Seismic performance evaluation of steel building frames with modified dual-pipe damper

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Abstract. Building performance against resistance to earthquake depends on selection of right building material with right properties. Steel frame structures are widely accepted due to its flexibility and seismic resistance property. However the practice of seismic retrofitting techniques in steel structures helps in the betterment of seismic performance of the building. A number of researches on simple and cost effective Metallic Yielding Device (MYD) are being conducted to evolve the best equipment. Dual-Pipe Damper (DPD) is one of the MYDs, which works on the principle of passive energy dissipation. A recent study brings the effective dimensions of pipes in DPD which can be implemented in a steel building frame conforming to IS 800:2007. This paper aims to study the effect of number of pipes in DPD by conducting parametric study using push over analysis. Three different configurations of optimized DPD installation in the multi-storey building frame are also studied. The Modal and Time-History analyses are performed on multi-storey frame with optimized DPD fixed at three configurations of steel frame conforming to IS 800:2007 to optimize the configuration.

1. Introduction

Bureau of Indian Standards grouped India into four seismic zones, based on the past seismic history. The seismic waves have tremendous amount of kinetic energy which cannot be predicted before the occurrence of earthquake. Different types of dampers are used to resist seismic activity during earthquake. We cannot prevent the total ill-effects of the action, but only to reduce the seismic energy in a building. Mostly, the destructions caused during a natural disaster are due to the mis-construction or mis-design by human. The increased mass of structure and brittleness of the construction material are the two known factors which trigger the vandalism. The commonly practiced building material (cement concrete), which is brittle in nature and has greater mass, is therefore ineffective as a seismic resistant construction material. The best way of a structure to be seismic resistant is, it must dissipate the kinetic energy of seismic waves entering the building. According to World Steel Association, ductile buildings are safer as they dissipate energy from seismic waves [1]. A building which has ductile parts can undergo plastic deformations without complete structural failure during an earthquake [1]. Steel is the most common type of material for such parts [1]

In order to further improve the seismic performance of steel buildings, a number of techniques have been introduced. Metallic Yielding Device (MYD) is one of those techniques, which work on the principle of passive energy dissipation. Dual-Pipe Damper is a type of MYD, which is introduced recently. It dissipates energy by deformation of its original shape. This simply means that, the device bends by absorbing energy after loading. Figure 1 shows the schematic representation of DPD before loading and Figure 2 shows the same after loading.
DPD consists of two horizontal pipes welded together and welded at the top and bottom. The main advantage of DPD is that, they have larger energy dissipation capacity than any other MYD [3,4]. Also they have larger ratio of force to weight and dissipation energy to weight [2]. When compared to other MYDs, DPD is light weight and cost effective [2,3]. They possess easy to medium degree of installation and replaceability [4].

Parametric study on DPD by pushover analysis is performed to find out the suitable model dimensions of DPD for a selected building frame (IS III-8) conforming to IS 800:2007. The diameter, thickness and length of pipes in DPD model with building frame are changed accordingly to test the lateral resisting capacity of the models. The ultimate load, yield strength and ductility of each model are compared. The optimum model DPD 300-15-75 having 300 mm pipe diameter, 15mm thickness and 75mm length is obtained as a suitable DPD for a building frame conforming to IS 800:2007 [5].

The current study is aiming to get the suitable number of pipes in DPD and the suitable configuration for DPD installation in multi-storey frame for an effective seismic retrofitting.

2. Numerical analysis
The numerical analysis of single storey building frame implemented with suitable DPD model (DPD 300-15-75) is performed to study the effect of change in number of pipes in DPD model. The diameter, thickness and length of pipes in DPD 300-15-75 are 300 mm, 15 mm and 75 mm respectively [5]. Parametric study using pushover analysis is done for the sole purpose. The study is extended to the evaluation of different configurations of DPD installation in multi-storey building frame, to evolve the best one. ANSYS 16.1 Workbench is used for the modelling and the numerical analysis.

2.1 Finite element modelling of the problem
The model’s material properties were assigned in the engineering data section of the software. The material properties assigned for the building frame as well as the DPD model are given in the table 1 [5]

| Material              | Steel               |
|-----------------------|---------------------|
| Yield strength        | 345 MPa             |
| Modulus of Elasticity | $2 \times 10^{11}$ Pa |
| Poisson’s ratio       | 0.3                 |
| Density               | 7850 kg/m$^3$       |
The selected building frame is considered as residential, implemented with suitable DPD [5,6]. The length of the plan is varied in X direction and breadth of the plan in Y direction [6]. The storey height is varied through Z direction [6]. The specifications of building frame chosen for modelling are given in the Table 2 [6]. The building is having fixed support situated on medium soil of various seismic zones of India [6]. The nomenclature of building starting as Indian Standards (IS), plan and number of storey in building [6].

| Building Frame | Plan dimension | Storey height (m) | Column size | Beam size |
|----------------|----------------|-------------------|-------------|-----------|
| IS III-8       | L=5@4 m       | 5                 | ISWB 450    | ISMB 400  |
|                | B=7@4 m       |                   |             |           |

The DPD consists of two horizontal pipes connected together [2]. A rigid plate is provided below the pipes for the proper connection and load transfer [5]. The V-bracing system is provided to support DPD in the model, which has a minimum section of 100 x 100 mm [5]. A parametric study has been conducted by varying diameter, thickness and length of the DPD, to determine the suitable dimensions of DPD model which can be implemented in the above mentioned building frame. Each model is given a fixed support at its bottom and the load is applied at top of the frames. According to the authors, the optimized DPD model suitable for the selected building frame is DPD 300-15-75, with pipe diameter, thickness and length as 300 mm, 15 mm and 75 mm [5]. Each DPD model in the present study is designated according to the dimensions of the pipes in DPD. For example, DPD 300-15-75 means, the DPD model have 300 mm, 15 mm and 75 mm as pipe diameter, thickness and length dimensions.

2.2 Parametric study using pushover analysis
The number of pipes in DPD model can be affected in the seismic performance of the building frame. The number of pipes in DPD 300-15-75 model is changed from 2 to 3 and pushover analysis is done. Figure 3 shows the model created for the analysis and Figure 4 shows the loading protocol for the pushover analysis. The ultimate load, ultimate deflection, yield load and yield deflection are noted directly from the ANSYS 16.1 Workbench. Yield stiffness and ductility of the model is calculated using the equations (1) and (2) respectively.

\[
\text{Yield stiffness} = \frac{\text{Yield load}}{\text{Yield deflection}} \quad (1)
\]

\[
\text{Ductility} = \frac{\text{Ultimate deflection}}{\text{Yield deflection}} \quad (2)
\]

The pushover analysis results of the model DPD 300-15-75 with 3 pipes from current study, such as ultimate load, ultimate deflection, yield load, yield deflection, yield stiffness and ductility values are compared with the corresponding values of the model DPD 300-15-75 with 2 pipes from reference [5]. The comparative results are shown in Table. 3.
DPD model with 3 pipes show increased values for ultimate load capacity (797.47 kN) and yield stiffness (25.75 kN/mm) than the DPD model with 2 pipes. But there is a drastic reduction in the ductility of the model with 3 pipes (11.15) compared to the model with 2 pipes (30.39). For a structure to be seismic resistant, it must have a decent value for ductility. Even though there is a considerable increase in the ultimate load capacity and yield stiffness of model with 3 pipes, due to its reduced ductility the model DPD 300-15-75 with 2 pipes is selected as optimum model. Hence as the number of pipes in DPD increases, the ductility decreases which lead to the sudden failure of the structure during seismic activity. Obviously there are chances of increased brittleness in the case of DPD.
models with other pipe dimensions because the scenario proves that the increase in number of pipes results in the addition of brittle behaviour.

Table 3. Comparatives results

| Specimen          | DPD 300-15-75 with 2 pipes | DPD 300-15-75 with 3 pipes |
|-------------------|----------------------------|----------------------------|
| Ultimate load (kN) | 742.5                     | 797.47                     |
| Ultimate deflection (mm) | 131.5                   | 70.384                     |
| Yield load (kN)    | 95.112                    | 162.62                     |
| Yield deflection (mm) | 4.3266                   | 6.3152                     |
| Yield stiffness (kN/mm) | 21.98                    | 25.75                      |
| Ductility          | 30.39                     | 11.15                      |

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2.3 Configurations of DPD installation in multi-storey building frames

The best configuration of optimized DPD installation in building frame conforming to IS 800:2007 was derived by distributing the DPD in different positions of the building frame and conducting the Time history and modal analyses. According to previous authors, each story of MDOF model responds proportionally to the equivalent SDOF model. In their study, the passive damper is distributed in proportion to the moment frame stiffness, which is the easiest method to apply in practice. They have distributed dampers in the longitudinal direction of corner frames for a 4-storey frame and in the longitudinal direction of middle frames for a 10 storey frame [7]. In the present study, both the distributions are taken into consideration. Bare frame (without DPD installed) was also tested for establishing a comparison, shown in Figure 5. The three different configurations adopted for the analysis are; building frame with DPD installed all over which is shown in Figure 6, building frame with DPD installed at middle frames only which is shown in Figure 7 and building frame with DPD installed at corner frames only which is shown in Figure 8.

Modal analysis is the study of the dynamic properties of systems in the frequency domain. Modal analysis considers only the free body vibration hence no load is applied in models during the analysis. Only the inertia is considered for the analysis, in which, time period and frequency of free body vibration of each model are obtained as results. The mode participation factor can also be taken from this particular analysis. Mode participation factor is a scalar that measure the interaction between the modes and the directional excitation in a given reference frame. Larger values indicate a stronger contribution to the dynamic response. The results of modal analysis provide the input for Time-History analysis. Basically, modal analysis is done to get the time period and frequency of free body vibration of each model. The mode participation factor can also be taken from this particular analysis. Larger values indicate a stronger contribution to the dynamic response. The results of modal analysis of each model are given in the Table 4, below.
**Figure 5.** Bare frame

**Figure 6.** Building frame with DPD installed all over

**Figure 7.** Building frame with DPD installed at middle frames only

**Figure 8.** Building frame with DPD installed at corner frames only

**Table 4.** Results of modal analysis

| Model                      | Frequency (Hz) | Time Period (Sec) | Mode participation factor |
|----------------------------|----------------|-------------------|---------------------------|
| Bare frame                 | 1.8318         | 0.5459            | 10                        |
| DPD installed all over     | 3.4729         | 0.2879            | 17                        |
| DPD at middle frames only  | 2.5987         | 0.3848            | 14                        |
| DPD at corner frames only  | 2.8468         | 0.3513            | 16                        |
In the time-history analysis the structural response is computed at number of subsequent time instants. Here each model is subjected under El Centro Peak Ground Acceleration data (El Centro PGA) to get directional deformation and base shear. The 1940 El Centro earthquake (or 1940 Imperial Valley earthquake) occurred at 21:35 Pacific Standard Time on May 18 (05:35 UTC on May 19) in the Imperial Valley in Southern California near the international border of the United States and Mexico. It was the first major earthquake to be recorded by a strong-motion seismograph located next to a fault rupture [8]. Figure 9 shows the El Centro PGA data.

Figure 9. El Centro PGA data

The maximum values of directional deformation and base shear from time-history analysis are given in the Table.5 below:

| Model                        | Directional deformation (mm) | Base shear (kN) |
|------------------------------|------------------------------|----------------|
| Bare frame                   | 23.597                       | 47.861         |
| DPD installed all over       | 5.6407                       | 46.943         |
| DPD at middle frames only    | 7.5163                       | 50.466         |
| DPD at corner frames only    | 8.3769                       | 47.577         |

The directional deformation is the displacement of the system in a particular axis or user defined direction. Higher the value, lesser will be the seismic performance. While comparing the maximum values of directional deformation of all the models, it is observed that models with DPD are low compared to that of bare frame, among which model with DPD in all over the frame is the lowest. Base shear is an estimate of the maximum expected lateral force on the base of the structure due to seismic activity. From Table.5, it is observed that the model with DPD at middle frames has the maximum value of base shear (50.466 kN), which is greater than that of bare frame. Both DPD
installed all over and DPD installed at corner frames show satisfactory results (low base shear with low directional deformation). Since base shear and directional deformation values of both the models are having approximately same value, both the models are suggested as optimum configuration.

3. Conclusions
Parametric study using pushover analysis on building frame with DPD model is done for studying the effect of change in number of pipes. The Modal and Time-History analyses of multi-storey frame are performed with optimized DPD fixed at three configurations of multi-storey frame conforming to IS 800:2007. Based on the performance of building frames, the following conclusions are made.

- DPD 300-15-75 model with 2 pipes is selected as optimum model compared to DPD 300-15-75 with 3 pipes by considering the load carrying capacity and ductility together. Better the value of ductility, better seismic retrofitting is ensured.
- Since the mode participation of models except the bare frame fall in same range and greater than the mode participation factor of bare frame, it is ensured that all the 3 models have better seismic retrofitting property than bare frame.
- The directional deformation of all the three models show low value compared to that of bare frame and hence ensures better seismic retrofitting.
- The comparison of base shear of the configuration of DPD installation reveals that, the base shear value of the middle configuration has a greater value than others. Since base shear and directional deformation values of both the models (one with DPD at corner frames only and the other with DPD all over the frame) are having approximately same value, both the models are suggested as optimum configuration.

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