EARTHQUAKE-RESISTANT DESIGN OF RC FRAME WITH "DUAL FUNCTIONS" METALLIC DAMPERS

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ABSTRACT :

In this paper, a new idea for designing metallic damper is presented, i.e. metallic damper with "dual functions", because they not only provide certain added stiffness to the building under normal use, but are also of good ability for seismic energy-dissipation. Also, quasi-static tests with these type of dampers are carried out. Furthermore, seismic responses of the structure with and without metallic damper are calculated and compared. The results show that the metallic dampers with "dual functions" not only provide certain added stiffness under normal application, but also are of good ability for seismic energy dissipation.

KEYWORDS: frame structure; metallic damper; energy-dissipated structure; seismic response

1. INTRODUCTION

Earthquakes can make structures damaged and crumble. The traditional approach to seismic design has been based upon providing a combination of strength and ductility to resist the imposed loads. Thus, the level of the structure security cannot be achieved, because the designing method lacks the ability for adjusting to an uncertain earthquake. The presence of some damping devices (energy dissipation) in buildings has been recognized and studied by professional researchers. Passive energy-dissipated system, as a category of vibration control methods, lead the input energy from earthquake directly to the dissipation device, thereby reducing energy-dissipating demand on primary structural members and minimizing possible structural damage.

One of the most effective mechanisms available for the dissipation of input energy of a structure during an earthquake is through the inelastic deformation of metallic substances. The idea of utilizing separate metallic dampers in a structure to absorb a large portion of the seismic energy started with the conceptual and experimental work of Kelly et al.(1972) . Also, numerous different types of energy-absorbed devices have been proposed, such as the X-shaped and triangular plate dampers by Whittaker et al.(1991) and Tsai et al.(1993).

From the promising theoretical results, researchers and practitioners turned their interest to possible applications of metallic dampers in real structures. The first structural implementation of metallic energy-dissipated devices took place in New Zealand , which obtained effective seismic response reduction of the building. Another example is that of the 6-story Cardiology Hospital complex constructed in Mexico City in the 1970s, which suffered form severe damage and the collapse of some part of the buildings during the 1985 Mexico Earthquake. After the event, the building was retrofitted with 18 external steel-trussed buttresses linked to the building floors through 90 ADAS devices. Nonlinear analytical results showed significant reductions in both inter-storey drift and base shear of the retrofitted building, resulting from the combined effect of stiffening and increased energy dissipation through the ADAS devices.

The commonly used metallic dampers use the out-of-plane bending deformation of the metallic plate to provide damping for the structure in order to reduce its dynamic response to environmental loadings. Since the bending curvature is produced by a uniform force perpendicular to the metallic plates of the damper, the plate can inelastically deform without deflection concentration. However, the inelastic deformation of the damper may occur even when subjected to relatively small disturbances (wind or earthquake), since the out-of-plane stiffness of the metallic plates of the damper is very small. As a result, the dampers have to be replaced after the disturbance. An important issue when dealing with metallic dampers is finding new ways for improving their stiffness.

In this paper, a new idea of designing metallic damper is presented and realized through the improved dampers that are of a certain bearing forces in plane of plate and suitable energy-dissipating capability by making metallic dampers in different shapes. New types of metallic dampers are called as “dual functions” metallic damper (DFMD), because it not only provides certain stiffness in normal use for a building, but also are of good ability of the seismic energy-dissipation. The structural configuration and mechanical characteristics of the models and prototypes of the DFMDs are analyzed and experimented, so as to verify the seismic performance of the dampers. Finally, the DFMDs applied to a new building in China are introduced and numerical results demonstrate the effectiveness of the DFMD.

2. Quasi-Static Test for Models of DFMD

Quasi-static tests with five types of mild metallic dampers made out of thick steel plates were conducted in the State Key Laboratory of Structural Analysis for Industrial Equipment of Dalian University of Technology. The objective of the tests is to choose the dampers with more energy-dissipating capabilities among the five proposed dampers. The test setup is shown in Fig.1. First, each of the dampers is subjected to repeated cyclic loadings in its plane of action. The force-controlled and displacement-controlled loading ways are respectively adopted during experiments. Failure criterion for the dampers is defined as follows: once a crack appears on the surface of damper or the decrease of bearing capability exceeds overall, the damper is regarded as having failed. The process and results for the model tests with the five different kinds of metallic dampers are given and discussed in the following sections.

Fig 1 Experimental setup of model

2.1. X-shaped metallic damper

The photograph of X-shaped damper is shown in Fig.2(a). Typical hysteresis curves from the test is depicted in Fig.2(b). It is noted that the X-shaped damper has such properties as large initial stiffness and high bearing capability. Yet, pinching in the middle of curve is observed from the experimental results. A reason of the above phenomena may be explained as stress concentration at the range of the center and the corner of the damper, and another is that the shear deformation is more than bending deformation. The results of test indicate that the X-shaped damper is not adaptable to be an energy-dissipating device because it is relatively lack of enough deformation and dissipating capability.

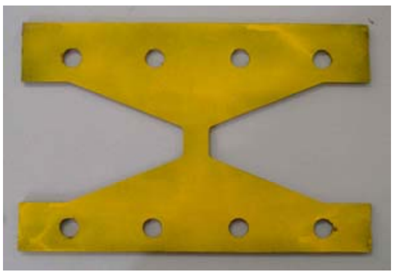

Fig 2(a) X-shaped metallic damper

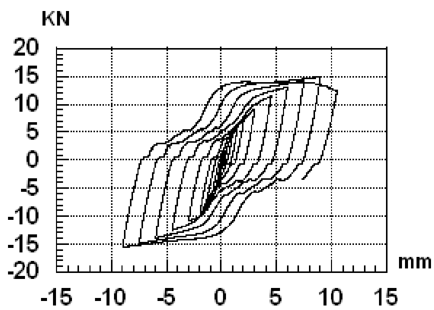

Fig 2(b) Hysteretic curves of X-shaped metallic damper

2.2. Double round-hole metallic damper

The photograph of double round-hole metallic damper and its typical hysteretic curves from the test are shown in Fig.3(a) and 3(b), respectively. During the test, it was observed from the hysteretic curves that the damper is good with large initial and 3(b), respectively. During the test, it was observed from the hysteretic curves that the dumper is good with large initial stiffness. However, the crack along horizontal direction appeared around the center of damper as soon as the deformation reached to only about 6mm. The results of test reveal that the geometrical shape of double round-plate damper is undesirable.

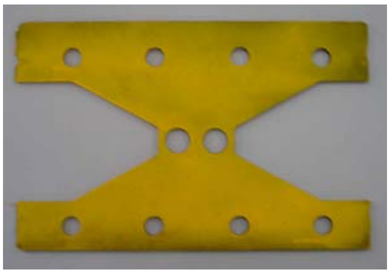

Fig 3(a) Double round-hole metallic damper

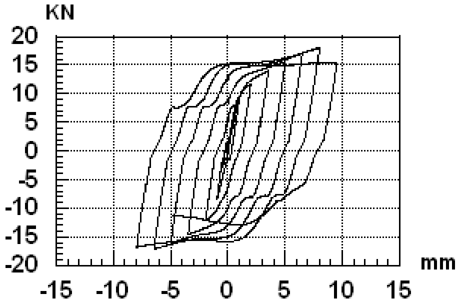

Fig 3(b) Hysteretic curves of double round-hole metallic damper

2.3. Strip metallic damper

Fig. 4(a) depicts the photograph of strip metallic damper. Its typical hysteretic curves from the test is shown in Fig. 4(b). The experimental results exhibit that the strip metallic damper has both large initial stiffness and better capability of plastic deformation, except for a reduction of load due to buckling observed at the final stage of the test. Hence, the strip plate damper is of good energy-dissipated capability, but it is not adequate to bear the cyclic force due to the lack of stability.

Fig 4(a) Strip metallic damper

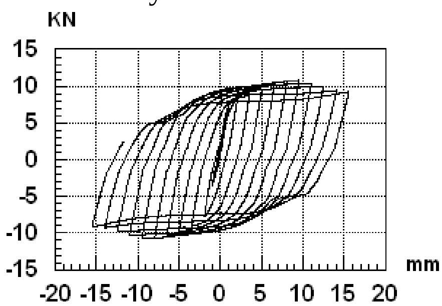

Fig 4(b) Hysteretic curves of strip metallic damper

2.4. Single round-hole metallic damper

The photograph of single round-hole metallic damper is shown in Fig.5(a). Typical hysteretic curves from the test is shown in Fig.5(b).

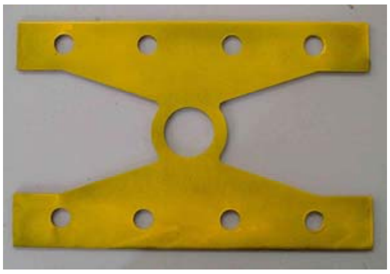

Fig 5(a) Single round-hole metallic damper

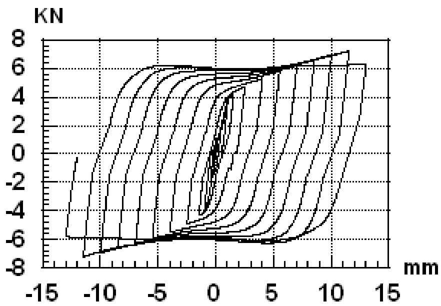

Fig 5(b) Hysteretic curves of single round-hole damper

The experimental results indicated the single round-hole damper not only has good energy-dissipated capability, but also is of high initial stiffness. It is suitable to be as an effective energy-dissipated device.

2.5. Double X-shaped metallic damper

The photograph of double X-shaped metallic damper is detailed in Fig.6(a). Typical hysteretic curves from the test is shown in Fig.6(b). The buckling problem described above in the strip metallic damper is solved in the way of making the damper as double X shape. It can be noted from the experimental results that the damper is of both large initial stiffness and energy-dissipated capability. Together with the single round-hole damper, they are all selected as effective dampers to be implemented in a practical project.

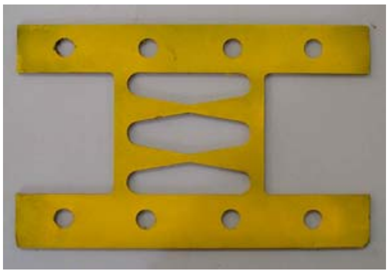

Fig 6(a) Double X-shaped metallic damper

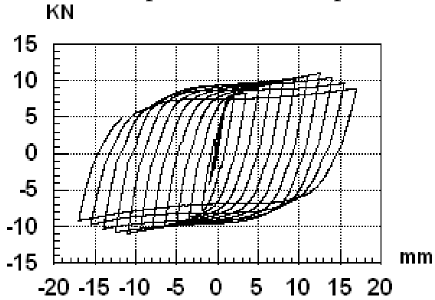

Fig 6(b) Hysteretic curves of Double X-shaped metallic damper

On the basis of the above-presented results, the following conclusions can be drawn as: Over all properties of single round-hole and double X-shaped dampers are better than the others. The geometrical shapes of new types of dampers make the energy uniformly dissipated in several areas without local stress concentrations that may reduce its deformable capacity, even though it can provide certain stiffness for building.

3. Prototype Experiments of Dampers

Prototypes of single round-hole and double X-shaped metallic dampers were designed based on the results of above model tests, which will be all applied in a practical RC frame building. These two kinds of dampers are made of steel plates with 50mm in thickness. These prototype samples were fabricated with the identical material and processes. The quasi-static loading was supplied by the actuators, which are of 200KN capacity. The test setup of the damper is shown in Fig.7.

Fig 7 Test setup of prototype damper

Fig.8 presents the curves of shear force P versus displacement of the two metallic dampers obtained from the tests. As observed in this figures, the DFMD exhibits the stable hysteretic behaviors and much energy-dissipated capacity because the area of their hysteretic loops are both large and substantial. Since they yield quickly even under proper small shear deformation, it is a good choice to use the dampers to absorb earthquake energy. Based on experimental results, several parameters of DFMD can be defined from the prototype test. The elastic lateral stiffness of the single round-hole damper is $K_{d1} = 170.5KN/mm$, the plastic yielding force is $P_{y1} = 375KN$ and the displacement at yielding point is $\Delta_{d1} = 2.2mm$. The corresponding parameters of double X-shaped metallic damper are $K_{d2} = 102.5KN/mm$, $P_{y2} = 410KN$ and $\Delta_{d2} = 4mm$.

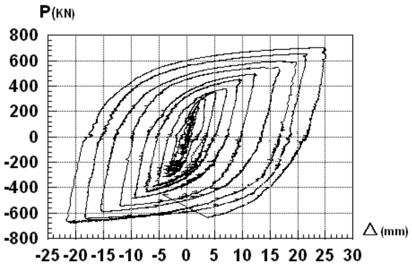

Fig 8(a) Hysteretic curves
of prototype single round-hole damper

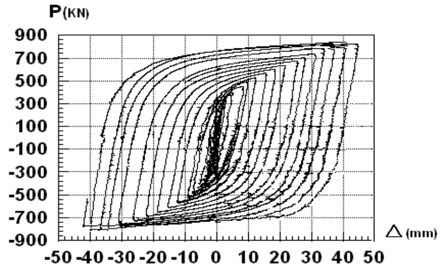

Fig 8(b) Hysteretic curves
of prototype double X-shaped damper

Several parameters of DFMD can be defined from the prototype test. The elastic lateral stiffness of the single round-hole damper is $K_{d1} = 170.5KN/mm$, the plastic yielding force is $P_{y1} = 375KN$ and the displacement at yielding point is $\Delta_{d1} = 2.2mm$. The corresponding parameters of double X-shaped metallic damper are $K_{d2} = 102.5KN/mm$, $P_{y2} = 410KN$, $\Delta_{d2} = 4mm$.

4. Application in Actual Building

4.1. Description of building

A RC frame building shown in Fig.11 is located on campus of the Dalian University of Technology in China. The project includes two parts—five-story RC building part A and six-story RC building part B. The sketch of part A is depicted in Fig.9. In order to reduce the seismic response of inter-story drift caused by the first story with the height of 7500 mm, where the laboratory of hydraulic dynamics to simulate ocean waves is situated, the single round-hole and double X-shaped metallic dampers, i.e. DFMDs, above presented are installed in the first story of building. The seismic protection intensity on this building site is Ⅶ degree, and the site soil belongs to the type Ⅱ based on China code(GBJ2001-11).


Fig 9 RC frame building with DFMDs

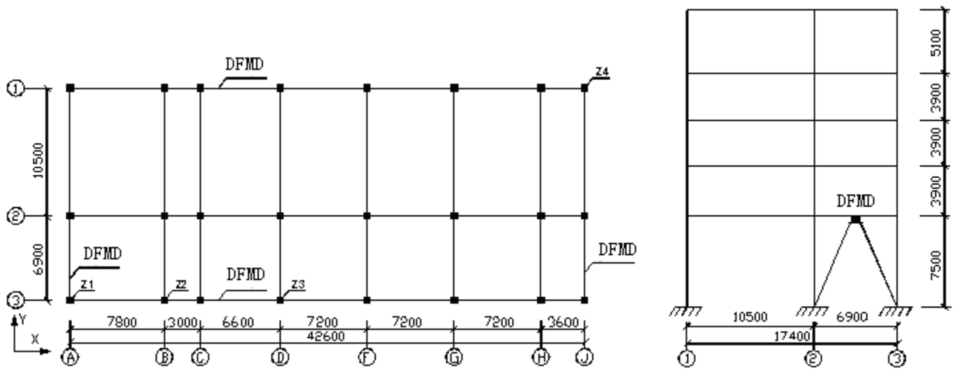

Fig 10 The sketch of the building part A

4.2. Installation of dampers

Since yielding parts of the DFMDs are easily concentrated to the small angle parts of plates, the dampers should be manufactured very carefully so as to avoid excessive local strain concentration. The DFMD dampers are as a group formed with three DFMD plates parallel to be placed together. The single round-hole metallic dampers are installed between the C and D axes along the ① and ③ axes, and the double X-shaped metallic dampers are arranged between the ② and ③ axes along the A and J axes, respectively, which are all at the first floor in the part A of building shown in Fig.10. The DFMDs are fixed on the nodes between beams and braces (Fig.10). In the installation process, the upper side of the DFMDs are welded on the embedded level steel plate in the beam, and the underside of the DFMDs are welded on the another level steel plate, which is attached with braces, the photographs of which are given in Fig.11.

Fig 11 (a) Installation of single round-hole damper

Fig 11 (b) Installation of double X-shaped damper

5. Dynamic Analysis of Structure with DFMDs

In normal cases, the RC structures are calculated following simplified procedures. Although traditional empirical methods remain adequate for ordinary design of RC members, the development of computer technology and the finite element method have provided efficient means for analyzing more complex systems. To obtain more exact structural story-drifts and evaluate the effectiveness of structural vibration reduction with the DFMDs, a three-dimensional frame model is established with the ADPL language in the ANSYS program.

5.1. Establishment of computational model

The BEAM188 in the ANSYS program was used to model the beams and columns of the frame structures, which is based on the Timoshenko's beam theory and apply a linear or a quadratic three-dimensional beam element. The SHELL143 in the ANSYS program, which is of both bending and membrane capabilities, was adopted for modeling the metallic dampers. They are all of six degrees of freedom at each node, ignoring the interactions between the structure and base soil.

5.2. Modal analysis

As an important step of numerical simulation, the calculation of natural frequencies and modal shapes of the structure are based on the elastic property of materials of structure. Two different software, the ANSYS and PKPM, are applied to compare the precision of them. The first five natural periods calculated by these two program are listed in Table1, and the compare the precision of them. The first five natural periods calculated by these two program are listed in Table 1. It is observed from the results that there is little errors in the first two periods. The natural periods of building with the DFMDs are smaller than without dampers for the DFMDs, which provide certain stiffness for the building.

Table 1 Natural period comparison between software ANSYS and PKPM (Unit: second)

Method		1st period	2st period	3st period	4st period	5st period
Structure without DFMDs	ANSYS	1.0608	1.0443	0.9562	0.6837	0.6521
	PKPM	1.0604	1.0160	0.8335	0.3804	0.3704
Structure with DFMDs DFMDs	ANSYS	0.8591	0.6652	0.6615	0.5264	0.4697

5.3. Time history results

Earthquake intensity may influence the effectiveness of the structural vibration reduction. In this section, four earthquakes acceleration records is selected to calculate the seismic displacement reduction effectiveness of the structure with and without the DFMDs based upon the sites where the structure is located. To match the seismic acceleration peak values for different earthquake intensities in China Code(GBJ2001-11), the four earthquake record peaks are adjusted to 220cm/s^2 corresponding to the Ⅶ degrees in the grade of seismic intensity.

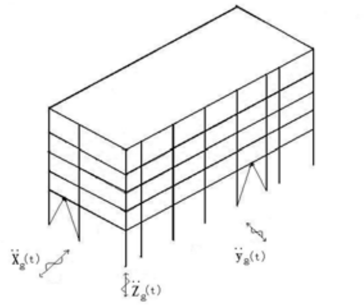

Fig 12 The sketch of building subjected to earthquake

The dynamic response of the building subjected to the earthquake excitations shown in Fig.12 is analyzed using ANSYS program. The acceleration is inputted the structure in three-dimentions, i.e. X, Y and Z directions. The results typically given in Fig.13 show the displacement response of the structure with and without the DFMDs only with the Taft record. It can also be seen from these figures that the peak displacements at the base of the building without the DFMDs are approximately 52 mm in X direction which is approximately 8 times the peak displacement of the building with the DFMDs. Fig.19(c) shows that the maximum displacement occurs also at the top floor and is reduced from 72 to 31.

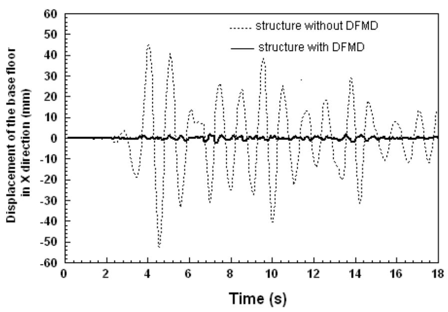

Fig 13(a) The displacement of the base floor in X direction

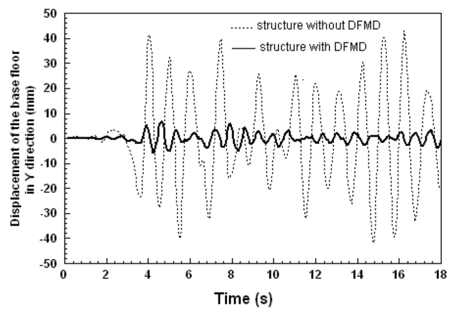

Fig 13(b) The displacement of base floor in Y direction

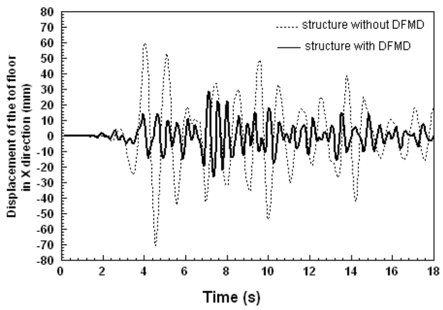

Fig 13(c) Displacement of top floor in X direction

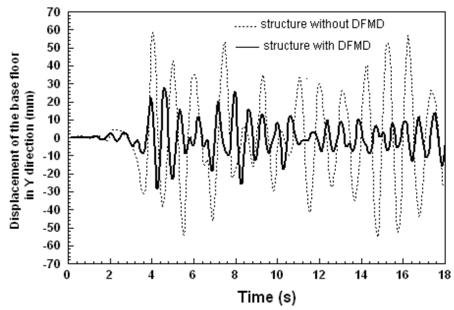

Fig 13(d) Displacement of top floor in Y direction

6. Conclusion

In this paper, the DFMD is presented utilizing the new idea of the force and steel plane being on one plane. Model and prototype test are carried out respectively, and test clearly reveal the properties of DFMD from its large and stable hysteresis curves. The DFMD is of not only provide certain stiffness, but also are of good ability of dissipating the energy. The design procedure and install method of actual building with DFMDs are introduced. The dynamic analysis of this building with and without DFMDs is carried out individually. The results presented that the DFMD is an effective dissipator, and it is feasible that calculate the response of the structure with dampers utilizing the software ANSYS.

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