Design of and Experimental Research on a New Type of Steel Damper

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ABSTRACT :

The design of and the experimental research on a new-invented steel damper applied to seismic resistance of bridge structure were introduced in this paper. The damper, a non-uniform mild steel cylinder, with a set of accessories, provides comparatively big damping force and stroke, either biaxial or uniaxial. Its hysteretic energy consuming and low-cycle fatigue life were proved through a series of full-scaled tests. Further discussions were carried out on the design and properties of the damper as well as the material.

KEYWORDS: steel damper, bridge structure, seismic resistance, experiment, fatigue

1. Introduction to the research and application of steel dampers

Steel damper is one kind of energy dissipation devices in structure passive control. During the earthquake or wind, structure vibration could be well controlled through energy dissipation with hysteretic plastic deformation.

Because of it's simple structure, clear conception, reliable performance and easy implementation, scholars around the world have been conducting theoretical and experimental researches on it and developing dampers with various structural forms, since J.T.P.Yao, an American scholar proposed the concept of structure vibration control in 1972.

Table 1.1 Research and application of steel damper

Year	Inventor	Forms of damper	Remarks
1972	Kelly, etc.	Rectangular steel plate	First put forward the metal yielding dampers
1975	Skinnery, etc.	U-shaped steel plate	First used in the government building in New Zealand in 1980
1978	Tyler	Tapered steel plate	Implemented in a 29-storey steel building
1981	Stiemer, etc.	Steel pipe	Applied to a 6-storey government building in New Zealand
1991	Whittaker, etc.	Triangular steel plate	Widely used
1992	Tsai, etc.	X-shaped steel plate	Widely used
1995	Gao J.Z.	Improved stiffening steel plate	Improved forms of triangular and x-shaped damper
1996	Ou J.P.	Composite steel plate	Solved the buckling problem
1997	Zhou Y.	steel ring/ double ring	Experimental researches have been conducted
2001	Brown AP	Buckling restrained brace system	Inner steel supporter providing damping force, while outside bondage offering restrain to prevent deflection
2005	Wang J.M.		
2003	Xing S.T.	Voided lozenge steel plate	Simultaneously yielding

2004	Li Y.S.	Extra-low yielding point	Full-scaled tests have been conducted
2004	Li H.N.	Composite X-shaped/ round hole-shaped	Patent is subjected to approval

Because the forms and structures of existing steel dampers are complicate, less effort has been devoted to practical application than research, especially in the field of seismic resistance of bridge structure.

2. The new design of steel damper

The steel damper introduced in this paper is designed for the seismic resistance of bridge structure. The following requirements are taken into account: a) providing damping force in all directions on the plane; b) most part of the damper yielding simultaneously; c) meeting the demand of the force and stroke; d) satisfactory low-cycle fatigue life.

A cantilevered steel column with varying circular cross section is chosen as the energy-consuming component, whose contour is a cubical parabola. According to the material property and the maximum strain, the approximate dimension of damper can be calculated with formula 1.1, simply derived from mechanics of material.

$$\begin{cases} H = \left(\dfrac{5k}{9\varepsilon_L}\delta\right)^{\frac{3}{5}} \\ D = kx^{\frac{1}{3}} \end{cases}; \qquad k = \frac{6P}{\sigma_y} \tag{1.1}$$

where: P is the yielding force, $\pm\delta$ is the stroke, H is the total height, x is the section altitude, D is the varying section diameter. The coefficient k equals $\dfrac{32P}{\pi\sigma_y}$ in elastic case, while is close to $\dfrac{6P}{\sigma_y}$ at high plastic level, as adopted here.

A practical bridge is taken as an example, on which the seismic analysis requires dampers with following parameters: yielding force 300kN, stroke ±200mm. Illustrated as Figure 1 (unit: mm), a set of steel damper is equipped vertically between the top of the pier and the bottom of the beam.

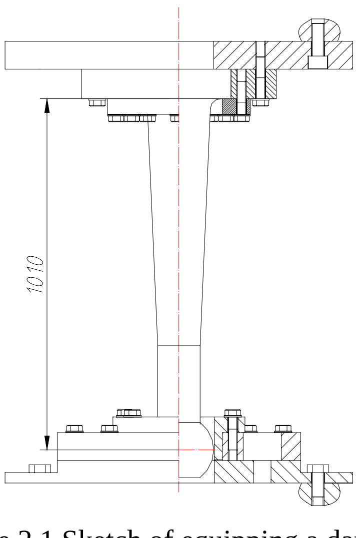


Figure 2.1 Sketch of equipping a damper

Five types of steel were selected: Q295, Q235, 10#, L-1077, ST035. Figure 2.2 demonstrates their constitutive curves (except ST035) obtained through uniaxial tensile tests.

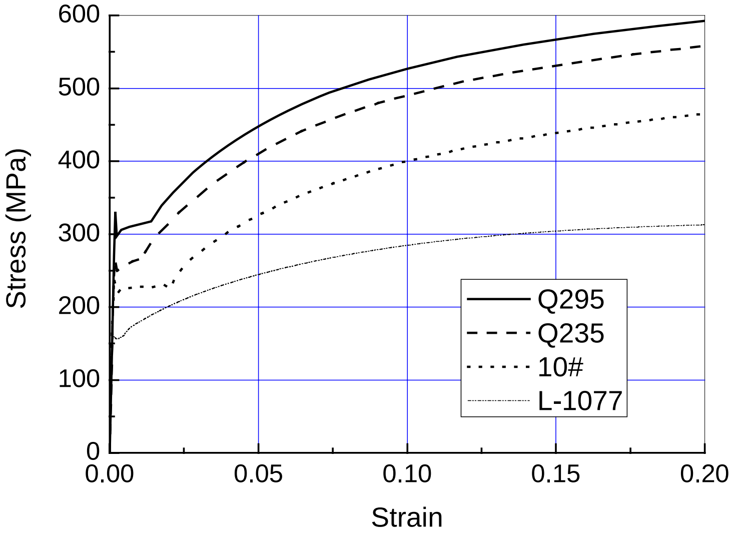
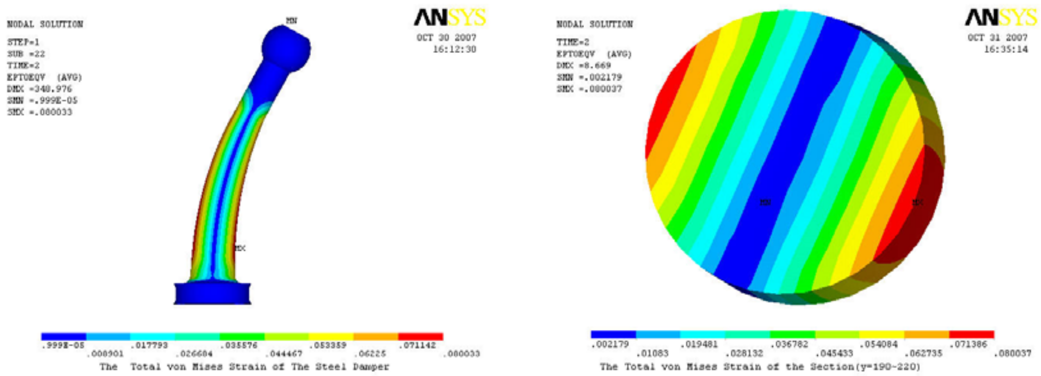


Figure 2.2 Constitutive curves from tensile tests

The dimension of the damper can be calculated with formula 1.1. With the strain amplitude 0.08～0.12（±0.04～±0.06）, the three kinds of steel dampers are designed to be of the same height, yet different diameters.

During the design of the Dimensions of the dampers, pushover analyses were carried out with ANSYS. Figure 2.3 shows an example of the results.



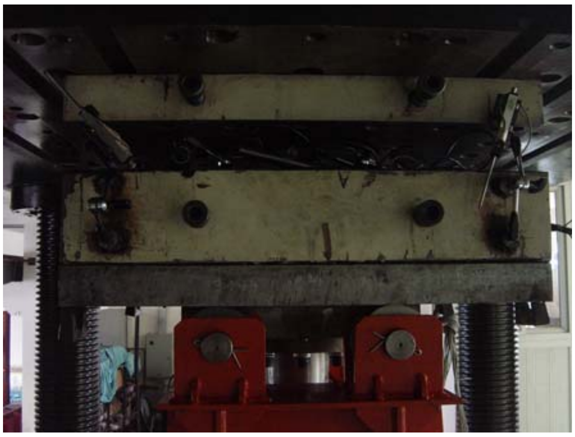
(1) Von Mises stress

Figure 2.3 Stress result from ANSYS, an example

3. Full-scaled model test

3.1. Test equipment

In the State Key Laboratory of Tongji University, the FSC loading system shown in Picture 3.1, is an electro-hydraulic servo with three channels working with following technical parameters: horizontally uniaxial ±500mm stroke and 2000kN maximum work force of the actuator; vertically 20000kN maximum dynamical pressure or 30000kN maximum static pressure.



(1) Actuator table (2) Fixed platform

(3) Support (4) Specimen (5) Strain gauge (6) Displacement gauge

Picture 3.1 Photo of the loading device, specimen and testing gauges

The loading device is previously employed in the pressed shearing test on bearings, thus it is not directly applicable to the pure shearing experiment of the damper. During the experiment, the actuator table could be a little elevated and rotated, causing the inaccurate reflection of deformation of the damper by loading displacement.

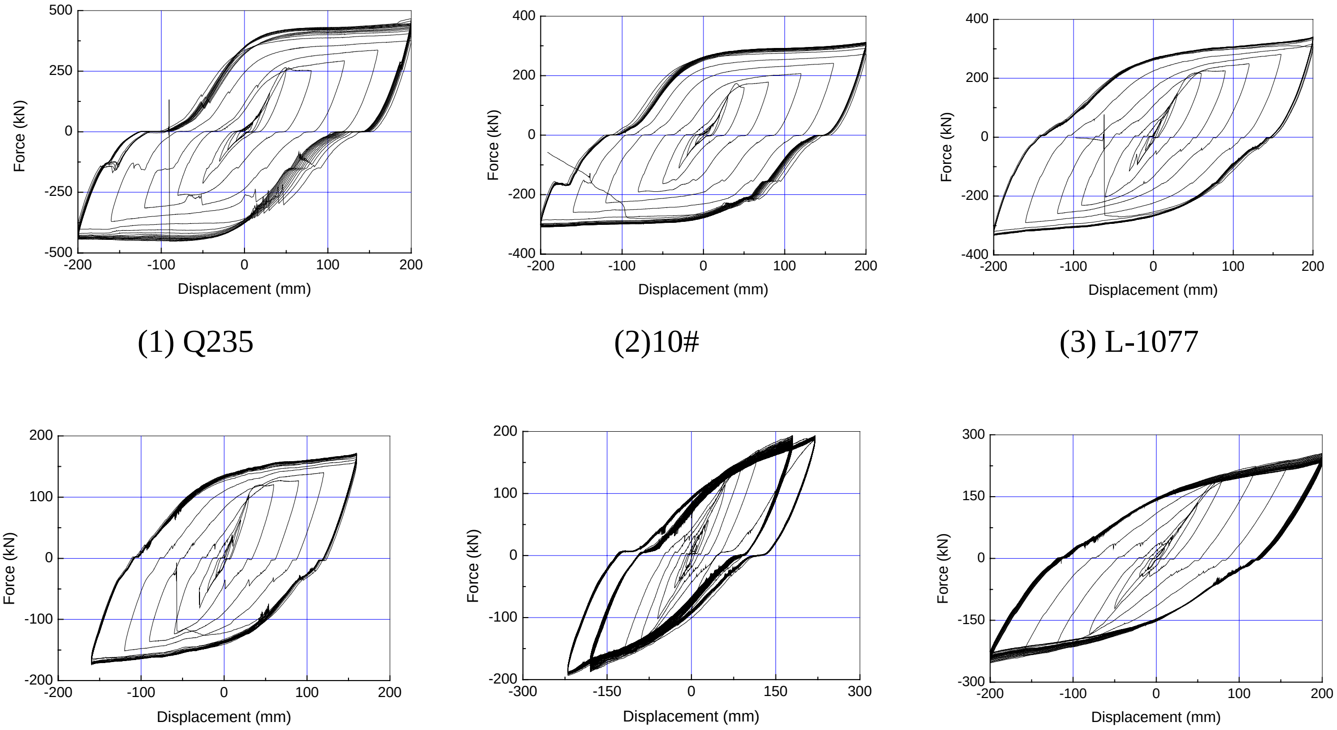
According to the features of the loading device, the fixed end of the damper was assembled to the above fixed platform and the free end to the actuator table, so that the arm of the shear force acting on the actuator table can be efficiently reduced. In the meantime, a pair of supports with rollers was fixed on the actuator table in order to limit its vertical movement. These helped to ensure the ideal loading condition.

3.2. Working condition and result of the experiments

Quasi-static experiments were carried out, inputting reciprocate displacement, gradually increasing the strokes from 10mm to 200mm in 6~8 cycles and then repeating the constant stroke with frequency $f<0.01$Hz until enough cycles were achieved or the damper broken down.

Due to the high temperature on the damper surface during the test, all the strain gauges run out, and it’s unsuccessful to get the strain signal directly. Five displacement gauges are distributed along the damper so as to collect its deformation curve. Useful data are obtained, but are not to be further discussed here. The force-displacement hysteresis loops and the low-cycle fatigue life are particularly concerned.

Figure 3.1 displays several typical hysteresis loops, with a certain post yielding stiffness.



(1) Q235 (2)10# (3) L-1077

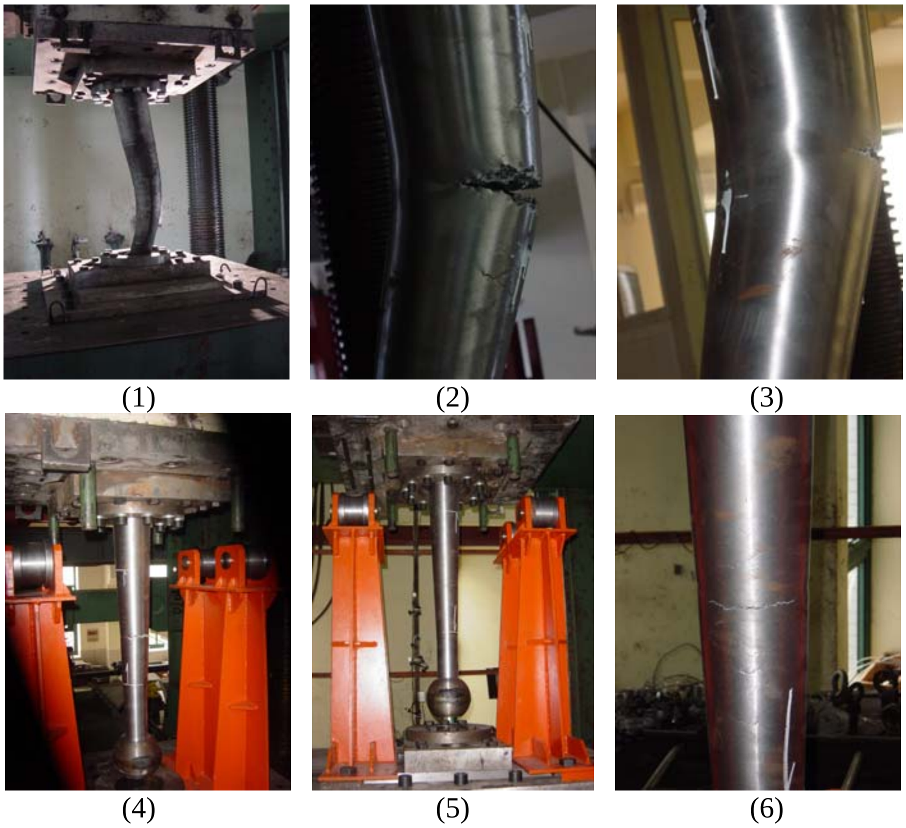
(4) Q235 (5) ST035 (6) ST035

Figure 3.1 Force-displacement hysteresis loops

Table 3.1 reflects the whole process in which the ideal result is finally achieved after the design of damper and the experimental condition was improved step by step.

Table 3.1 Summary of the experiments

No.	Material	Yielding force (kN)	Full stroke cycles	Remarks
1	10#	1900	> 51	The displacement of damper is false because of the loading system.
2	Q295	2960	> 50	
3	10#	3820	13	Loading system improved to get the true displacement. Hysteresis loops are quite full while fatigue lives are not satisfactory. Steel with lower strength hardens after yielding.
4	Q235	4590	14	
5	Q235	3100	18	
6	L-1077	3370	12	
7	L-1077	1720	22	
8	ST035	1930	> 68	Steel with higher strength softens after yielding. Hysteresis loops are not so full while fatigue lives are quite satisfactory.
9	ST035	2550	> 55	
10	ST035	2550	> 58	



Picture 3.1 Photo of the loading device, specimen and testing gauges

4. Discussions

4.1. The influence of steel material on damper's properties

When the height, yielding force and displacement of dampers are determined, steel material can affect the properties of dampers in the following aspects:

1) The higher the yielding strength, the smaller the diameter of the damper is, the smaller the maximum strain is and the better the low-cycle fatigue life is, while the less full the hysteresis loop is.

2) If the steel hardens after yielding, the yielding force increases gradually and the damper may deform into S-shaped (shown in the picture 3.1) during the reciprocating loading, which can remarkably deteriorate the low-cycle fatigue life.

3) If the steel softens after yielding, the yielding force decreases gradually and deformation of damper keeps relatively ideal.

4.2. Decision between the low-cycle fatigue life and the fullness of hysteresis loop

In terms of engineering application, dampers are hoped to have full hysteresis loops and satisfactory low-cycle fatigue lives. However, as for the steel damper itself, these two items are contradictory. The strain amplitude is the major factor determining low cycle fatigue life. The fuller the hysteresis loop is, the larger the strain amplitude is and the lower the low-cycle fatigue life is.

Accordingly, it is necessary to have a choice since we cannot have both advantages. Although full force-displacement hysteresis loop means efficient energy dissipation, it's not wise to lay blind emphasis on it. Nevertheless, different choice spells different initial stiffness and post yield stiffness. Hence, the designers can propose reasonable suggestions based on the specific conditions in engineering application.

Seismic analysis on a continuous beam bridge is taken here as an example, which is isolated and equipped with steel dampers, and non-linear time-history analyses were carried out. Figure 4.1 shows a pretty interesting phenomenon. With the same earthquake exciting the same bridge structure but different dampers, Choice A got a fuller hysteresis loop than B did, while B outputted smaller max displacement and force than A did. For this case, the conception that 'more energy dissipation leads to better result' didn't work. Actually, the post yielding stiffness played a more important role here.

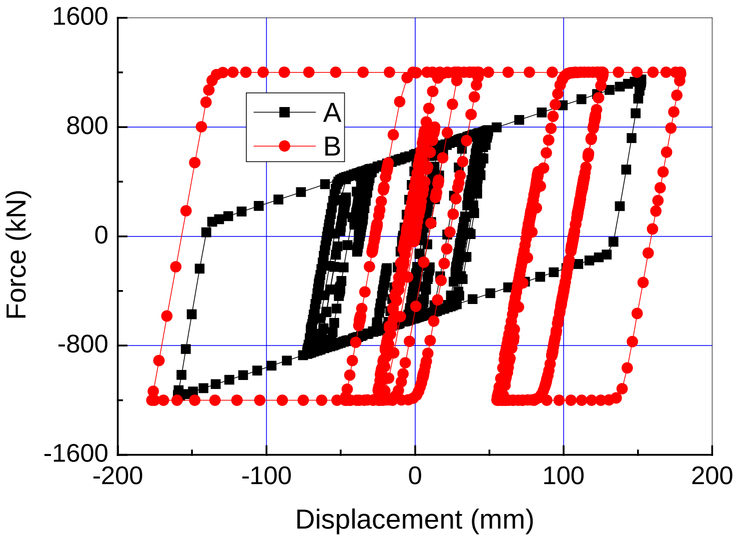


Figure 4.1 Hysteresis loops from seismic analysis

5. Conclusions and prospects

This paper briefly introduced a new type of steel damper, including the design method and a series full-scaled model experiments. From the work done here, following conclusions can be acquired:

(1) Applied to seismic resistance of bridge structure, a new type of steel damper with comparatively high requirements of damping force and stroke was successfully fabricated, together with satisfactory low-cycle fatigue life.

(2) Softening after yielding steel material seems to lead to much longer fatigue life than hardening material does.

(3) Between the full hysteresis loop and fatigue life, one has to make a reasonable choice depending on the requirements of practical engineering application.

The strain amplitude is one of the most important factors to the fatigue life of mild steel, while different steel materials and dampers' shapes will also count a lot. Next step of research work is expected to explore how these factors influence the fatigue life and whether other aspects may be affected.

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