STRENGTHENING AND REINFORCEMENT OF CHINESE MODERN TRADITIONAL-STYLE STRUCTURES UTILIZING VISCOUS DAMPERS

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Abstract

Chinese ancient architectures are characterized by unique appearances and reveal quite high standards in structural and artistic aspects. Most of these buildings are constructed by wood that requires expensive preservative expenditures. Consequently, limited Chinese ancient architectures survived and remained to date. However, a strong desire to preserve this ancient architectural styles has sprung up in recent years, especially for the critical structural protection unit. The modern traditional-style structures are constructed using modern fabrication techniques and building materials to replace wood materials, and they imitate the shape and appearance of Chinese ancient timber structures. The preliminary studies by the writers showed that when the Chinese modern traditional-style steel frame was subjected to the low reversed cyclic loadings, the Dou-Gong, which connected the beam and column end, were firstly damaged and dissipated seismic energy, and they played a critical role as the first seismic fortification line. Thus, increasing the bearing capacity of the Dou-Gong can prevent premature failure of the connections under seismic loads, and it will indirectly increase the bearing capacity of the beam-column joints and the overall structures as well.

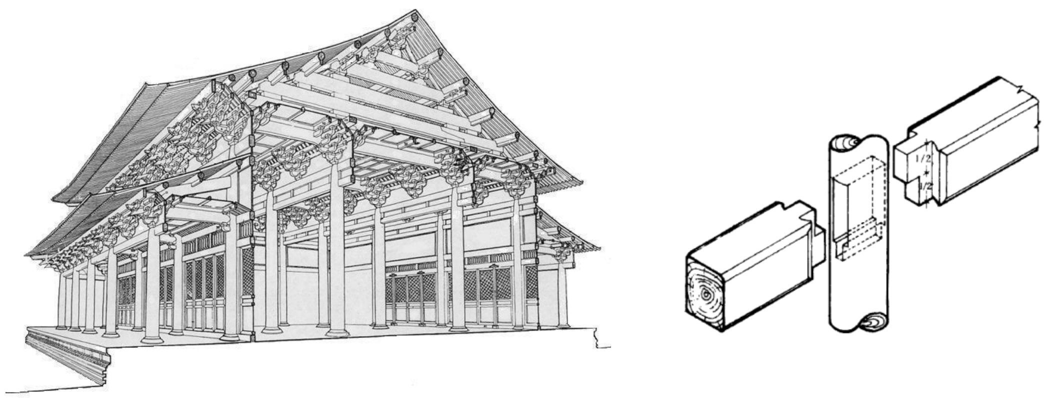
The viscous dampers were attached around the typical steel modern traditional-style joints to retrofit these irregular connections. These dampers substitute the weak Dou-Gong and are decorated outside to imitate the shape of Dou-Gong. Two newly-designed 1/2.66 scale joint specimens with viscous dampers were fabricated and tested under periodic dynamic loads, and the other one without dampers was tested as well for comparison. The influence of viscous damper on the seismic performance of modern traditional-style irregular steel beam-column joints was assessed by hysteretic performance, ductility, energy dissipation capacity, and stiffness degradation. Test results showed that the newly designed steel damping joint improved the mechanical performance of the modern traditional-style steel irregular joints, the maximum bearing capacity increased by 17.9%-34.4% compared with the common joint. The hysteresis curve of the retrofitted joint was fuller and the energy-dissipating capacity was better as well. Utilizing the viscous dampers delayed the development of the plastic hinge at the beam end and avoided the fracture of beam flange to column reinforcing fillet weld. The secant stiffness of the retrofitted joint was significantly higher than that without dampers, and the stiffness of the retrofitted specimens degraded slowly before the loading reached the peak point. The installation of viscous dampers around the irregular beam-column joints, instead of the conventional Dou-Gong, is an effective alternative for increasing the bearing capacity of the beam-column joints in the Chinese modern traditional-style structures.

Keywords: Structural retrofitting; viscous damper; traditional-style structures; dynamic test

1. Introduction

Ancient Chinese wood structure is unique in the history of world architecture. After thousands of years of evolution, it has a unique appearance and structural system, and reflect important historical, cultural and social values [1-4]. Many of these buildings consist of complex wood structures (Fig. 1(a)) that require constant expensive maintenance; consequently, only a few have survived after thousands of years of natural disasters and wars [5]. On request of the urgent demand of preserving the architectural cultural heritage, a new kind of architecture with Chinese traditional style built by modern materials (i.e., steel or concrete) and technologies sprung up in contemporary China. These modern structures that mimic traditional Chinese architectural styles will be called Modern Traditional Steel (MTS) structures in this paper. MTS overcomes the disadvantages of poor durability and high initial and maintenance costs associated with wood structures. In addition, they allow designers to take advantage of the higher strength and stiffness of steel, as well as its ability to provide good seismic performance.

In ancient timber buildings, columns and beams are connected by mortise-tenon joints (Fig. 1(b)). Pocket holes need to be drilled in the timber columns to insert the beams and connect the structural members. When the structure is subjected to seismic excitation, the mortise-tenon joint is able to resist limited bending moments and allow significant rotations. The tenon and mortise squeeze with each other and dissipate the inputting energies. However, the structural components are mostly welded together in MTS [6].



(a) Timber frame structure (b) Mortise-tenon joint

Fig. 1 The ancient wood building

The mechanical properties of the mortise-tenon joint briefly described above are very different from those rigid joints in MTS structures, though the shapes of these two joints are consistent. Previous researches showed that the typical damages of timber mortise-tenon joint are mortise splitting, tenon fracture and tenon pulling out from the mortise [7-9]. For the joints in the MTS, most of the failure were concentrated on the welding cracks, local buckling of column and base metal fractures, etc. [5, 10, 11] It can be seen the force flow and stress characteristics in MTS are obviously different from that of mortise-tenon joints used in older wooden buildings. Furthermore, there is a sudden change of strength and stiffness in the connecting section between upper columns and lower columns in MTS; the upper column is a smaller rectangular steel tube which is connected to a larger lower circular steel pipe. The rectangular tube is inserted into the circular pipe and the insertion depth is extended to the bottom beam flange. Several stiffeners and a circular ring plate are welded to ensure robust force transfer. In some cases, two beams are connected with the bottom column to ensure aesthetic needs. The details are illustrated in Fig. 2.

Sparrow brace (Fig. 3a) is an exclusive structural member in ancient Chinese timber architecture, and it is usually placed at the junction of the beam and the column to act as the decoration members. While for MTS, steel Dou-Gong (Fig. 3b) replaces the timber sparrow brace, and it is often welded on the lower circular column and horizontal beams. The steel Dou-Gong can reduce the span between the columns and increase the shear capacity of the irregular joints to some extent. In this paper, to make the most use of Dou-

Gong in MTS to enhance the seismic performance of the overall structure, the small viscous dampers are employed and installed at the Dou-Gong positions to improve the energy dissipation capacity of the irregular beam-column joints in MTS. In addition, installing a decorative cover on the outside of dampers can minimize the appearance influence of traditional-style buildings.

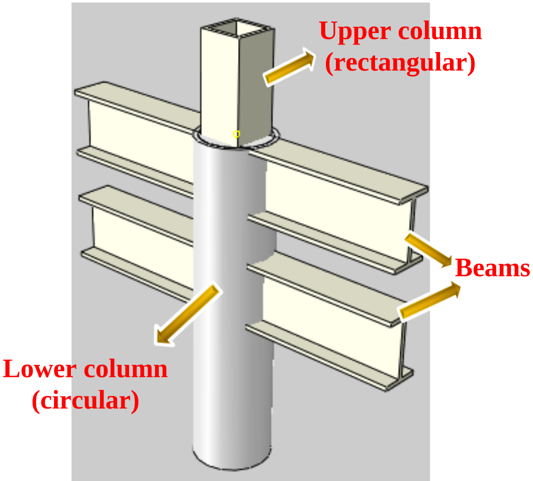
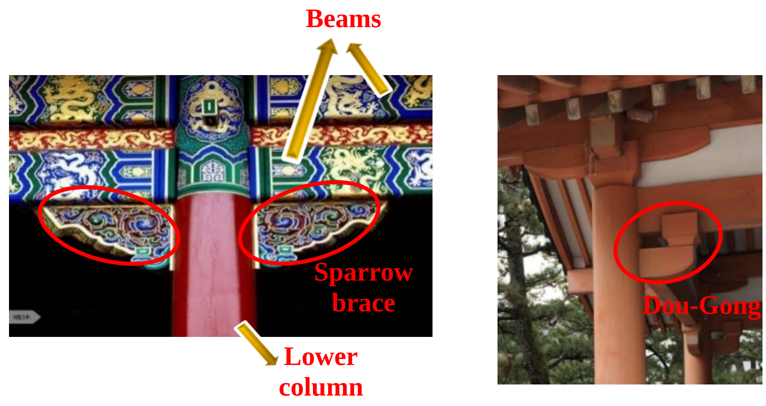


Fig. 2 Beam-column connection in MTS



(a)Sparrow brace in timber structures (b) Dou-Gong in MTS

Fig. 3 Construction instance

In the past decades, utilizing different types of dampers at controlling the structural damage and improving the seismic performance of the architectures has been widely accepted in academia. Soong and Spencer [12] made an effort to introduce the basic concepts of passive and active structural control and to bring up-to-date damper development into structural applications. Chung et al. [13] proposed a hydraulic displacement amplification damping system (HDADS) to retrofit non-seismic reinforced concrete beam-column joints. Two 1/2 scale reinforced concrete beam-column joint specimens designed for gravity loads only were constructed and tested under reverse cyclic displacements at low frequencies. The experimental results indicated that HDADS is an effective and convenient energy dissipation system for the strengthening of reinforced concrete beam-column joints. Koetaka et al. [14] developed a system to mainly utilize bolts with the number of welds minimized, a wide-flange beam was joined to a wide-flange column by bolted splices at the top flange and newly invented hysteretic damper was at the bottom flange. The corresponding tests revealed that the proposed system was capable of achieving stable hysteresis behavior in an extensive deformation range. Xue et al. [15, 16] analyzed the dynamic mechanical properties of viscous dampers on the concrete Chinese traditional style structure with dual-lintel joints under seismic excitation. The hysteretic curve of viscous damper on the concrete Chinese traditional style structure with dual-lintel joints were plumper, and the structure had good ductility and capacity of energy dissipation.

This paper proposes a retrofitting option using the viscous dampers to strengthen the irregular joints in modern traditional steel structures, Three MTS joints (including two retrofitted joints with viscous damper and one joint without damper) were designed and tested under dynamic cyclic loading, the seismic behavior improvement of the viscous dampers on the MTS irregular joints are discussed in detail. This paper provides a theoretical basis for the structural design and a practical approach for the retrofitting of traditional-style steel buildings.

2. Typical damage in traditional-style structures

The structural performance of the traditional-style steel frame was first investigated. A one-storey and two-bay steel frame specimen, constructed following an actual scenic hall building as the prototype, was fabricated strictly based on the Building Standards of the Song Dynasty, and then tested under the cyclic loads. The specimen possesses the same appearance as the typical ancient Chinese architectures, such as the sloping roof, circular columns, and a large space, etc. Besides, the simplified welded Dou-Gong components were installed between the column and beam. The dimensions and details are shown in Fig. 4 and Table 1.

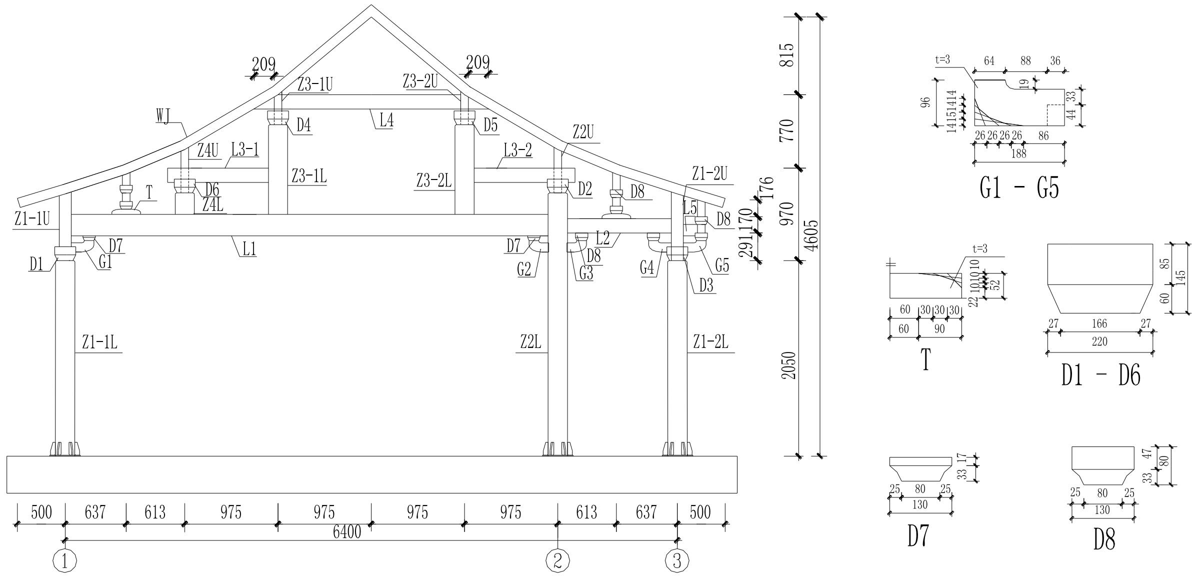


Fig. 4 Details of traditional-style steel frame

Table 1 Size of component

Components	Control numbers	Section
Columns	Z1-1L, Z1-2L, Z2L	φ203×6
	Z1-1U, Z1-2U	□125×5
	Z3-1L, Z3-2L, Z4L	□125×3
	Z2U, Z4U, Z3-1U, Z3-2U	□80×3
Beams	L1	□225×125×3
	L2, L3-1, L3-2, L4	□150×100×3
	L5	□120×100×3
Roof Truss	WJ	□100×3

Based on the load code of China and similarity relations of the model [17], the vertical loads of 7.8 kN, 13.4 kN, 9.4 kN, 7.1 kN, and 5.6 kN were imposed on the top of frame columns (i.e., Z1-1, Z3-1, Z3-2, Z2 and Z1-2, respectively) by concrete mass. The cyclic loading test was carried out by using a multi-functional electro-hydraulic servo actuator; the applied horizontal force was applied at one end of the structural girder.

Fig. 5 shows the damage evolution of the specimen. D1 and G1 (see Fig. 4) firstly reached the yielding, and then tearing appeared along with the interface of the web and flange of G2, G3 and G4 along the horizontal direction. After the apparent failure of Dou-Gong components, the plastic hinge at the beam end developed sufficiently, and convex deformation and rupture occurred at the beam ends. It can be concluded that the seismic performance of the steel traditional-style structure is different from the conventional steel frames. Dou-Gong starts to work and resists the seismic loads firstly, and protects the overall frame from significant damage.

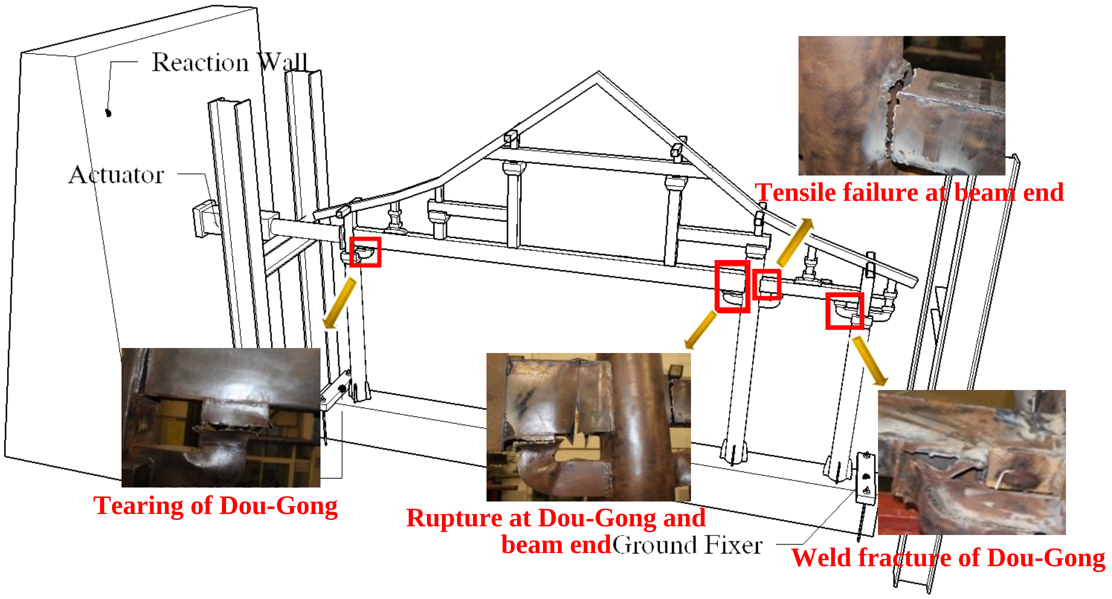


Fig. 5 Damage observation of traditional-style steel frame

3. Retrofitting of irregular joints in traditional-style structures

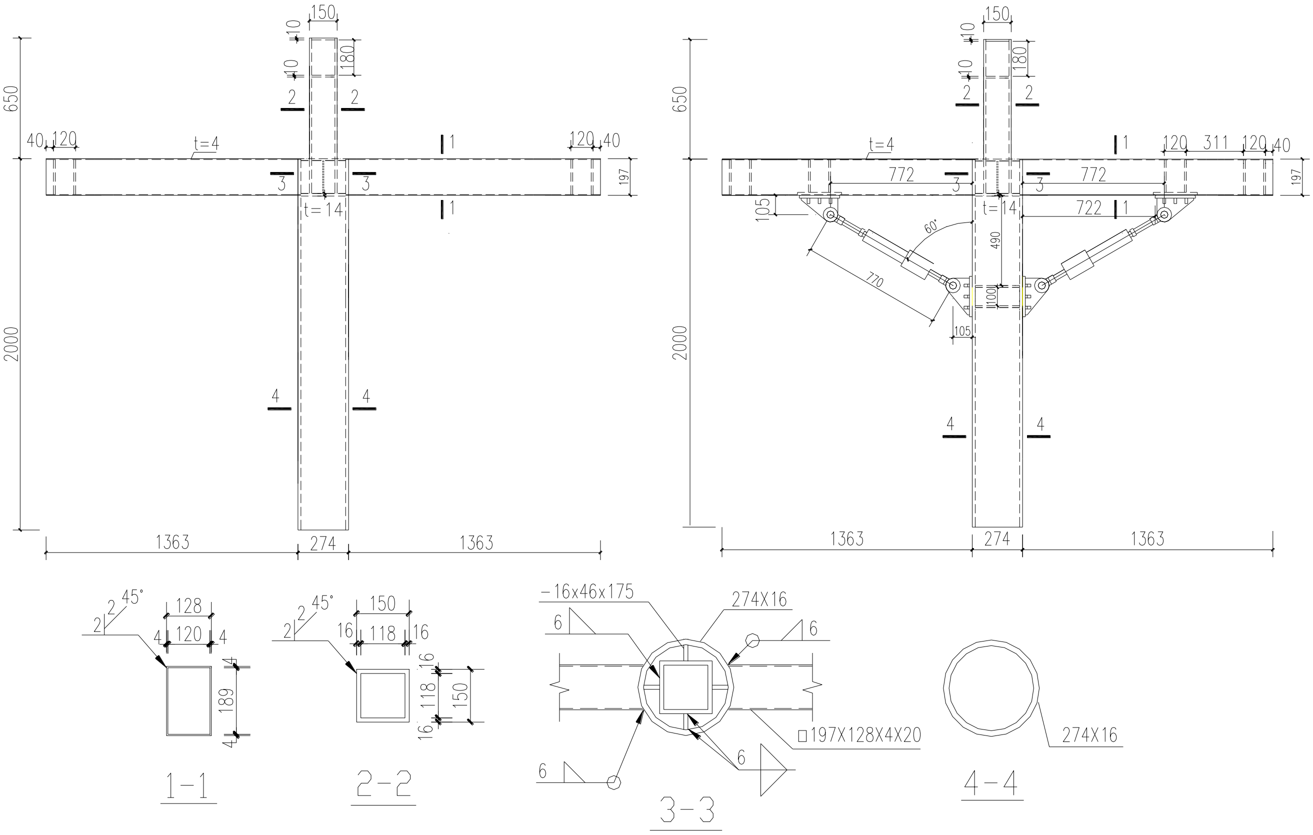
3.1 Experimental program

From the above damage observations, Dou-Gong acts as the critical component in controlling the strength of the overall structures. Increasing the bearing capacity of the Dou-Gong component can prevent the premature failure of the irregular connections in traditional-style buildings under seismic load.

To investigate the improvement of viscous dampers on the seismic performance of irregular joints in traditional-style buildings, the viscous dampers were utilized instead of Dou-Gong component to construct the new kind of retrofitted irregular joints. Three 1/2.6 scaled specimens were fabricated based on the engineering instance of a traditional-style building, and the structural size was modified according to the relevant regulations of Building Standards of the Song Dynasty. The lower column is the circular seamless steel pipe, at the same time, the upper square steel column and the box beam are welded by four steel plates. The steel used in this test was Q235B and the fillet weld was used when connecting thin plates and penetration groove welding for thick plates. Among the specimens, two retrofitted joints with viscous dampers (SBJ-2 and SBJ-3) were tested under periodic dynamic loads (Fig. 6b), the other one without dampers (SBJ-1) were tested as well for comparison (Fig. 6a). Two ends of viscous dampers were connected with the steel joints by bolt pins. The dimensions and the detailed construction of the specimens are shown in Fig.6. Table 2 lists the design parameters of the three specimens.

Table 2 Design parameters of specimens

Specimen	Damping coefficient (kN s/m)	Damping exponent	Axial compression ratio	Beam Flange (mm)	Beam Web (mm)	Lower Circular pipe (mm)	Upper square tube (mm)
SBJ-1	/	/	0.3	128×4	197×4	274×16	150×16
SBJ-2	60	0.38	0.3	128×4	197×4	274×16	150×16
SBJ-3	80	0.38	0.3	128×4	197×4	274×16	150×16



(a) Common joint (b) Retrofitted joint

Fig. 6 Dimensions of specimens

The beam end was connected to the ground beam using a tie rod, and the column bottom was restrained by hinge support. The axial load was firstly applied in the vertical direction at the column top end, then the cyclic load was applied horizontally. Given that the seismic wave can be seen as a collection of sine waves of different frequencies, so the sine motion with five repeated loading loops under the same loading displacement was adopted. Fig. 7 shows the on-site loading, and the loading protocol is illustrated in Fig. 8.

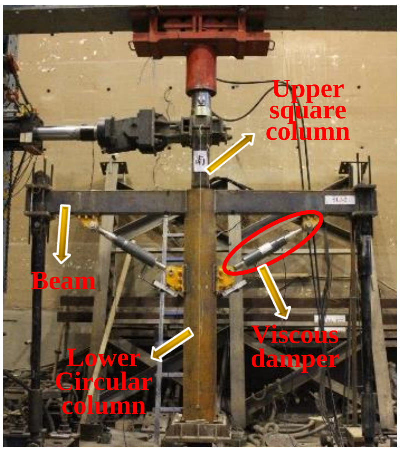


Fig. 7 On-site loading

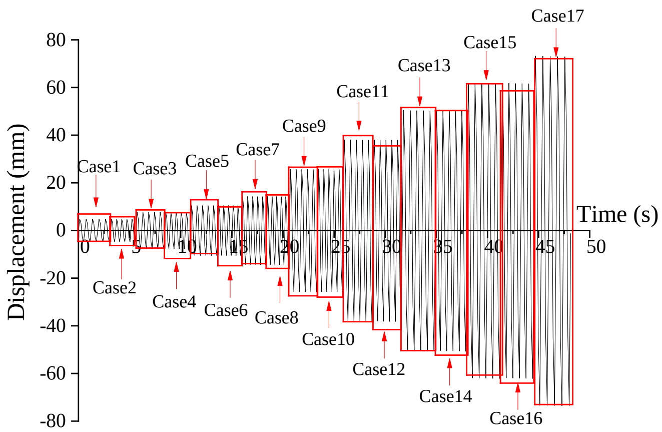


Fig. 8 Loading protocol

3.2 Damage observation

The test specimens were designed based on the principle of “strong column-weak beam.” Thus, the visible damage phenomena of the plastic hinge zone appeared at the beam ends during the test, while no significant damage was observed in the panel zone region. Fig. 9 shows the typical failure patterns of the specimens.

(a) SBJ-1

(b) SBJ-2

Fig. 9 Failure patterns

The following can be seen from Fig. 9.

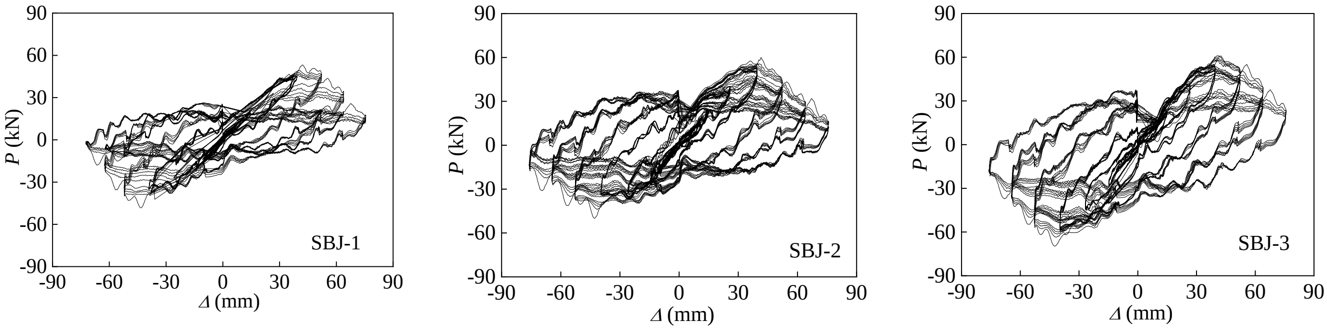
(1) During the whole loading process, the deformation of the retrofitted joints (SBJ-2 and SBJ-3) concentrated on the beam hinge region, which was about 5-10 cm from the column surface; while the welding of beam to column cracked for SBJ-1, this demonstrates that the plastic hinge region moved a little bit outwards after installing the dampers.

(2) The bearing capacity of the joint specimen with viscous damper improved greatly, and the failure mode of the specimen changed as well. The weld at the beam-column connection no longer cracked, but tearing of the base metal in the plastic hinge area at the beam end were observed, demonstrating that the viscous damper has a noticeable effect of damage development of the irregular joint in the traditional-style buildings.

(3) The deformation development of the retrofitted joint with a viscous damper was delayed. The steel flange buckling at the beam end, cracks in the base metal and tearing failure lagged behind the corresponding common joint (SBJ-1).

3.3 Hysteresis loops

The experimental hysteresis loops are shown in Fig.10, where P is the horizontal load at the column top end, and Δ is the corresponding horizontal displacement. Under the dynamic load effect, the hysteresis curve of the specimen fluctuated up and down. That was because the pump and valve capacity of the test setup could not match the loading acceleration requirement, and the output signal from the actuator was not consistent with the input command very well.



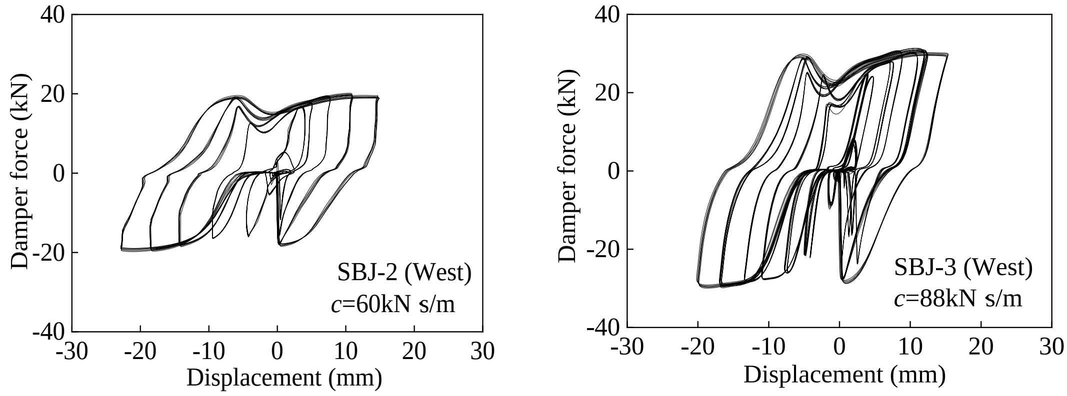
(a) SBJ-1 (b) SBJ-2 (c) SBJ-3

Fig. 10 Hysteresis loops

Before the plastic hinge area yielded, the load-displacement curves cycled along a straight line basically, and the specimen was in elastic stage. The hysteresis loop area was relatively small, and no stiffness degradation and residual deformation can be observed.

With the loads increasing, the buckling phenomenon emerged in the plastic hinge area. Correspondingly, the hysteresis curves were roughly spindle-shaped and gradually became plump, showing remarkable energy-consuming characteristics. In addition, a more considerable residual deformation began to appear. The initial slope decreased gradually, indicating that the stiffness of the specimen was deteriorating with the plastic deformation aggravating of the plastic hinge region and the continuous development of cracks.

The hysteresis loop of the retrofitted joint was fuller than the joint without dampers. It shows that the retrofitted joint with viscous damper has a stronger energy dissipation ability. The larger the damping coefficient of the damper is, the fuller the hysteresis loop of the joint and the stronger the energy consumption capacity occur.



(a) West damper of SBJ-2 (b) West damper of SBJ-3

Fig. 11 Load-displacement curves of viscous dampers

The damper force-displacement curves are shown in Fig. 11. It can be seen that “sunken” phenomenon appears, this is mainly because when one circle of loading was completed in the test, a short pause occurred before the next circle of load started, which would result in the damper piston starting from the middle position and ending at the middle position at the beginning of each loading circle. The relative speed of the ends of the damper decreased to zero, so the damper output also dropped to zero.

When the loading displacement was small, the hysteresis curves of dampers were still very full, indicating the viscous dampers still have good energy dissipation capacities at small displacements. With the loading increase, the hysteresis loop area continued to increase, showing the energy dissipation increased with the loading displacement amplitude.

3.4 Backbone curves

The influence of viscous damper on the strength of traditional-style irregular steel beam-column joints was assessed by the backbone curves. Fig. 12 shows the comparison of backbone curves of three specimens.

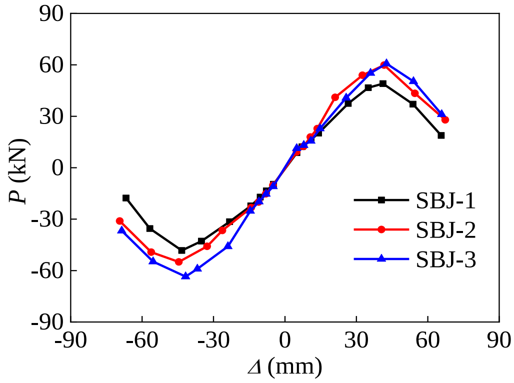


Fig. 12 Backbone curves

When the specimen entered the yield stage, the slope of the skeleton curve became smaller, the deformation developed faster than the load increase, and the stiffness of the specimen decreased continuously. After the specimen reached the peak load, due to the tearing of the base metal and cracking of the weld, the skeleton curve showed a descending segment.

The steel retrofitted joint improved the mechanical performance of the traditional-style steel irregular joints, the maximum bearing capacity was increased by 17.9%-34.4% compared with the common joint (SBJ-1), and the increasing amplitude was more obvious with the larger damping coefficient.

4. Conclusions

This paper proposes a retrofitting option using the viscous dampers to strengthen the irregular joints in modern traditional steel structures. The findings are summarized as follows:

1. Increasing the bearing capacity of the Dou-Gong component by viscous dampers can prevent premature failure of the connections under seismic load.
2. The viscous damper increases the maximum strength of the beam-column joint and postpones the development of the plastic hinge at the beam end, avoiding premature cracks at the connection region.
3. Viscous damping device is an alternative retrofitting method to strengthens irregular steel connections in traditional-style buildings.
4. The variation of the viscous factors for dampers herein is limited in this research, and further study is needed to determine the reasonable range for retrofitting dampers.

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