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COMBINATION OF BRBS WITH TUBE METAL DAMPERS FOR SEISMIC RESISTANCE OF BUILDING STRUCTURES UNDER VARIOUS INTENSITY LEVELS

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Abstract

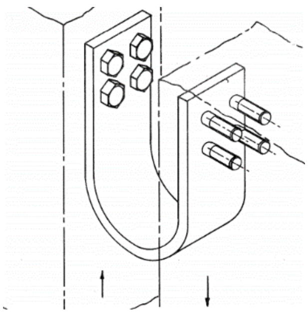
A novel brace is recommended by combining a conventional buckling restrained brace (BRB) with a steel tube damper, which is called two-level yielding buckling-restrained brace (TYBRB), for seismic resistance of buildings structures under various intensity levels. Under frequent earthquakes, the steel tube damper in TYBRB yields to dissipate seismic energy and the BRB in the TYBRB remains elastic to provide stiffness and bear loads. Under rare earthquakes, the BRB of TYBRB yields to dissipate much more seismic energy furthermore. Two steel tube damper specimens are designed. The cyclic loading tests are carried out to verify the excellent energy dissipation capacity of tube dampers. A practical configuration combining a conventional buckling restrained brace (BRB) with a steel tube damper to form a TYBRB has been proposed. TYBRB specimens are designed and cyclic loading tests are carried out to validate the functions of TYBRBs to dissipate seismic energy under various intensity levels. A case study was carried out on the actual building of Shanghai Tonghua Cold Warehouse to identify the effectiveness of TYBRBs with comparing to traditional BRBs. The seismic response of the TYBRB-frame structures and BRB-frame structures under frequent earthquakes is compared. It is found that the seismic response of the building structure under frequent earthquakes can be greatly reduced with TYBRBs while that under rare earthquakes is similar to that with BRBs.

Keywords: Two-level yielding, Buckling-restrained brace, Configuration, Experimental study, Engineering application

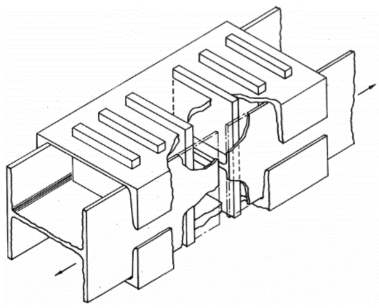
1. Introduction

Metal damper is a kind of displacement dependent damper. According to the different materials of metal damper, it can be mainly divided into steel damper, lead damper and shape memory alloy damper. Steel damper is the most widely used because of its relatively low cost [1]. When the deformation of steel damper is less than its elastic deformation limit, the storage and release of elastic strain energy in the process of loading and unloading does not play the role of energy consumption. However, when the deformation is greater than its elastic limit, the steel damper produces irrecoverable plastic deformation and consumes seismic energy. According to the mechanical characteristics of steel damper, it can be divided into bending steel damper, shearing steel damper and axial steel damper, to respectively consume seismic energy mainly through bending deformation, shearing deformation and axial deformation.

As early as 1970s, steel U-damper and bending plate damper (Fig. 1) [2] were proposed to be installed in the building structures to reduce the seismic response. The seismic energy can be dissipated by the out-of-plane bending plastic deformation of steel.



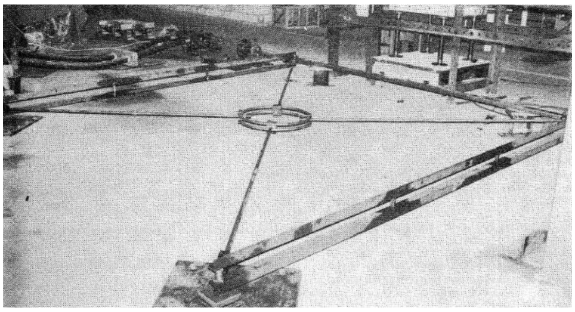
(a) U-damper



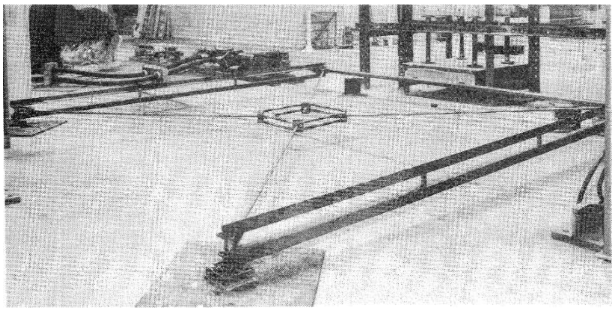
(b) Bending plate damper

Fig. 1 Steel bending damper [2]

At the same time, a conical cantilever damper [3], which dissipated energy mainly by out-of-plane bending plastic deformation of the upper conical cantilever part was proposed. In addition, circular damper (Fig. 2a) and square damper (Fig. 2b) [4, 5] were also proposed and tested.



(a) Circular damper



(b) Square damper

Fig. 2 Circular and square damper [4, 5]

A kind of steel bending stripdampers [6] was shown in Fig. 3. It dissipates energy by in-plane bending plastic deformation of steel strips. The upper and lower ends of the damper are connected with the structure by bolts. When the upper and lower ends are staggered horizontally, the steel strips in the middle will bend and yield, consuming seismic energy under the action of earthquakes.

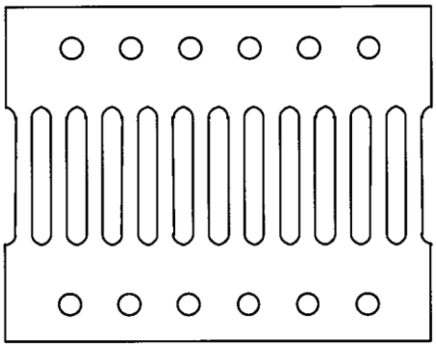


Fig. 3 Steel strip damper for Sapporo Art Center [6]

A conventional shearing steel dampers is shown as Fig. 4, including web, end plates, and flanges. As connecting components, the upper and lower end plates are usually connected with the structural components with large relative lateral displacement. The web is the main energy dissipation component of the shearing steel damper. When the component is subject to large shearing deformation, the web plays the role of energy dissipation. The flanges, as stiffeners of the web, play an role of enhancing the out-of-plane stiffness of the web. The common connection ways of shearing steel damper mainly include V type, wall type and coupling beam type [7].

Fig. 4 Conventional shearing steel damper

Buckling restrained brace (BRB) is a typical example of axial steel damper originated in Japan. The typical BRB (Fig. 5) mainly includes the core plate which bears the axial force and the steel tube restrainer which keeps elastic all the time. The mortar is filled between the restraining part and the core plate, and a thin layer of unbonded material is wrapped around the core plate to reduce the friction between the core plate and the mortar, which also provides space for the transverse deformation of the core plate[8-17].

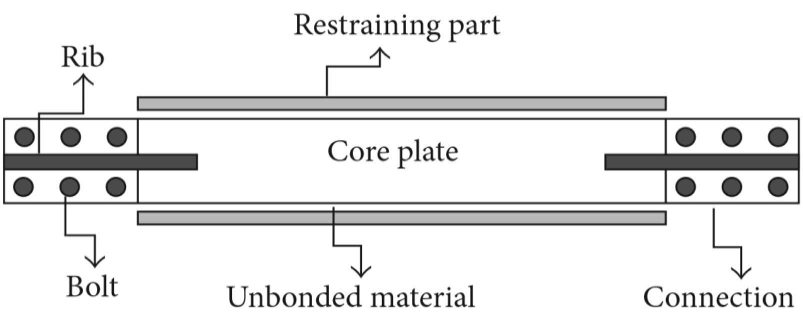


Fig. 5 Buckling restrained brace [18]

Due to the limitation of low cycle fatigue performance, steel dampers are often designed to yield and consume energy under a certain level of earthquakes. Due to the ramdomness of earthquakes, the intensity of actual earthquakes may be less or greater than that of the design earthquakes. When the intensity of the earthquake is less than that of designed, the steel damper will not play a role. However, when the intensity of the earthquake is much greater than that of designed, the steel damper will be failed due low cycle fatigue fracture. So how to deal with the seisic resistance of building structures using steel dampers under various intensity levels is an inportant issue.

In this paper, a two-level yielding buckling restrained brace (TYBRB) is proposed, which combine a conventional BRB with a steel tube damper. The tube damper in TYBRB is deigned to yield and dissipate seismic energy under frequent earthquakes, while the BRB in TYBRB is designed to yield and dissipate seismic energy under moderate or rare earthquakes. So TYBRBs can be applied for mitigating response of building structures subjected to earthaquekes with a wide range of intensities.

2. Configuration of TYBRB

A two-level yielding buckling-restrained brace (TYBRB) is composed of a conventional buckling-restrained brace and a steel tube damper, as shown in Fig. 6 [19]. The steel tube restrainer of the conventional BRB, filled with mortar, is inserted into the steel tube damper. One end of the tube damper is fixed to the steel restraint tube of the BRB by fillet welding and the other end is connected to an end plate which is fixed in the end region of the BRB. The steel strips of the tube damper could yield when the relative displacement of their two ends reaches a specific threshold value.

The steel tube damper in a TYBRB is designed to yield to dissipate energy under frequent earthquakes, while the BRB in the TYBRB is designed to yield to dissipate energy under moderate or rare earthquakes. Therefore, the goal "two-level yielding" of TYBRB under various intensity earthquakes can be achieved.

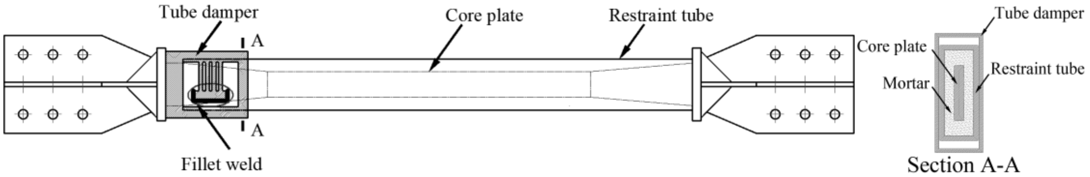


Fig. 6 Configuration of TYBRB [19]

3. Experimental study

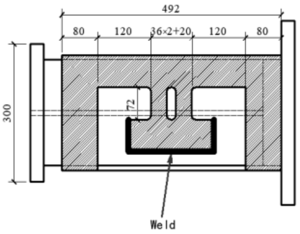
3.1 Experimental study on steel tube dampers

Two tube damper specimens were designed with different aspect ratio (*H*/*B*) of strips for tests, as listed in Table 1, and cyclic loading was exerted to specimens [20].

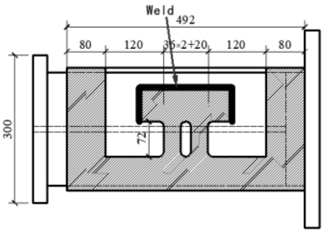
Table 1 – Tube damper specimens

Specimen No.	Aspect ratio of steel strips	*H*(mm)	*B*(mm)	Number of strips
1-1	2	72	36	2
1-2	4	96	24	3

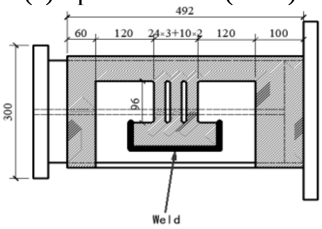
Two walls of the tube which were in contact with the flanges of the I-section element were slotted to form steel strips between slots. The slotting was also to facilitate the welding between the I-section flange and tube wall. Because of the asymmetric welding in the specimens, an asymmetric layout of slotting on the two sides (front and behind) of the tube was applied (Fig. 7) to avoid asymmetric axial force. The specimens had the same *R* of 5 mm and *D* of 10 mm, where *R* and *D* were the radius and width of the slot, respectively.



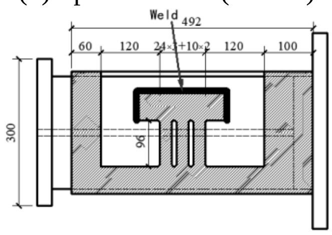
(a) Specimen 1-1 (front)



(b) Specimen 1-1 (behind)



(c) Specimen 1-2 (front)



(d) Specimen 1-2 (behind)

Fig. 7 Layout of tube damper specimens [20]

The arrangement of strain gauges and Linear Variable Differential Transformers (LVDTs) is shown in Fig. 8. The strain gauges were attached to the ends of steel strips to identify the yielding of strip ends. LVDT1 was used to measure the relative displacement between the two ends of steel strips, while LVDT2 was to measure the relative displacement between the two end plates.

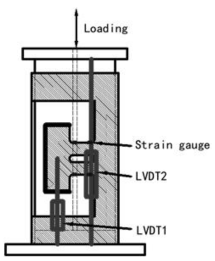


Fig. 8 Layout of measurements of steel tube damper specimens [20]

The installation of specimens and the loading actuator is shown in Fig. 9. One end of the specimens was connected with the reaction frame, and the other end was connected with the actuator. The specimens were subjected to monotonic compression until yielding of strip ends. At that moment, the displacement measured by LVDT1 was recorded as *d*y. Cyclic loading was then imposed according to *d*y. For the two specimens, cyclic loading with a constant amplitude of 10*dy* and 25*dy* was imposed, respectively. The failure of specimens was assumed to occur when the maximum force of the current cycle decreased to 85% of the maximum value in the previous cycles.

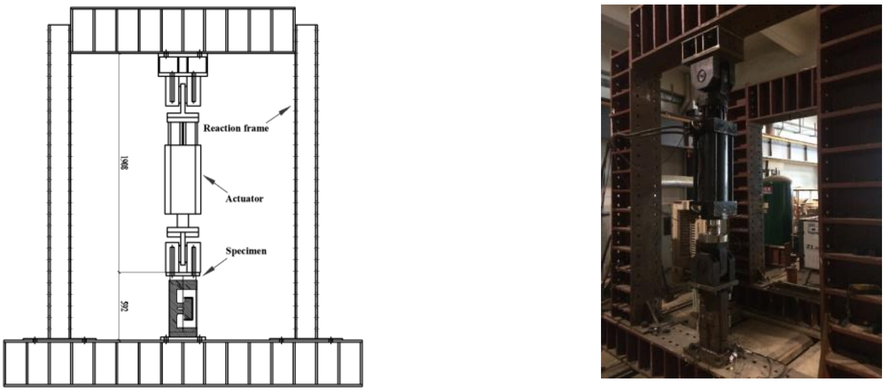
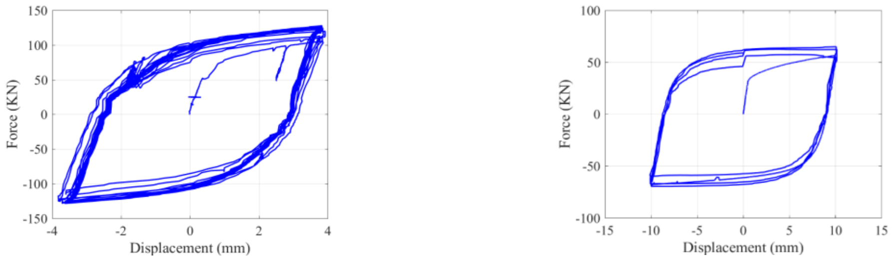


Fig. 9 Setup of steel tube damper specimens [20]

The hysteretic curves of the tube damper specimens are shown in Fig. 10. Plump hysteretic curves were achieved, demonstrating an excellent energy dissipation capacity of steel tube dampers.

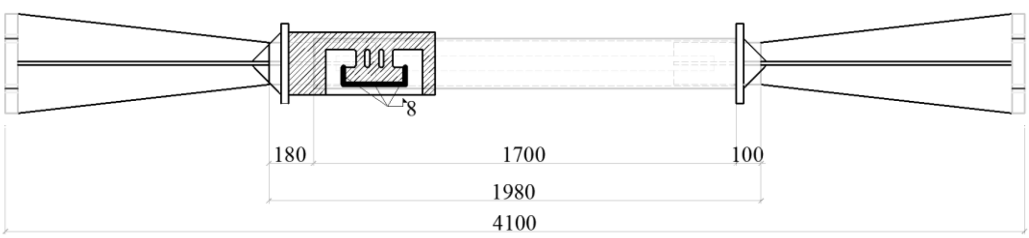


(a) Specimen 1-1 (b) Specimen 1-2

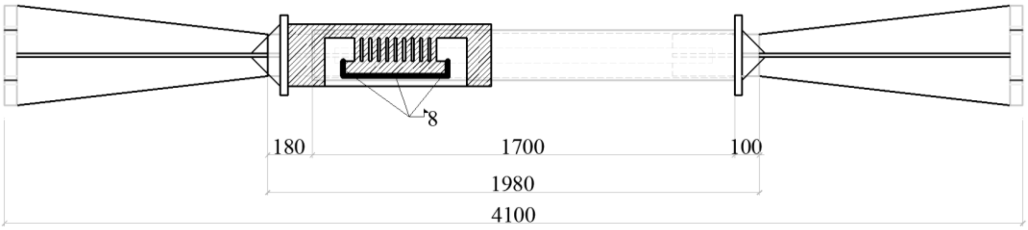
Fig. 10 Hysteretic curves of steel tube damper specimens [20]

3.2 Experimental study on TYBRBs

Two TYBRB specimens (Specimen 2-1 and Specimen 2-2) were designed and manufactured, as shown in Fig. 11. The two specimens had the same BRB length (1980mm), core plate section (20mm×60mm) and steel tube restrainers (200mm × 80mm × 10mm), but different configuration of tube dampers. The tube damper in Specimen 2-1 had a strip aspect ratio of 2, compared with the value of 4 for Specimen 2-2. The aspect ratios of strips of the two specimens were the same as those of specimen 1-1 and specimen 1-2 respectively, and thus the static properties, hysteretic properties and the low-cycle fatigue properties of strips were supposed to be all the same. The number of strips for the two specimens was 6 and 20 in total, respectively.



(a) Specimen 2-1



(b) Specimen 2-2

Fig. 11 Layout of two TYBRB specimens [19]

The arrangement of strain gauges and Linear Variable Differential Transformers (LVDTs) is shown in Fig. 12. The strain gauges were attached to the ends of steel strips to identify the yielding of tube dampers. LVDT1 was used to measure the axial deformation of the BRB, while LVDT2 was to measure the relative displacement between the two ends of damper strips.

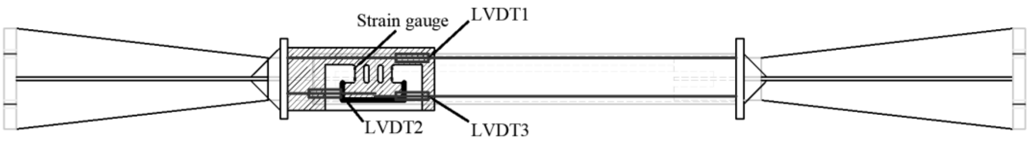


Fig. 12 Layout of measurements of TYBRB specimens [19]

The test setup of the specimens is shown in Fig. 13. One end of the specimen was connected with the reaction frame, and the other end was connected with the sliding rigid beam which was connected with the actuator. During the loading process, the sliding rigid beam was driven by the actuator to impose load. In order to check the low-cycle fatigue performance of the tube damper, as the loading displacement amplitude, the yielding displacement of the BRB (1.69mm) was imposed for 30 cycles firstly. After that, 1/300, 1/200, 1/150 and 1/100 of the length of the BRB as the amplitude, the specimens were loaded for 3 cycles at each amplitude to confirm the performance of BRBs. After that, the load amplitude was reduced to 1/150 of the BRB length, at which was repeated for 30 cycles to further evaluate the low-cycle fatigue performance of BRBs.

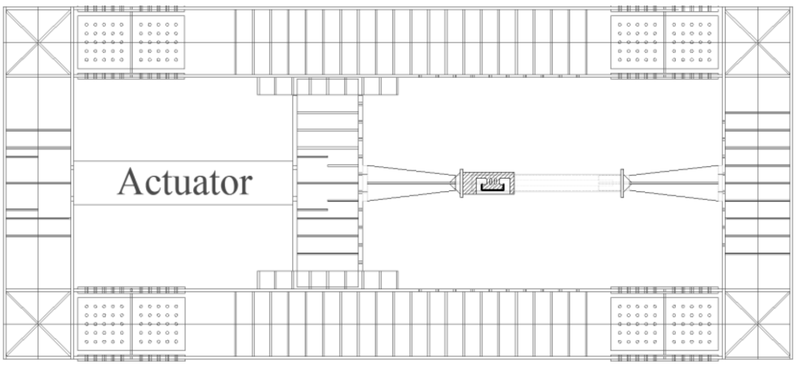
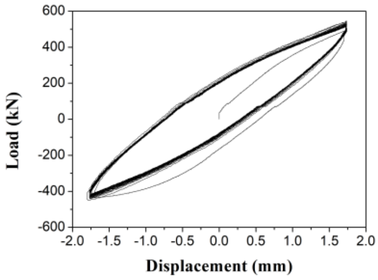
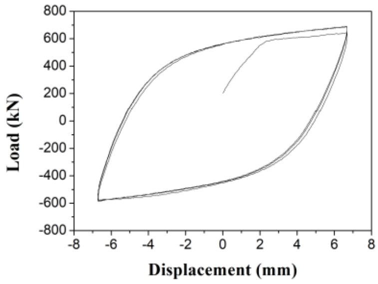


Fig. 13 Setup of TYBRB specimens [19]

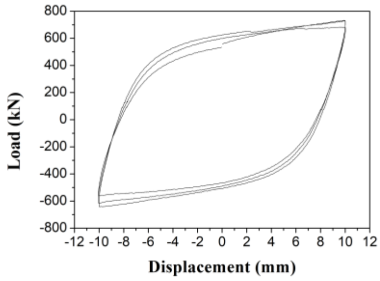
The hysteretic curves of the specimens are shown in Fig. 14 and Fig. 15. After the first loading phase, the tube dampers yielded but the BRB remained elastic. The energy dissipation capacity of the steel tube dampers was stable and the low-cycle fatigue resistance of the steel tube damper was reliable. It is validated by the following loading process that the BRBs exhibited good energy dissipation capacity and low-cycle fatigue resistance, which did not degrade by the combination with the steel tube dampers. So the TYBRBs could dissipate seismic energy under various intensity levels.



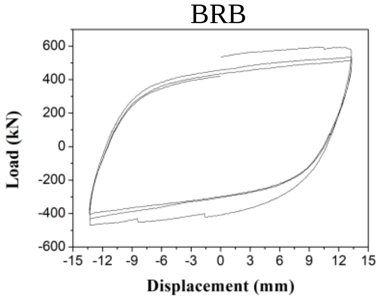
(a) First phase: 30 cycles of yielding displacement of BRB



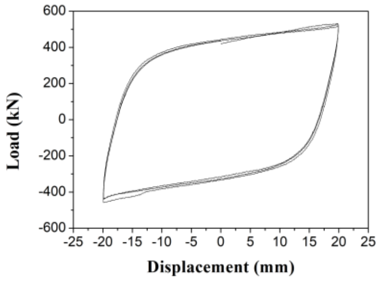
(b) Second phase: 3 cycles of 1/300 length of BRB



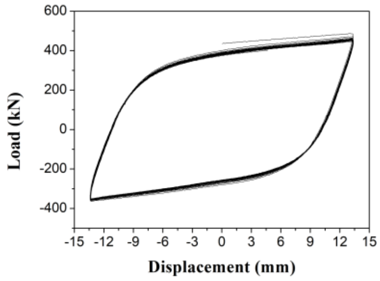
(c) Third phase: 3 cycles of 1/200 length of BRB



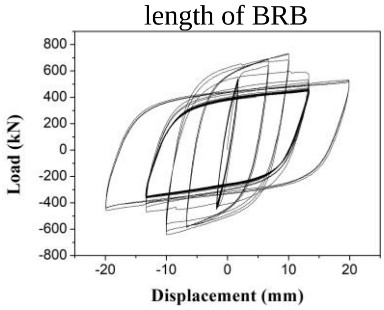
(d) Fourth phase: 3 cycles of 1/150 length of BRB



(e) Fifth phase: 3 cycles of 1/100 length of BRB

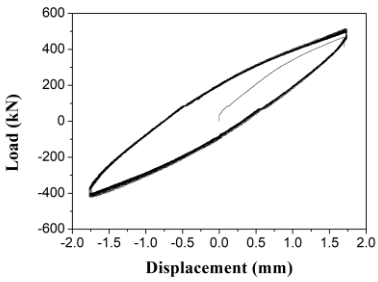


(f) Sixth phase: 30 cycles of 1/150 length of BRB

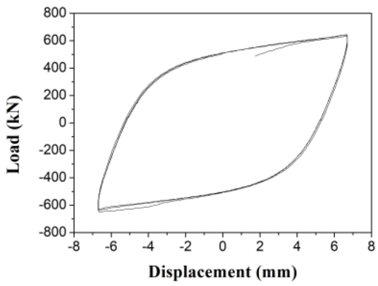


(g) Complete hysteretic curve of the experiment

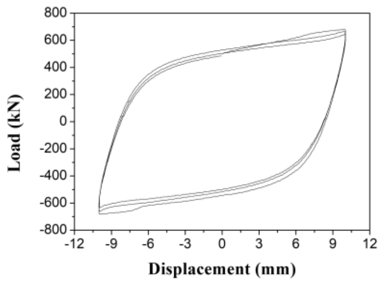
Fig. 14 Hysteretic curves of TYBRB specimen 2-1 [19]



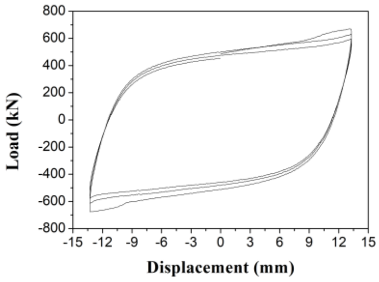
(a) First phase: 30 cycles of yielding displacement of BRB



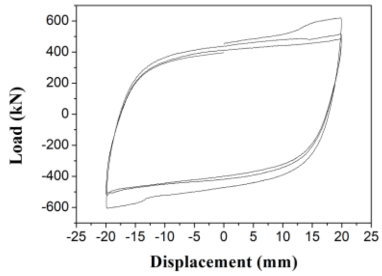
(b) Second phase: 3 cycles of 1/300 length of BRB



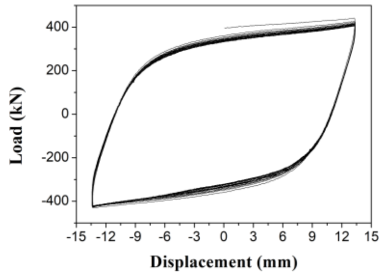
(c) Third phase: 3 cycles of 1/200 length of BRB



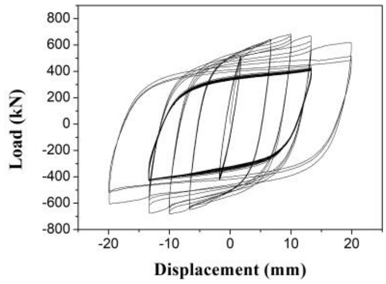
(d) Fourth phase: 3 cycles of 1/150 length of BRB



(e) Fifth phase: 3 cycles of 1/100 length of BRB



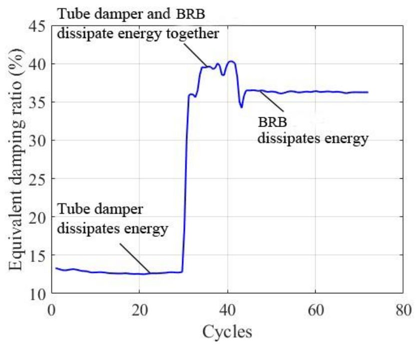
(f) Sixth phase: 30 cycles of 1/150 length of BRB



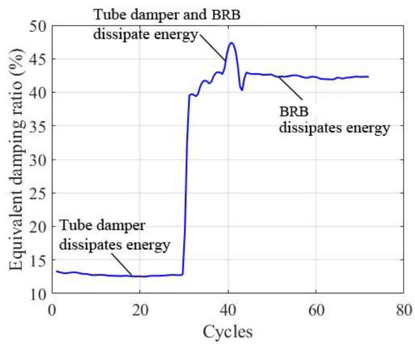
(g) Complete hysteretic curve of the experiment

Fig. 15 Hysteretic curves of TYBRB specimen 2-2 [19]

The variation of equivalent damping ratio of each loading cycle of the two specimens is showed as Fig. 16. In the first stage, the equivalent damping ratio mainly reflected the plasticity of the tube damper since the BRB kept elastic. After the BRB yielded, the equivalent damping ratio greatly increased. Especially for the middle loading stage, the equivalent damping ratio reached its highest value because that both the tube damper and the BRB experienced plastic deformation, dissipating energy together. In the later stage, the BRB broke down and the BRB was left to dissipate energy individually. The equivalent damping ratio kept stable until the end of the loading procedure. For practical application, it is reliable and conservative to ignore the contribution of tube dampers to the equivalent damping ratio after the yielding of BRBs.



(a) Specimen 2-1



(b) Specimen 2-2

Fig. 16 Variation of equivalent damping ratios of the specimens against number of cycles [19]

4. A case study

A case study was carried out on a actual building structure of Shanghai Tonghua Cold Warehouse to identify the effectiveness of TYBRBs for mitigating the seismic action. The layout of the braces, either TYBRBs or conventional BRBs, in the building is shown in Fig. 17.

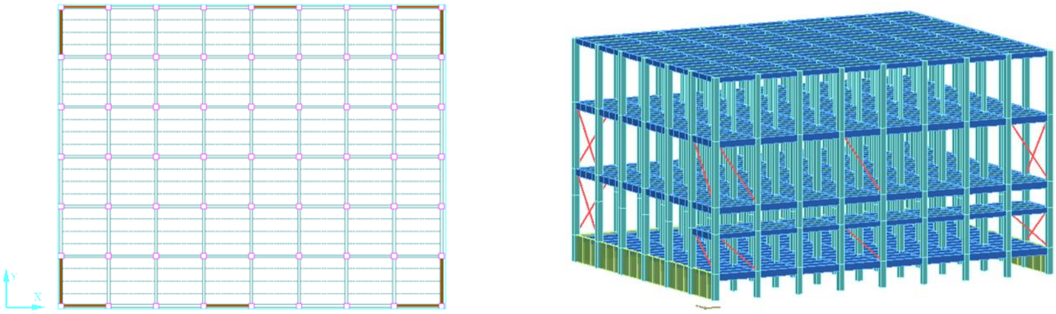


Fig. 17 Brace layout

The finite element analysis software ETABS was used to simulate the seismic behavior of the building. The first three natural vibration period of the building braced with TYBRBs are 1.60s, 1.50s and 1.18s respectively. Comparatively, the first three natural vibration period of the building braced with conventional BRBs are 1.67s, 1.60s and 1.29s respectively, which are close to the values of the TYBRB braced building.

Seven earthquake waves (5 natural waves and 2 artificial waves) were selected, including Chi-Chi,Taiwan_NO_1207 (wave 1), Chi-Chi,Taiwan_NO_1225 (wave 2), HectorMine_NO_1790 (wave 3), LomaPrieta_NO_740 (wave 4), Kobe,Japan_NO_1120 (wave 5), SHW2 (wave 6) and SHW9 (wave 7). The acceleration peak value of seven earthquake waves was adjusted to 35cm/s^2 for frequent earthquakes and 200 cm/s^2 for rare earthquakes. The time history analysis of both BRB-frame building and TYBRB-frame building was carried out with the seven earthquake waves excitation. The story drift of the building braced with conventional BRBs amd TYBRBs under frequent earthquakes were compared in Table 2 and 3, and under rare earthquakes were compared in Table 4 and Table 5.

Table 2 Seismic response of BRB-frame building (Frequent earthquakes)

	Wave 1	**Wave 2**	**Wave 3**	**Wave 4**	**Wave 5**	**Wave 6**	**Wave 7**	**Average**
Story drift	1/651	1/428	1/785	1/729	1/703	1/646	1/585	1/625

Table 3 Seismic response of TYBRB-frame building (Frequent earthquakes)

	Wave 1	**Wave 2**	**Wave 3**	**Wave 4**	**Wave 5**	**Wave 6**	**Wave 7**	**Average**
Story drift	1/770	1/485	1/787	1/1060	1/708	1/765	1/705	1/721
Reduction rate compared with BRB-frame	15.49%	11.61%	0.31%	31.27%	0.77%	15.51%	16.97%	13.13%

The average value of the story drift under frequent earthquakes of the TYBRB-frame building was 1/721. Compared with the BRB-frame building, the story drift was reduced by about 10%. The steel tube dampers yielded and played the role of energy dissipation, and the BRBs remained elastic.

Table 4 Seismic response of BRB-frame building (Rare earthquakes)

	Wave 1	**Wave 2**	**Wave 3**	**Wave 4**	**Wave 5**	**Wave 6**	**Wave 7**	**Average**
Story drift	1/132	1/113	1/130	1/141	1/131	1/133	1/135	1/130

Table 5 Seismic response of TYBRB-frame building (Rare earthquakes)

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Wave 6	Wave 7	Average
Story drift	1/128	1/121	1/134	1/166	1/137	1/141	1/139	1/137
Reduction rate compared with BRB-frame	-3.23%	6.49%	2.41%	13.63%	4.12%	5.52%	2.97%	4.56%

The average value of the story drift under rare earthquakes of the TYBRB-frame building was 1/137. Compared with 1/130 of the BRB-frame building, the story drift was also reduced generally.

Since the TYBRBs bear the benefit to further reduce seismic response of the building under freaquent earthquakes with the similar capacity to mitigate the action on the building under rare earthquakes, TYBRBs were applied in buildings of Shanghai Tonghua Cold Warehouse, as shown in Fig. 18.

Fig. 18 Application of TYBRBs in Shanghai Tonghua Cold Warehouse

5. Conclusions

Through experimental and numerical analysis, the following conclusions can be drawn as follows:

(1) A novel two-level yielding buckling-restrained brace (TYBRB) has been proposed, consisting of a steel tube damper and a conventional BRB. The former is designed to yield and to consume seismic energy under frequent earthquakes, while the latter is supposed to yield to further dissipate energy under moderate or rare earthquakes.

(2) Cyclic loading tests are carried out on two steel tube dampers and two TYBRB specimens. The excellent energy dissipation characteristics of the proposed steel tube dampers were displayed. The energy dissipation capacity of TYBRBs under various intensity levels has been validated.

(3) A case study on an actual building braced with conventional BRBs and TYBRBs illustrated that TYBRBs bear the benefit to further reduce the seismic response of the BRB-frame building under frequent earthquakes while keep the same mitigation capacity for the seismic response of the BRB-frame building under rare earthquakes.

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