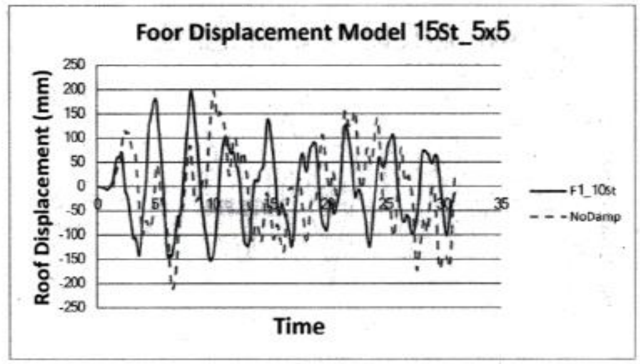

Fig 5. Displacement history of structure roof with 15 floors and damper with frame 1 up to the 10th floor and without damper

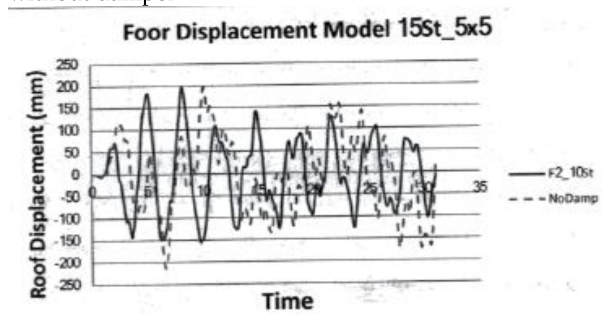

Fig 6. Displacement history of structure roof with 15 floors and damper with frame 2 up to the 10th floor and without damper

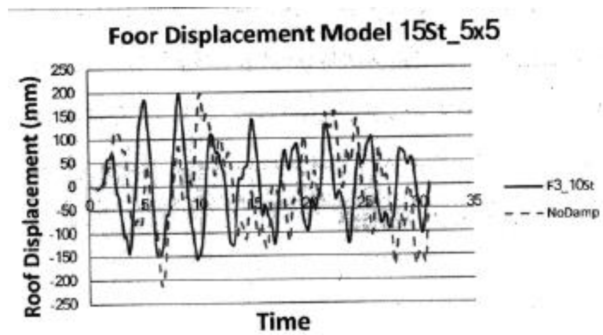

Fig 7. Displacement history of structure roof with 15 floors and damper with frame 3 up to the 10th floor and without damper

4.2 Evaluation of Base Shear History

The history of structures’ base shear in structures with 6, 10 and 15 floors studied once with 3*3 plan and once with 5*5 plan and damper’ various arrays. According to fig 8, 9 and 10, results showed that when damper was in 3 frame, the time base shear increased the hardness of structure in compared with other states. Consequently, the level of structure base shear has increased in this state. In another models in which damper continued up to special floor and then it removed, the base shear level has increased and then decreased heterogeneously. Such state might lead to twisting of the structure; however, it might improve the seismic behavior of some structures.

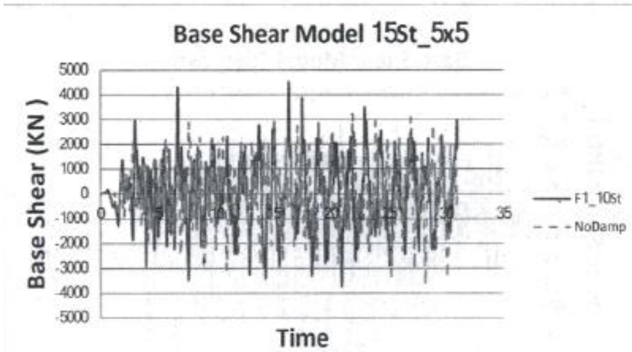

Fig 8. Base shear of structure with 15 floors- with 1 frame damper up to the 10th floor and without damper

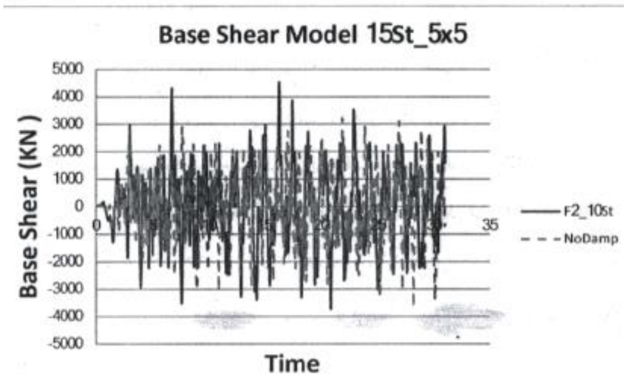

Fig 9. Base shear of structure with 15 floors- with 2 frame damper up to the 10th floor and without damper

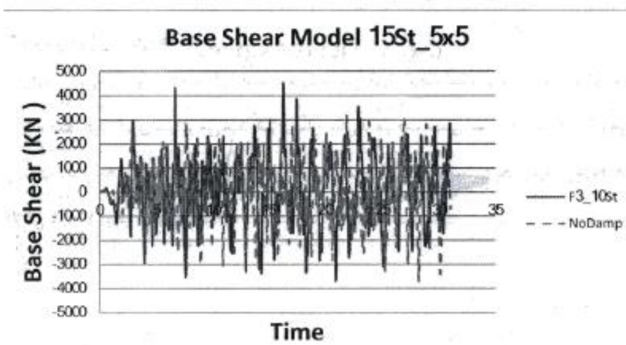

Fig 10. Base shear of structure with 15 floors- with 3 frame damper up to the 10th floor and without damper

4.3 Evaluation of Structure Performance Levels

One of the most important results of this section is to evaluate the elements of beam and column and their failure level given to situation and color of plastic joints. The created plastic joints in structure show the failure level based on their color.

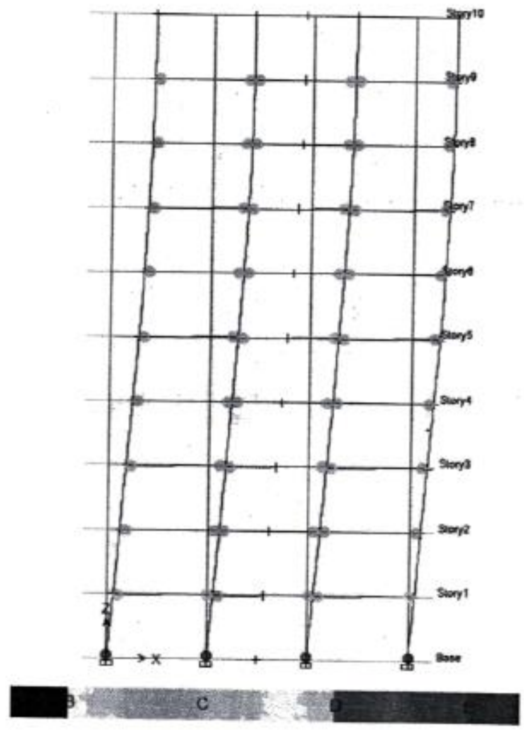

Fig 11. Performance level of Structure with 10 floors without side-plate connection

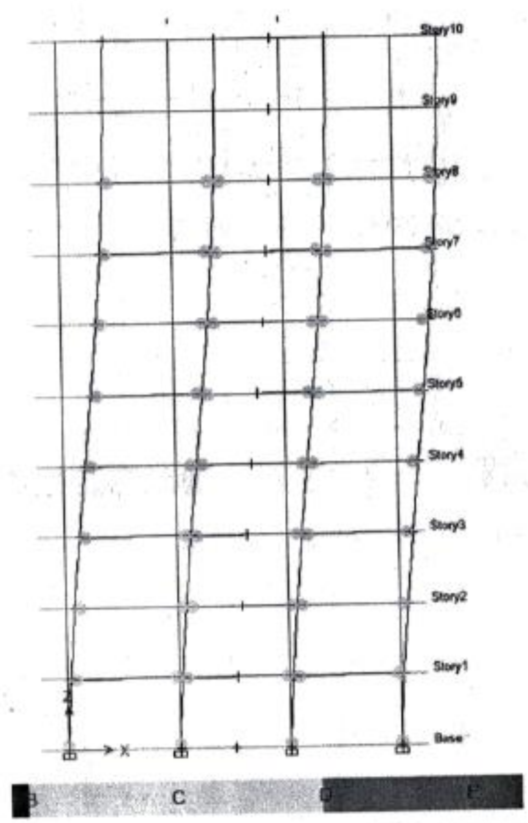

Fig 12. Performance level of Structure with 10 floors with side-plate connection

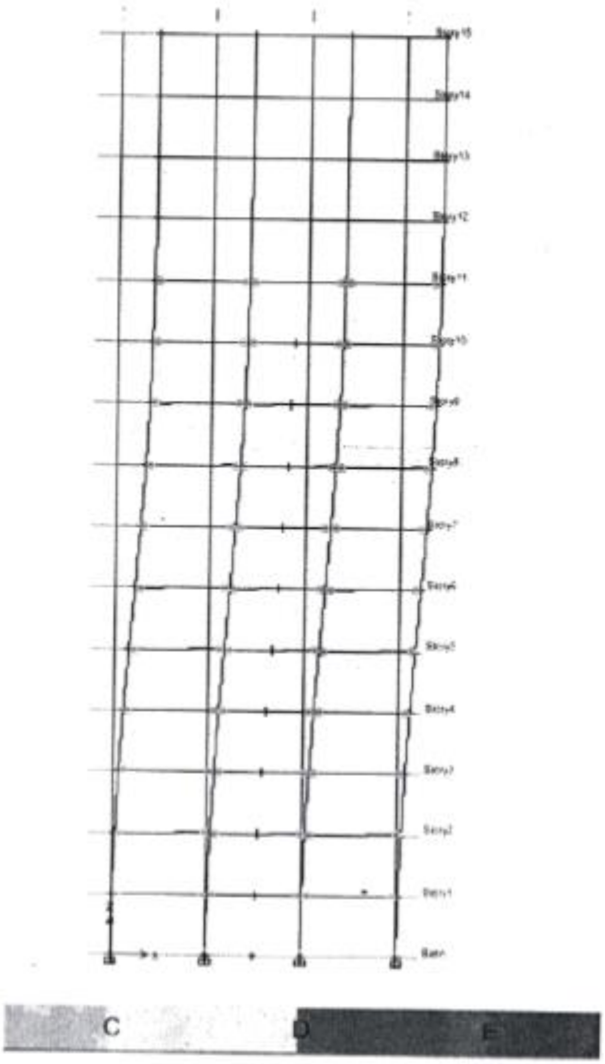

Fig 13. Performance level of Structure with 15 floors without side-plate connection

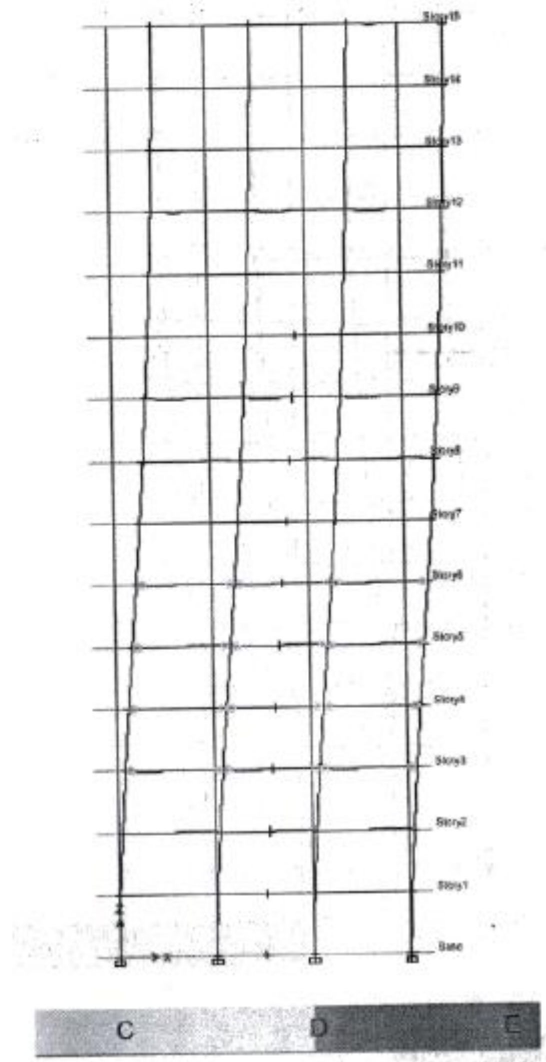

Fig 14. Performance level of Structure with 15 floors with side-plate connection

As results showed, failure level in beam and column elements in structures equipped with side-plate connections increased structure' resistance through creating hardness in the structure, in particular, in connection point and as a result it could prevent from elements maximum failure until the connection point flows. To create failure in structures equipped with side-plate connection, we need to higher power in compared to structures without side-plate connections.

CONCLUSION

Through the evaluation, results of effect of damper location in the system are as follows:

- According to result, damper presence in the structural systems decreased structure' displacement level due to the absorption of imported energy and dissipation of imported power to the structure. However, the optimal location of damper is also so important in addition to the reduction of displacement level. Results showed that in some structures, in particular, in the structures with less opening numbers, the damper had better seismic response in the internal frames, however, in some structures that their frames were more, the damper had the better response in external frames related to displacement level. Furthermore, the side-plate connections with damper had significant effect on the reduction of structure' displacement level than to structure without side-plate connections through creating hardness in the connection of beam and column.
- Results showed that base shear history level in the system without damper was always more than the

system with damper. In fact, the damper presence lead to absorption of more energy in the system and as a result it increased hardness and base shear. Of course, as much as the damper creates hardness in the structure, it has the same effect in dissipating the power, because, as much as the hardness increase, the absorbed power increase, that could be dangerous for the structure. However, the damper could control the hardness arising from its presence and could improve the seismic behavior. In another models in which damper continuous up to special floor and then it has been removed, the base shear increased and then decreased heterogeneously. It might could twist the structure in some states of the structure, but it might optimize the seismic behavior in some structures.

Conflict of interest

The authors hereby confirm that there is no conflict of interest.

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