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Mechanical performance of lintel-column joint of Chinese traditional style architecture with viscous damper

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Abstract: By using a fast dynamic loading method, six Chinese traditional style lintel-column joints were tested and studied, seismic performance indicators of the joints were obtained. Results indicate that seismic behavior of Chinese traditional style architecture with lintel-column joint was superior to contemporary beam-column connection, load-bearing capacity and dissipation energy capacity of specimens with viscous damper is superior to specimens without viscous damper. Compared with single lintel-column joints, dual-lintel-column joint had higher bearing capacity stiffness and fuller hysteretic curve. Dual-lintel-column structure form located in the outer eave column has a role similar to ring beam, which could enhance the overall performance of structure use. And a series of damage models were used to evaluate the whole process damage for 6 specimens. Furthermore, the results and proposals not only benefits to further development for Chinese traditional style structure, but also has reference value to the design, construction and research of Chinese traditional style structure.

Keywords: Chinese traditional style architecture; dynamic cycle loading; viscous damper; mechanical behavior; damage evolution

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Introduction

The architecture of China is as old as Chinese civilization. From every source of information-literary, graphic, exemplary-there is strong evidence testifying to the fact the Chinese have always employed an indigenous system of construction that has retained its principal characteristic from prehistoric times to the present day. That this system of construction could perpetual itself for more than five thousand years over such a vast territory and still remain a living architecture, retaining its principal characteristic in spite of repeated foreign invasions-military, intellectual and

spiritual-is a phenomenon comparable only to the continuity of the civilization of which it is an integral part. Chinese ancient buildings are mainly made of wood, for thousands of years they have experienced sorts of earthquakes but remain intact. Such as yingxian wood pagoda, main hall of Foguang temple in Wutai Mountain and toshodaiji monastery in Japan. The architecture of China have highlighting the local culture and history. They are the invaluable cultural and historical legacy of China.

Currently, with the coming of reinforced concrete and steel framing, Chinese traditional architecture faces a serious delimma. Indeed, there is a basic similarity between the ancient Chinese architecture and the contemporary building systems. But can they be combined? Can the traditional Chinese structural system find a new expression in these new materials? Possibly. But that must not be the blind imitation of “periods”. Something new must come out of it, or Chinese architecture will become extinct. Hence, how to use modern buildings materials to inheriting and creating new modern architectural style with national culture and regional style, which will provide an important reference the development and construction of city. Chinese traditional style architecture is an exploration and innovation with good prospects of popularization and application. Chinese traditional style structures are just similar to ancient Chinese structures in external appearance, but with respect to the materials, the force transmission mechanisms and seismic behaviors, they are quite different. Modern building materials(i.e. concrete and steel) and construction technologies were adopted in Chinese traditional style structures, but the structural mechanical properties and analytical method are different from modern structure.

Chinese traditional style structures is about more than easily copied Chinese timber structures, "traditional style" as an element of conscious or unconsciously, many architect and structural engineer in the building of being, which is popular in domestic and foreign construction and achieves good results. Chinese traditional style element is widely used in many architecture at home and abroad, which has an eye for both the telling detail of aesthetic perception under Chinese timber structures and the broad sweep of practicability, just like spatial arrangement and harmony

between man and nature.

The most famous case is that of the Chinese National Pavilion, which be called Crown of The East, at the Shanghai World Expo. From the outside it appears to be a Dougong brackets of Chinese timber structures, and the structure type is steel concrete composite structure. With distinctive shape and bright red, brilliant performances stunned the domestic and overseas tourist. For Chinese traditional architecture, which will be applied more widely in future. Of a nation, of the world.

Currently, most of the research on mechanical property of the Chinese traditional style architecture is just in the beginning phase and an integrated technical system has not been formed. Xie et al (2014; 2015 and 2016) have studied the mechanical behavior of four 2/3 scaled reinforced concrete Chinese traditional style column-beam joint by means of tests. Compared with contemporary reinforced concrete column-beam joint, the displacement ductility factor and the energy dissipation coefficient of the column-beam joint are smaller, and the ductility and energy dissipation capacity were relatively worse. Xue et al (2016; 2017 and 2018) have studied the failure mode, hysteretic performance, and ductility of Chinese steel and concrete traditional style architecture by experiments and numerical simulation analysis. The failure mode of the beam-column joint is the shear failure of joints when subjected to axial load, bending moment, and shear force in the core area. The maximum deformation occurred firstly in the lower core area, then in the middle short column. Sui et al (2017 and 2018) have studied the mechanical property and seismic behavior of Chinese traditional style architecture with viscous damper. The results reflect that the steel beam-column joint specimens equipped with viscous dampers have plumper hysteretic curves and better energy dissipation capacity. The energy dissipation capacity of joint with viscous damper significantly decreased at the yielding points but then it was enhanced with the deformation increasing.

Earthquakes always cause unfavorable damage to structures, and it is difficult to quantitatively describe the structural damage due to the uncertainty of earthquake excitation in the seismic analysis and design. However, the

prediction of damage during earthquake is important for the structural seismic design and analysis of new-built and existed buildings. So far, the evaluate the seismic performance based on structural damage is used widely in modern architecture, but it is still blank in Chinese traditional style architecture. Passing to the damage evolution law under earthquake and establishing the reasonable earthquake damage assessment model have great significance on the elastic-plastic time-history analysis, dynamic reliability analysis and post-earthquake safety assessment and emergency response for Chinese traditional style architecture (Massumi et al. 2013; Ghosh et al. 2011).

Consequently, in order to better explore the seismic performance and damage development of Chinese traditional style architecture, six specimens of Chinese traditional style architecture lintel-column joints were tested under dynamic cyclic loading, including four specimens with viscous damper called the controlled structure. And two specimens without viscous damper called the non-controlled structure. Dynamic cyclic loading laws were adopted, and the failure characteristics, mechanical behavior, such as the load-displacement curves, load carrying capacity, degradation of strength and rigidity, ductility and energy dissipation of the joints, and seismic damage of specimens were analyzed. The research here was expected that the study could provide some references to the design, construction and research of Chinese traditional style structure in the future.

1 General conditions of Experiment

1.1 Design summary

Six Chinese traditional style architecture with lintel-column joint were designed for the tests, and the specimen was divided into dual-lintel-column joint series and single lintel-column joint series, every series including 3 specimens. For dual-lintel-column joints series, there are two specimens with viscous damper(specimens TD-2, TD-3), and a specimen without viscous damper(specimen TD-1). Similarly, single lintel-column joint with viscous were TS-2, TS-3, and without viscous was TS-1. Specimens without dampers, TD-1 and TS-1, were designed for comparison. Considering the convenience for fabrication and limitation of test conditions, all the specimens are 1/2.6 scaled.

Dynamic cyclic loading test was performed on these specimens to study the influence of design parameter of viscous damper and types of joints on seismic performance. Tested specimens were designed according to the requirements from Construction Technology of Chinese Ancient Timber Structures (Ma 2017), Code for Seismic Design of Buildings (National Standard of PRC 2010) and Code for Design of Concrete Structure (National Standard of PRC 2010).

Fig.1 demonstrated the design details and geometric configurations of the tested specimens, and the reinforcing configuration of the main section. The concrete-filled steel tubular was adopted in the upper column due to the variable cross-section of column, and the material of steel tube was Q235B.

In the study, concrete with grade C40 with cube compressive strength of concrete of 58.2 MPa was adopted in all lintels and columns. Mechanical properties of steel members were shown in Table 1, based on material test. Ratio of axial compression stress to strength of 0.25 was used.

1.2 Experiment procedure

Fig.2 illustrated the experiments loading device, where the axis for column and lintel would be vertical and horizontal with this configuration, respectively. Vertical compressive load was slowly applied at the top of the column by a 100ton hydraulic jack until reached the expected axial compression ratio. Then the horizontal load of sine wave dynamic cyclic load was applied at the side edge of the column by MTS electro-hydraulic servo actuators with range of 100 kN(± 200 mm). Considering that the speed-nonlinear-relevant type viscous damper was adopted for specimens, the loading protocol was determined by controlling displacement (amplitude) and loading frequency. The displacement-controlled loading protocol for each specimen consisted of ten cycles at a series of progressively increasing displacement amplitudes in each hoop(see table 2), and Fig. 3 illustrated the loading protocol.

The experiments did not terminate until the load dropped down to less than 85% of peak load.

1.3 Model selection and installation of viscous damper

Generally, the type of viscous damper and its parameters could be determined according to the length and force of viscous damper determined under the Caifen modular system of ancient Chinese building citations. Therefore, the range of the main parameter (i.e. damping coefficient and damping exponent) could be determined under the type of viscous damper provided by manufacturer, and the optimized result of these parameters could be obtained by means of optimization study.

The design parameters of viscous damper adopted in the research were shown in table 3, while Fig.4 to Fig.6 demonstrated the details of viscous dampers. In Fig. 6, the angle θ was 60° , the height (h) of the lintel was 240mm and the length (L) of viscous damper was 770mm, the vertical length from screw of hinged shoe with lintel to the bottom of the lintel (L_b) and the horizontal length from screw of hinged shoe with column to the edge of the column (L_h) were 667mm, 120mm and 120mm, respectively.

2 Analysis of experimental results

2.1 Load-displacement curves

Fig.7 and Fig. 8 exhibited the hysteretic curves and skeleton curves for tested specimens, where P means the horizontal resistance and Δ means the corresponding horizontal displacement.

From Fig. 7, some main results could be obtained as follows:

(1) At the beginning of experiment (control displacement ≤ 15 -mm), enveloped area of load displacement curves was tiny for all specimen, the ratio of horizontal resistance and corresponding horizontal displacement (the slope of curve) was basically superposition under every loading conditions, and horizontal resistance linearly changed with increase of horizontal displacement, strength and stiffness degradation of all specimens were not notable, and it was considered that specimen was still in elastic state.

(2) With increase of the control displacement ($27\text{-mm} \leq \text{control displacement} \leq 65\text{-mm}$), the ratio of horizontal resistance and corresponding horizontal displacement (the slope of curve) did not coincide with each other gradually, and horizontal resistance was not linear with corresponding horizontal displacement any longer. In this stage, strength and stiffness degradation of all specimens were notable with concrete crushing at a small scale, indicating that specimen turned into elasto-plastic phase.

(3) At the later stage of the loading ($77\text{-mm} \leq \text{control displacement} \leq 115\text{-mm}$), there was a decrease in load of all specimens degradation in load of controlled structure was mild compared with non-controlled structure, while the degradation in load of single lintel-column joint were slowly compared with dual-lintel-column joint. This phenomenon was caused by the installation of viscous damper to some extent, which improved carrying capacity and delay the damage development.

(4) For dual-lintel-column joint, it could not make best of the mechanical qualities of the two lintel due to the uncoordinated deformation and uneven internal force distribution. Compared with static load, particularly with the dynamic impact load, the reinforced concrete construction failed easily and resulted in a great loss in capacity, and hysteretic curve of joints fluctuated to a certain extent.

Fig. 8 illustrated the seismic performance of specimens more concisely with skeleton curve and the difference caused with and without viscous damper. Some results were obtained as follows:

(1) During the loading process, the curve could be divided into four stage: crack point, yield stage, ultimate state and failure, respectively. There has been no significant yield point in the back-bone curves, this reflect that yield is develop from microcosm to macrocosm gradually. Based on the test results, the longitudinal steel rebar yield was considered as the initiation of yield stage.

(2) From Fig. 8(a) to Fig. 8(c), it could be seen that the bearing capacity of dual-lintel-column joints were significantly superior to single lintel-column joints illustrating that the construction measure of dual-lintel-column

locate in eave column was similar to the ‘Theory of Hooping Strengthening’ (Wei 2020), internal elements of buildings could be tightly encircled by column grid consist of several dual-lintel-column, therefore, the mechanical properties and system reliability of Chinese traditional style architecture with dual-lintel-column improved obviously, and which had similar effect as flank feet and raise of wooden structure of ancient buildings.

(3) As shown in the Fig. 8((d)~(e)), the bearing capacity of controlled structure were significantly superior to the non-controlled structure, with milder degradation in resistance. The bearing capacity and ductility performance could be obviously increased by attached viscous damper. Consequently, the combination of viscous damper and Chinese traditional style architecture could be considered as a better method for improving the seismic performance as well as protecting the main structure.

2.2 Analysis of bearing capacity and ductility

Failure load P_u is equal to $0.85P_m$ and its corresponding displacement is Δ_u , where P_m is the ultimate load, which is the peak load value of back-bone curve, as shown in Fig.9, its corresponding displacement is Δ_m . P_{cr} is the crack load, that is load under first crack can be megascopic in the loading process, and its corresponding displacement is Δ_{cr} .

The yielding load P_y and yielding displacement Δ_y can be determined by “Park-Method” (Elnashai et al. 1995), the calculation method as shown in Fig.9. And the determination steps are as follows, the yield load P_y and yield displacement Δ_y identified are as follows, firstly, to confirm the point A of $0.6P_m$ in back-bone curve, then, do a straight line from point A and origin of coordinates, which intersect at point B with the straight line of horizontal line though ultimate load P_m , do vertical line at point B , which intersect at point C with back-bone curve, the point C is yielding load P_y , and the corresponding displacement is Δ_y .

Ductility coefficient μ refers to the ratio of the Δ_u to the Δ_y . All data from the load cell and the actuator’s displacement transducer was recorded by using a computer controlled data acquisition system.

Just as shown in back-bone curve at Fig. 8, every curve has both of positive and negative directions, for a

comprehensive comparison, an analytical comparison of the both of two directions calculation results was conducted to make sure its validation, which corresponding to the values of table 4. For average displacement ductility coefficient $\bar{\mu}$, which was the average of positive displacement ductility coefficient and negative displacement ductility coefficient.

With the above method, the load values and displacement values of all specimen can be obtained. In order to compare and make decision more conveniently, the histogram be selected to reflect the load values' and displacement values' variation tendency. Figure 10 reflect the load values of all specimen, and Figure 11 reflect the displacement values of all specimen.

Fig.10 and Fig.11 and table 4 listed some major results of bearing capacity and deformation. Some conclusions could be obtained as follows:

(1) For dual-lintel-column joint, compared with non-controlled structure TD-1, the crack load of controlled structure was improved by 12.5% for TD-2 and 7.0% for TD-3, respectively. For lintel-column joint, compared with non-controlled structure TS-1, the crack load of controlled structure was improved by 8.3% for TS-2 and 15.5% for TS-2, respectively. Generally, the increasing range was not obvious. However, the load and displacement for yield point, ultimate point were significantly increased for controlled structure. Results showed that although the influence of viscous damper on the crack resistance performance was relatively small, it helped to improve the seismic performance of Chinese traditional style architecture under elasto-plastic stage and plastic stage, implying that the viscous damper could better play its own effectiveness in high intensity area.

(2) For dual-lintel-column joint, compared with the TD-1, the increase of crack load was 15.2% for TD-2, and 13.1% for TD-3. For single lintel-column joint, compared with the TS-1 that the joint without viscous damper, the increase of crack load was 1.6% for TS-2, and 4.8% for TS-3. The results reflected that the viscous damper improved the plastic deformation capacity and seismic behavior of Chinese traditional style architecture, and the improvement of single lintel-column joint was inferior to the dual-lintel-column joint. With the viscous damper for dual-lintel-column

joint, the magnitude of the uncoordinated deformation and uneven internal force distribution were effectively reduced, and the global stability of structure was improved obviously. It was concluded that the viscous damper should be given to the eave column of dual-lintel-column structure in priority, in this way, the seismic behavior of Chinese traditional style architecture could be considerably improved effectively.

2.3 Analysis of energy-dissipating capacity

Equivalent damping coefficient h_e and energy ratio I_w (Gosain et al. 1977) were used to evaluate energy-dissipating capacity of Chinese traditional style architecture. In the section, h_{ey} , h_{em} and h_{eu} were expressed as equivalent damping coefficient under yield point, ultimate point and failure point, respectively. I_w was expressed as energy ratio under failure point.

The equation of energy ratio I_w and equivalent damping coefficient h_e were described in Eq.(1) and Eq.(2).

$$I_w = \sum_{i=1}^n P_i \Delta_i / (P_y \Delta_y) \quad (1)$$

$$h_e = \frac{E_d}{2\pi}, \quad E_d = \frac{S_{(ABC+CDA)}}{S_{(\triangle OBE + \triangle ODF)}} \quad (2)$$

Where, P_i and Δ_i are refers to load and displacement of structure under cyclic load at the i^{th} time; P_y refer to the yielding load, and Δ_y refer to yielding displacement; h_e refers to the equivalent damping coefficient; E_d refers to the energy dissipation coefficient; $S_{(ABC+CDA)}$ refers to combined of shaded part area be encircled by hysteresis loop; $S_{(\triangle OBE + \triangle ODF)}$ refers to combined of area of triangle in Fig. 12.

Fig. 13 illustrated the calculated results of equivalent damping coefficient h_e and energy ratio I_w : from which it could be known that:

(1) Compared with non-controlled structure, the equivalent damping coefficient and energy ratio for controlled structure increased significantly, approximately 30.3%~31.5% higher under yield point, 29.7%~34.4% higher under ultimate point and 48.0%~48.7% higher under failure point, respectively. Similarly, the increased range of energy ratio

was approximately 20.2%~23.7% under failure point. The results again reflected that viscous damper improved the energy-dissipating capacity greatly. In this way, it was possible to achieve the performance objective of no damage under medium seism and reparability under severe earthquake.

(2) For dual-lintel-column joint, the equivalent damping coefficient of controlled structure was about 0.271~0.275, and the equivalent damping coefficient of non-controlled structure was 0.141. For single lintel-column joint, the corresponding value is 0.392~0.397 and 0.223, respectively, which was significantly superior to reinforced concrete joint and closed to that of Steel Reinforced Concrete (Han 2007). It indicated that the energy dissipation capacity of the Chinese traditional style architecture with viscous damper was excellent and could meet the requirement of seismic design.

(3) Generally, the energy ratio of all specimens was better than those of contemporary concrete members, which indicated that the Chinese traditional style architecture of steel-concrete composite structure had better ductility property and adequate bearing capacity after ultimate point (Sivaselvan et al. 2000; Song et al. 2001). The energy ratio of Chinese traditional style architecture with viscous damper was obviously superior to contemporary concrete members and concrete Chinese traditional style architecture (Dong et al. 2019 and 2020), showing that the construction measures improved the overall seismic performance and mechanical property of Chinese traditional style architecture effectively.

Fig. 14 and Fig. 15 showed the energy dissipation for specimens and viscous dampers. From the comparison of energy dissipation, it could be known that the energy dissipation of all specimens was unapparent under small control displacement, since that the degradation in stiffness and strength was not distinct and residual deformation was almost zero. With the increases of control displacement, energy consumption value of Chinese traditional style architecture with viscous damper was larger than architecture without viscous dampers.

2.4 Analysis of stiffness

The calculated value of stiffness degradation under every control displacement was shown in Fig. 16, and the stiffness variation of all specimens under different control displacement was shown in Fig. 17. Initial stiffness value is defined as secant stiffness at the first positive and negative hysteresis loop of control displacement, shown in Table 5, and Fig. 18 gave the histogram of stiffness variation. Fig. 19 indicated the ratio of stiffness under different performance point. In the table 5, the K_e is initial stiffness, K_{cr} , K_y , K_m and K_u are the stiffness under crack, yield, ultimate and failure point, respectively.

From the figures, some results were listed as follows:

(1) Generally, stiffness decreased with the increase number of cycles under constant control displacement, which indicated the influence of load cycles on the stiffness degradation. The damage accumulated due to the cracking and crush of concrete, yield of rebar with the increase of load cycles, resulted in the stiffness degradation.

(2) Stiffness degraded fast at the beginning and then the degradation slowed down. On the one hand, stiffness decreased with the increase of number of cycles under constant control displacement, especially under second cycles under constant control displacement, indicated in Fig. 16. On the other hand, the rate of stiffness degeneration decreased obviously with the increase of control displacement, which was caused by the rapid increase of damage accumulation in elastic-plastic stage, and the damage did not change obviously when the specimen was severely destroyed.

(3) Compared with non-controlled structure, the stiffness degeneration rate of controlled structure was slow after the first fast, for the former, the stiffness degeneration rate was maintained rapid decreases, as is shown the red dotted lines in Fig. 16. For the dotted lines of non-controlled structure, TD-1 and TS-1, the dotted lines is almost a straight line, which indicate the stiffness degeneration tendency is linear degradation law. For the dotted lines of controlled structure, the dotted lines is a parabola with large curvature, the rate of stiffness degeneration is become smooth and

slow at the later stage of the loading. The results indicate that the viscous damper can enhance the energy dissipation capacity of the joint to some extent, and the stiffness degradation rate of the joint was inhibited by viscous damper.

(4) For the controlled structure, initial stiffness and secant stiffness at different performance point were greater than the non-controlled structure. For dual-lintel-column joint with viscous damper, the stiffness was 1.36、1.35、1.13、1.10 times of joints without viscous damper, respectively. For single lintel-column joint with and without viscous damper, the corresponding value are 1.27、1.10、1.03、1.34, respectively. Results illustrated that the viscous damper enhanced the stiffness capacity of the joint to some extent, and compared with single lintel-column joint, the effect of viscous damper of the stiffness of dual-lintel-column joint was much more notable. It proved again that viscous damper could effectively improve the seismic performance and guarantee the overall performance of the structure.

3 Analysis of the earthquake damage

Establishing rational evaluation mechanism of seismic performance is one of the important key issues in performance-based seismic design of structure (Banan et al. 1981). At present, there is yet no unified damage evaluation model due to the complexity of seismic influence mechanism and diversity of structural damage affect factors. Many researchers have conducted a series of studies on structural damage and the description of damage, and proposed damage index to quantify both local and global damage when subjected to earthquake excitation. Damage index was typically normalized within range varying from zero to unity, where zero represents undamaged condition and unity represents collapse state of structures.

Considering the features of earthquake, accumulative seismic damage model could give considerations to the strength, deformation and energy-dissipation at the same time, and it was universally accepted to describe the damage development of structure under earthquake. Commonly used damage evaluation model were deformation model (Newmark et al. 1971; Krawinkler et al. 1983; Mehanny et al. 2001), energy-dissipation model (Darwin et al. 1986;

Gosain et al. 1977) and combination model (Hwang et al. 1984; Park et al. 1985).

The damage index was given as zero (undamaged hypothesized) at the beginning and as unity when the load capacity decreased to 85% of peak load. Fig. 20 demonstrated the normalized calculated results for the commonly used damage evaluation model.

From Fig. 20, the characteristic of damage development for every specimen based on different damage model could be summarized as follows:

(1) The damage index was small initially, indicating that the accumulated damage is not obvious under the elastic stage. The damage index developed with the increase of control displacement, due to the increase of plastic deformation, resulting in the obvious residual deformation and accumulation of damage.

(2) The damage index of controlled structure was smaller than the non-controlled structure, indicating that viscous damper significantly improved the seismic performance of Chinese traditional style architecture, in terms of ductility, energy dissipation, hysteretic behavior.

(3) Different damage models had different descriptions of damage evolution, therefore, choosing reasonable damage evaluation model to express the damage evolution law of structure damage and failure process under the type and characteristic of structure was important.

Combined with the observation in tests, it is known that some damage evaluation models was inapplicable for lintel-column joint in traditional style building. Applicability analysis of damage evaluation model is following:

(1) The calculation results are very close for Newmark model and Mahin model, and the development tendency of damage evolution law both of them is well agreed with each other. However, the calculation curve are serration curve, which are not agree with practice situation. One of the main reasons is that the damage model is based on the evaluation of deformation, and the ductility ratio used as the sole deformation-based index. Therefore, Newmark model and Mahin model are not suitable for the description of damage evolution of Chinese traditional style

architecture.

(2) To better explain the accumulation effect of plastic deformation under cyclic load, the Mehanny model is proposed based on the accumulation plastic deformation. As shown in the Fig. 20, Mehanny damage model calculation curve is located in the below of other curves, which indicate the model is more suitable for structure with inferior ductility performance. For Krawinkler model, it is located roughly in the middle of other curves, which indicate the model is more suitable for structure with medium ductility performance. For Gosain model and Darwin model, both calculation curve and development tendency are very close, the damage index is less than the difference at the later stage of the loading. And Hwang model is more suitable for structure with medium ductility performance.

(3) In order to better describe the damage development of structure, multiple parameters model should be used. At the beginning, the specimens were in good condition with no crack or few slight cracks, the damage was insignificant, with increase of control displacement, more cracks occurred and previous cracks extended and widened, damage continuously accumulated, which leading to more serious damage. Under larger deformation, large residual deformation of structure, yielding of components and the crush of concrete resulted in the quick development of damage. Based on the analysis of results of different damage models, it was found that Park-Ang damage model and Banon damage model could pertinently reflect the actual damage development of Chinese traditional style architecture.

4 Conclusions and design suggestion

4.1 conclusion

On the basis of the analysis and discussion of the experimental results for 6 Chinese traditional style architecture lintel-column joint, the mechanical performances and the damage development based on different damage model were analyzed. Some major conclusions could be drawn as followings:

- The seismic performance of lintel-column joint of Chinese traditional style architecture under steel-concrete composite structure was superior to concrete Chinese traditional style architecture and contemporary systems. Viscous

damper could remarkably improve the carrying capacity and energy-dissipating capacity of Chinese traditional style architecture.

- Compared with single lintel-column joint, dual- lintel-column joint developed better the carrying capacity and energy-dissipating capacity. The construction measure of dual-lintel-column locate in eave column was similar to the ‘Theory of Hooping Strengthening’, where internal elements was tightly encircled by column grid consist of dual-lintel-column, and the mechanical properties and system reliability of Chinese traditional style architecture with dual-lintel-column were improved obviously, which had similar effect with flank feet and raise of wooden structure of ancient buildings.

- Generally, the development tendency of stiffness degradation for all specimens were fast initially and then slowed down. The viscous damper enhanced the energy dissipation capacity of the specimen to some extent, and the stiffness degradation rate of the specimens was inhibited by viscous damper. However, there was no direct relationship between the stiffness degradation and the design load of the viscous damper.

- In terms of different damage models, hybrid damage index could better describe the feature of damage development of structure and reflect the dynamic characteristics on the damage development. Results reflected that Park-Ang damage model and Banon damage model could pertinently reflect the actual damage development. Damage curve for both damage models had similar development feature, and the damage increased slowly when the deformation was small before yielding, then it increased quickly under large deformation.

4.2 discussion and suggestion

- Numerical simulation and optimized analysis of the viscous damper on Chinese traditional style structure with lintel-column joint under steel and composite architecture should be analyzed before the type of viscous damper to confirm design parameters. The experimental research and seismic damage evolution on seismic performance in this field not only fills the gap between the theory and method of traditional style architecture design but also provides

reference for engineering practice of this kind of structure.

- It is suggested that the viscous damper is should be given to the eave column of dual-lintel-column structure in priority, for the purposed of effectively improving the seismic behavior of Chinese traditional style architecture.

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view of

dual-lintel-column joint

Fig.1 Geometric configurations and reinforcing configurations of specimens

(b) lintel-column joint

Fig.2 Test set-up

Fig.3 Diagrammatic drawing of the loading system

Fig.4 Installation drawing of viscous damper

Fig.5 Installation parameter of damper

Fig.6 Installation drawing of hinged connection between viscous damper and specimen

Fig.7 Hysteretic curves of all specimens

Fig.8 Back-bone curves

Fig. 9 Park-Method

Fig.10 Load values of all specimen

Fig.11 Displacement values of all specimen

Fig. 12 Diagram for calculation of equivalent damping coefficient

Fig.13 Comparison of energy dissipation capacity histogram of Chinese traditional style architecture

(a) dual-lintel-column joint

(b) single lintel-column joint

Fig.14 Energy dissipation of all specimens

(a) dual-lintel-column joint

(b) single lintel-column joint

Fig. 15 Energy dissipation of viscous dampers

(a) TD-1

(b) TD-2

(c) TD-3

(e) TS-1

(f) TS-2

(g) TS-3

Fig.16 Curves of stiffness degradation

Fig. 17 Variation curve of stiffness

Fig.18 Stiffness comparison of specimen

Fig. 19 The ratio of stiffness under load characteristic value

Fig.20 Application of damage models for lintel-column joint in traditional style building

Table 1 Mechanical properties of steel members for specimens

type	yield strength/MPa	yield strain/ 10^{-6}	ultimate strength /MPa	elasticity modulus /GPa
Q235B	336.5	1435	463.3	201
Φ 8	323.5	1468	400.0	206
Φ 10	465.5	1395	596.5	201
Φ 12	450.1	1320	586.7	196

Table 2 The loading conditions of experiment

loading conditions No.	<i>a</i>	<i>s</i>	<i>f</i>	loading conditions No.	<i>a</i>	<i>s</i>	<i>f</i>
1	50	5	1.59	7	500	53	1.55
2	100	8	1.78	8	570	65	1.50
3	150	11	1.86	9	585	77	1.39
4	250	15	2.05	10	600	88	1.31
5	350	27	1.81	11	700	100	1.29
6	460	40	1.71	12	800	115	1.23

Note: *a*- acceleration (cm/s^2); *s*- control displacement (mm); *f*- loading frequency (Hz).

Table 3 Design parameter of viscous damper

No. of specimen	design force/kN	damping coefficient /(kN•s/m)	damping exponent	Design displacement/mm
TD-2/ TS-2	80	88	0.36	± 30
TD-3/ TS-3	50	60	0.30	± 30

Table 4 Ductility coefficient of specimen

No. of specimen	Δ_y	Δ_u	θ_{cr}	θ_y	θ_m	μ	$\bar{\mu}$
TD-1	28.3	68.1	1/335	1/94	1/39	2.41	2.66
	24.2	70.7	1/340	1/110	1/37	2.92	
TD-2	29.8	82.4	1/340	1/89	1/32	2.77	3.06
	25.2	84.4	1/340	1/105	1/31	3.35	
TD-3	26.3	75.7	1/379	1/101	1/35	2.88	3.02
	26.8	84.8	1/335	1/99	1/31	3.16	
TS-1	19.0	58.8	1/348	1/139	1/45	3.09	3.13
	22.4	70.9	1/335	1/118	1/37	3.17	
TS-2	25.5	73.1	1/344	1/104	1/36	2.87	3.18
	23.4	81.7	1/335	1/113	1/32	3.49	
TS-3	28.2	81.2	1/349	1/94	1/33	2.88	3.28
	19.5	71.9	1/340	1/136	1/37	3.69	

Note: Δ_y - yielding displacement; Δ_u - failure displacement; θ_{cr} - the inter-floor displacement angle under crack; θ_y - the inter-floor displacement angle under yield; θ_m - the inter-floor displacement angle under peak; μ - displacement ductility coefficient; $\bar{\mu}$ - average displacement ductility coefficient.

Table 5. Stiffness value under load characteristic value

No.	K_e /(kN/mm)	K_{cr} /(kN/mm)	K_{cr}/K_e	K_y /(kN/mm)	K_y/K_e	K_m /(kN/mm)	K_m/K_e	K_u /(kN/mm)	K_u/K_e
TD-1	1.95	1.74	0.86	1.43	0.75	0.95	0.46	0.56	0.28
TD-2	2.41	2.20	0.91	1.77	0.74	1.03	0.43	0.56	0.23
TD-3	2.99	2.55	0.85	2.13	0.72	1.12	0.37	0.49	0.17
TS-1	1.90	1.50	0.79	1.35	0.71	0.90	0.42	0.45	0.24
TS-2	2.29	1.81	0.79	1.44	0.62	0.91	0.40	0.46	0.20
TS-3	2.82	2.01	0.71	1.52	0.53	0.94	0.33	0.22	0.08