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Hysteretic Behaviour of Square Tubular T-joint With and Without Collar-Plate Reinforcement under Axial Cyclic Loading

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Abstract: For a square tubular T-joint under axial loading, failure occurs easily along the weld toe because high stress concentration exists in this region. This phenomenon can be used to explain why brittle fracture is dominant when the joint is subjected to cyclic loading, such as faigue loading or earthquake loading. To improve the seismic resistance of a square tubular joint, collar plate can be used to reinforce the joint connection. However, the aseismic behaviour of the collar-plate reinoforced tubular joint must be assessed because only the increase of the load carrying capacity can not guarantee the capacity of energy dissipation for this joint under seismic loading. Through both experimental investigation and finite element analysis, the hysteretic behaviour of square tubular T-joints with or without collar-plate reinforcement is studied. The hysteretic curves, the ductility ratio and the energy dissipation index are all analyzed. Based on the obtained results, it is found that a square tubular T-joint with collar-plate reinforcement can dissipate more energy before failure compared with the corresponding un-reinforced one. Therefore, the reinforced T-joints are more capable in resisting earthquake loading.

Keywords: Square tubular T-joint, Hysteretic behaviour, collar-plate reinforcement, axial cyclic loading.

1 Introduction

Tubular structures are used very widely in practical structures, such as stadium, bridge, tower, offshore platform and railway station etc. Two common types of these structures are classified by the shape of the cross section of the tubes, namely squaure tubular structures and circular tubular structures. In tubular structures, one or several smaller tubes (called brace member) are connected directly onto the surface of a bigger tube (called chord) by using penetrated welding to form a critical

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connection which is generally named as a tubular joint. Tubular joint is a significant position in a tubular structure because failure occurs in this region easily due to the fact that high stress concentration exists near the weld toe because stiffness in this location is discontinuous. Experimental studies have been condcuted by many reseachers to investigate the stress concentration facor of different types of tubular joints, such as Chiew, Lie, Lee and Huang (2004), Shao and Cao (2005). The reported results show that fatigue crack always initiates at the weld toe and propagates along the weld toe as well. Due to the formation of fatigue crack, brittle fracture failure may occurs when the crack propagates to a critcal state (Lie, Chiew, Lee and Yang, 2006). For a tubular joint under axial loading, failure is generally located on the chord surface near the brace/chord intersction because the radial stiffness of the chord is much weaker than the axial stiffness of the brace in most cases because of the thin-walled tube with hollow section.

To improve the load carrying capacity, the effective method is to increase the radial stiffness of the chord. In the literature, many strengthening measures have been used to enhance such stiffness. Some commonly used reinforcing methods include: internal stiffened ring (Lee and Lliwelyn-Parry, 2004; Thandavamoorthy, Madhava Rao and Santhakumar, 1999), doubler plate or collar plate (Choo, Liang, van der Vegte and Liew, 2004; Choo, van der Vegte, Zettlemoyer and Li, 2005; Choo, 2005; Fung, Chan and Soh, 1999; Hoon, Wong and Soh, 2001; van der Vegte, Choo, Liang, Zettlemoyer and Liew, 2005), rack/rib plate (Myers, Brennan and Dover, 2001) and chord thickness reinforcement (Shao, Lie and Chiew, 2010) etc. In these reinforcing methods, collar plate can be conveniently used for reinforcing a tubular joint in service. It is also proved to be much effective in improving the ultimate strength. However, previous studies on this method are mainly focused on strengthening circular tubular joints. Few work has been conducted to assess the efficiency of this method for reinforcing square tubular joints. In addition, most of previous studies are carried out to investigate the improvement of the static strength rather than the aseismic performance.

As it is well known that the hysteretic behaviour is capable to evaluate the energy dissipation for a tubular joint under cyclic loading, it is also reliable to provide an approximate estimation for the tubular joint under earthquake loading. Thus, this study then aims to do a further study on assessing the hysteretic behaviour of square tubular joint reinforced with collar plate.

2 Experimental investigation

The most accurate method for assessing the hysteretic behaviour of a tubular joint under cyclic loading is through experimental test since it can consider all the prac-itcal situations which are difficult to be included in the finite element simulation, such as the stiffness deterioration of the steel material, the realistic relationship of the stress-strain and the initiation and propagation of cracks. For this reason, experimental tests on the hysteretic performance of a square tubular T-joint specimen and a corresponding un-reinforced specimen are conducted.

2.1 Specimens

For a typical square tubular T-joint with collar plate reinforcement, the configuration is shown in Fig. 1. All the quantities with subscript 0 denote the dimensions of the chord, and the quantities with subscript 1 denote the dimensions of the brace. l_a, l_w and t_p denote the length, the width and the depth of the collar plate. In the fabrication of the specimen, the brace is firstly welded onto the chord surface directly. After that, the collar plate is placed around the weld toe of the brace/chord intersection, and it is welded to the chord surface along its four sides by using fillet weld. The collar plate is connected to the brace also by fillet weld. For comparison, an un-reinforced T-joint with same size is also fabricated.

The dimensions of both the un-reinforced specimen and the collar-plate reinforced specimen are tabulated in Tab. 1. In Tab. 1, model 1 is a collar-plate reinforced specimen, and model 2 is the corresponding un-reinforced specimen. For both specimens, the lengths of the chord and the brace are 2000 mm and 400 mm respectivley. Fig. 2 provides the picture of the two specimens.

Table 1: Dimensions of the specimens

No.	b_0 (mm)	b_1 (mm)	t_0 (mm)	t_1(mm)	t_p (mm)	l_a (mm)	l_w (mm)
1	160	100	4	4	6	130	130
2	160	100	4	4	-	-	-

Before experimental tests, the material properties of the tube steels are measured from Coupon test. The yield stress, the ultimate stress and the elongation are 310 N/mm^2, 412 N/mm^2 and 17% respectively. The Elastic modulus is 180000 N/mm^2, and Poisson's ratio is 0.3.

2.2 Test rig and loading scheme

The two specimens are all tested in a specially designed test machine which can be seen in Fig. 3. This test machine can provide axial cyclic loading at the brace end with a loading magnitude of 500 kN. The maximum axial cyclic displacement is ± 75 mm. During the tests, both ends of the chord are pinned, and the brace end is limited to move in its axial direction. The applied load at the brace end can

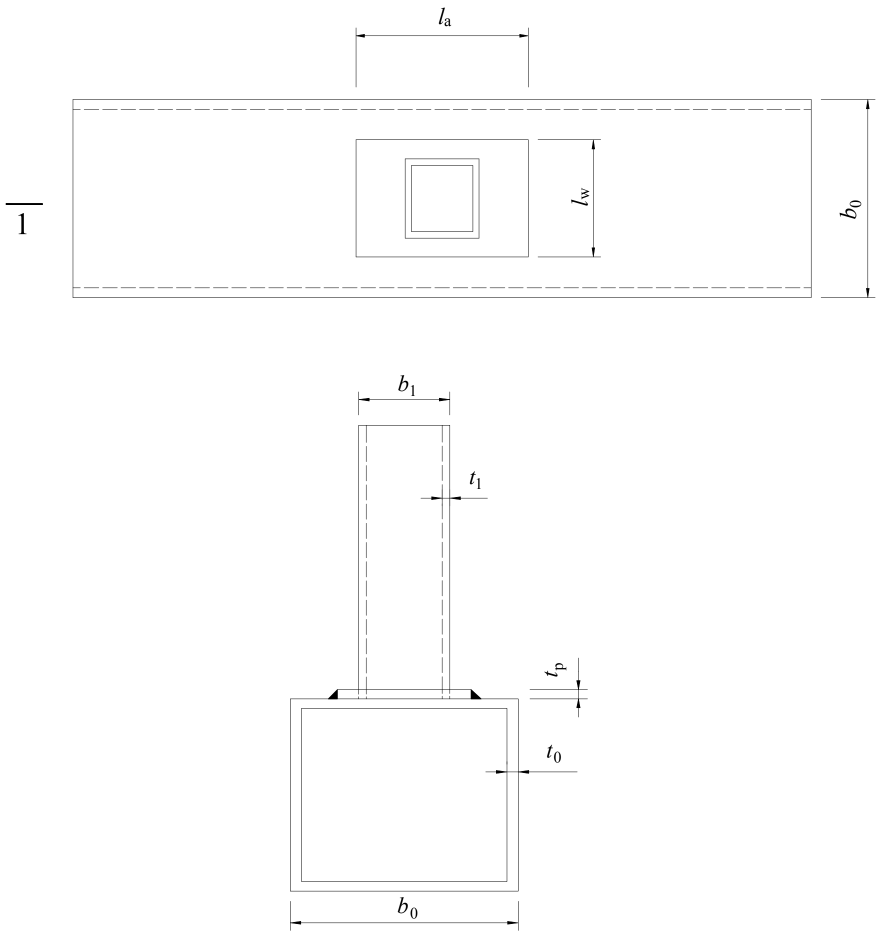


Figure 1: Configuration of a square tubular T-joint with collar plate reinforcement

be recorded automatically from a Data Acquisition Instrument as well as the axial displacement of the brace end.

In the experimental tests, the load is applied by controlling the axial displacement at the brace end of the specimen. Such displacement is applied incrementally in a cyclic way. For the un-reinforced specimen, four loading cycles are applied before the failure of the specimen. However, more loading cycles are applied to the specimen with collar-plate reinforcement before failure. The loading schemes for both the un-reinforced specimen and the collar-plate reinforced specimen are illustrated in Fig. 4 and in Fig. 5 respectively. In these two figures, the horizontal axis denotes

Figure 2: Picture of the specimens

the loading time, and the vertical axis denotes the axial displacement at the brace end. A positive value of u means the brace in a tension state, and a negative value of u then implies that the specimen is under compression.

2.3 Failure mechanism

The failure mechanism of the two specimens under cyclic loading can be explained based on the experimental observation. Figs. 6(a) and 6(b) show the failure mode of the un-reinforced specimen. As mentioned previously, very high stress concentration exists at the weld toe of the brace/chord intersection for the un-reinforced specimen because the stiffness at this region is discontinuous. High stress concentration can cause the stresses at some points to be in a state of tri-axial tension, which is the main reason for bringing the material to be in a brittle situation. Additionally, residual stresses caused by welding process also make the local region near the weld toe to be brittle. Due to the above two reasons, crack initiates firstly at the weld toe, and then propagates also along the weld toe because peak stresses are located in this position. Fig. 6(a) shows the formation of the brittle crack along the weld toe. With more loading cycles applied, the crack propagates quickly till it

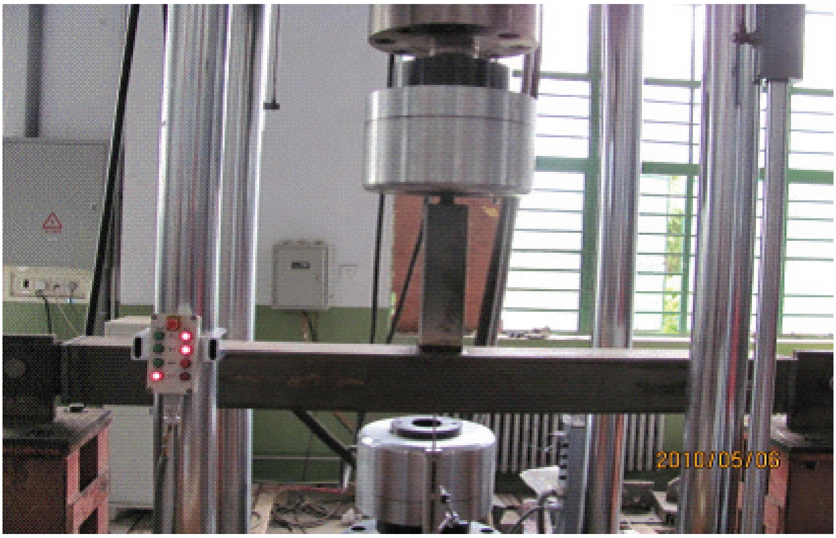


Figure 3: View of test rig

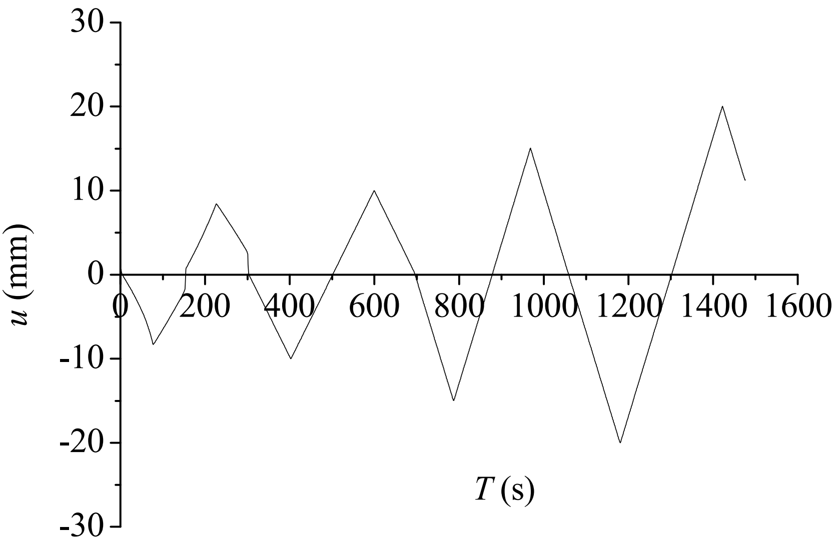


Figure 4: Loading scheme for un-reinforced specimen

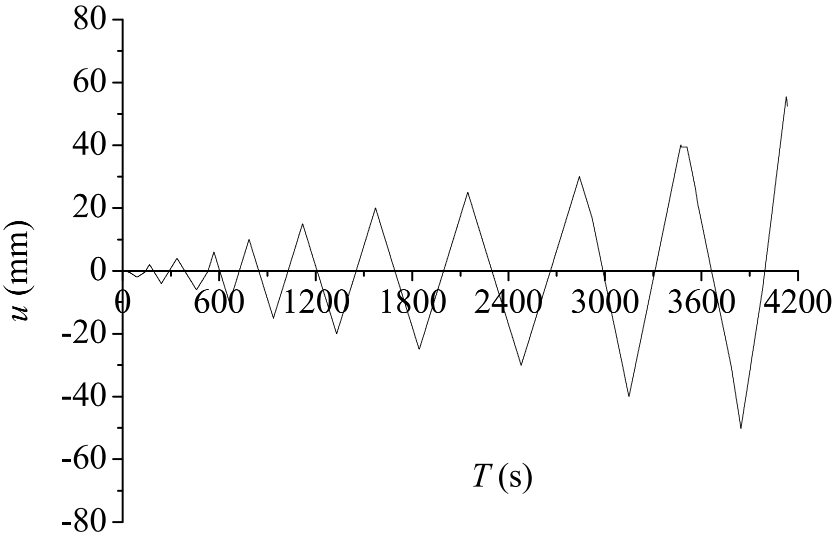
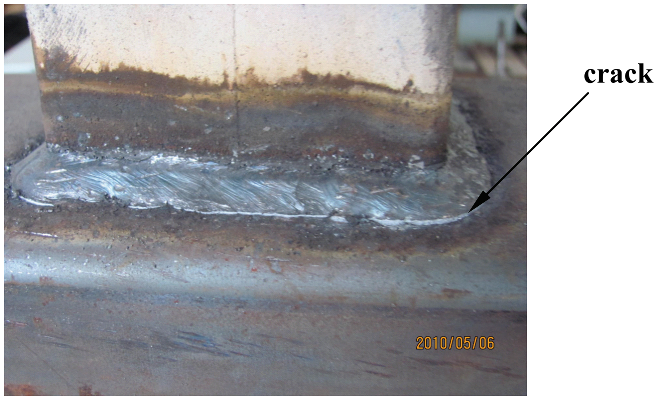


Figure 5: Loading scheme for collar-plate reinforced specimen

goes through the chord wall thickness. Finally, brittle fracture failure occurs in the specimen, and the T-joint loses its load carrying capacity and fails. The final failure mode of the un-reinforced specimen is shown in Fig. 6(b).

For the specimen with collar plate with collar-plate reinforcement, the failure mechanism is different. It can be found from experimental observation that very marked plastic accumulation is formed on both sides and on the bottom of the chord before final failure of the specimen, which can be seen in Figs. 7(a) and 7(b) respectively. Due to the collar-plate reinforcement, the peak stress is not located at the weld toe of the brace/chord intersection any further, and it moves to the fillet weld between the outer side of the collar plate and the chord surface. However, the stress concentration reduces greatly although brittleness still exists in this location. Even after the loading cycles shown in Fig. 5, there is only a small crack initiated at one corner of the collar plate, and no fracture failure occurs. Therefore, the reinforced specimen undergoes relatively larger deformation before failure compared to the un-reinforced one. This large deformation definitely dissipates more energy before final failure when the specimen is subjected to cyclic loading, and thus the reinforcement is effective in improving the energy dissipating capacity, which is especially advantageous in resisting earthquake load.



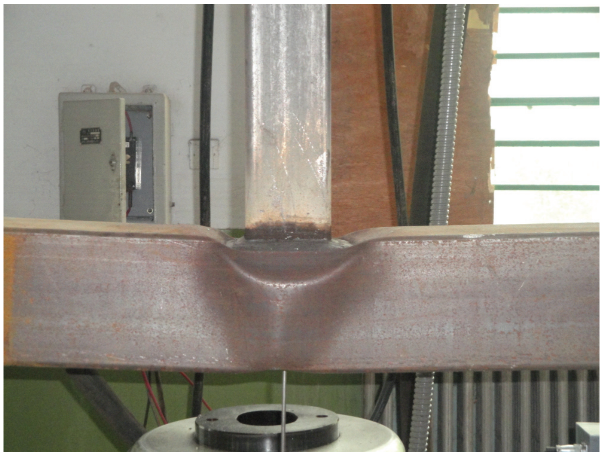
(a) initiation and propagation of crack along the weld toe

(b) final fracture failure

Figure 6: Failure mode for the un-reinforced specimen

3 Finite element simulation

Finite element (FE) analysis is an effective method to simulate many practical problems if suitable modelling scheme is used. Not like experimental testing method, which is very expensive and time-consuming in most cases, FE simulation is efficient in investigating the behaviour of a member or a structure in mechanism. However, FE method generally requires verification from theoretical or experimental results.



(a) plastic deformation at chord side

(b) plastic deformation at chord bottom

Figure 7: Failure mode for the collar-plate reinforced specimen

3.1 Mesh generation scheme

To model a tubular joint with or without collar-plate reinforcement in FE method, the choice of element type and the mesh generation are significant. Although both shell elements and solid elements have both been used in analyzing tubular structures, the later element type is more preferable in calculating a collar-plate reinforced tubular joint because solid element is more suitable for simulating the weld. In addition, it is convenient in defining a contact problem in FE analysis. Due to this reason, hexahedral elements are used in the mesh generation for both unreinforced and collar-plate reinforced square T-joints. Considering the requaired accuracy of the FE analysis and saving computing time, the mesh in the region near the brace/chord intersection and the collar plate is generated in a refined density. For the region far away from the high stress gradient, relatively coarse mesh is used. Using this mesh generation scheme, the FE mesh of a typical collar-plate reinforced square tubular T-joint is shown in Fig. 8.

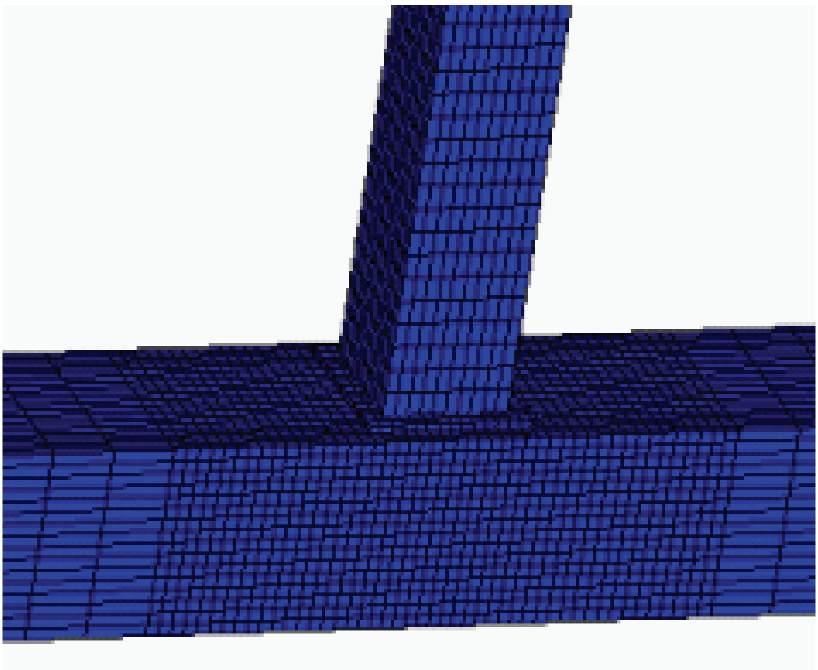


Figure 8: FE mesh of a collar-plate reinforced square tubular T-joint

In the FE analysis, the collar plate may contact with the chord surface when the T-joint is subjected to brace axial loading. Surface contact is used in the FE analysis, and hard contact between the bottom surface of the collar plate and the top surface of the chord is defined. Friction between such two surfaces is assumed to be existed, and the value of the friction coefficient is taken as 0.3.

3.2 Definition of material

The material property of the steel considered in the FE analysis is based on the obtained stress-strain curve from Coupon tests. However, for brevity, bilinear model is taken here since this model can be used in the FE analysis conveniently without losing the computed accuracy. In the bilinear model of the steel material, elastic modulus and tangential modulus are used. The value of the elastic modulus is measured from the stress-strain curve in the linear stage. For the tangential modulus, the value is taken as the slope of the line formed by connecting the two points at the yield stress and at the ultimate tensile stress. In the definition of yielding, Von Mises yielding criterion is used in this study. Von Mises stress is defined as follow

$$\sigma_e = \frac{1}{2}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2} \tag{1}$$

where σ_1, σ_2 and σ_3 are three principal stresses.

3.3 Results of FE simulation

To study the failure mechanism of the two specimens, it is more visible to investigate the stress distribution in the failure region. The FE results of the stress distribution for the un-reinforced and the collar-plate reinforced T-joint models are shown in Fig. 9 and in Fig. 10 respectively. It can be seen that stresses with high value are distributed locally for both the un-reinforced and the corresponding reinforced T-joint models. However, there are still some differences between the two models. For the un-reinforced model, peak stress is located at the weld toe of the brace/chord intersection. The stresses along the weld toe begin to yield firstly, and failure occurs in this location. For the collar-plate reinforced model, peak stress moves to the fillet weld between the collar plate and the chord top surface. Yielding occurs firstly in this position, and hence the failure position also shifts to here. The different deformations of the two models also prove this conclusion.

4 Hysteretic behaviour analysis

Based on the experimental and numerical studies in the above sections, the hysteretic behaviour of both the un-reinforced square tubular T-joint and the collar-plate reinforced one can be investigated in details. Hysteretic performance is frequently used for assessing the earthquake resistance of a member or a structure. It is obtained by plotting the applied load versus the corresponding displacement or deformation of a member or a structure. Due to the limitation of required instruments in the experimental test, quasi-static loading is usually applied to the member or the structure instead of actual dynamic loading. The product of the applied load and the corresponding displacement or deformation is an index of the input work to the member or the structure. For a tubular joint, it means the joint can dissipate more energy before failure if it can sustain more loading cycles. In another word, this joint is more capable in resisting dynamic loading.

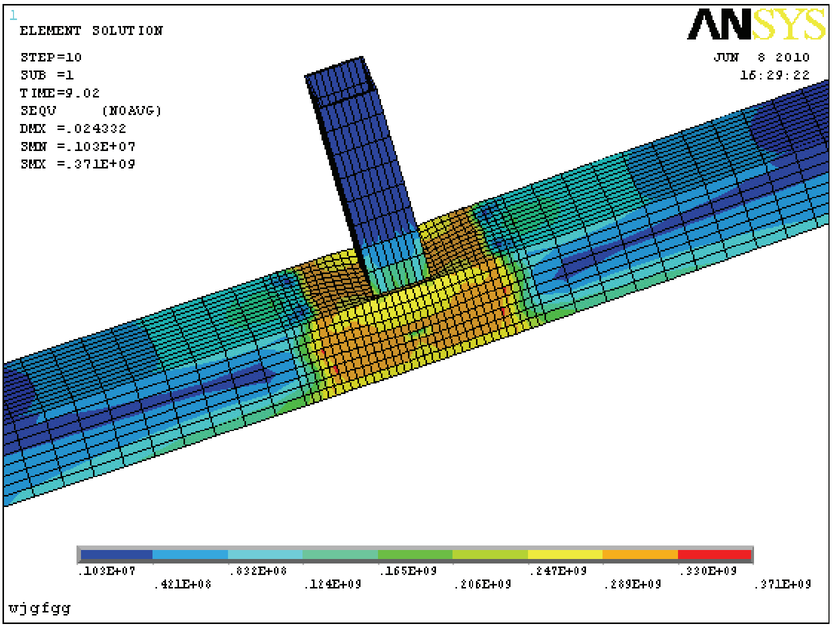


Figure 9: Stress distribution of the un-reinforced specimen

4.1 Hysteretic curves

In plotting the hysteretic curves of a tubular joint, both load-displacement and load-deformation can be used. However, it is more convenient to use load-displacement to plot the hysteretic curves for comparison. As both experimental and FE analysis have been carried out in previous sections, the hysteretic curves obtained from the two methods are both plotted in the figure. Fig. 11 and Fig. 12 show the hysteretic curves of the un-reinforced T-joint model and the corresponding reinforced one.

It can be found from Fig. 11 and Fig. 12 that the hysteretic curves of both the un-reinforced model and the reinforced model are plumper, which means they can both absorb much energy before failure under cyclic loading. However, compared to the un-reinforced T-joint, the collar-plate reinforced one has much plumper hysteretic curves. This conclusion can be explained from the following two aspects: (1) the maximum axial displacement at the brace end before failure of the reinforced model is bigger than that of the un-reinforced model. Fracture failure occurs in the un-reinforced T-joint when the tensile displacement reaches 20 mm. However, the reinforced specimen is still not fractured even the tensile displacement exceeds 50 mm. (2) the maximum applied load (defined as the peak value in the linear stage

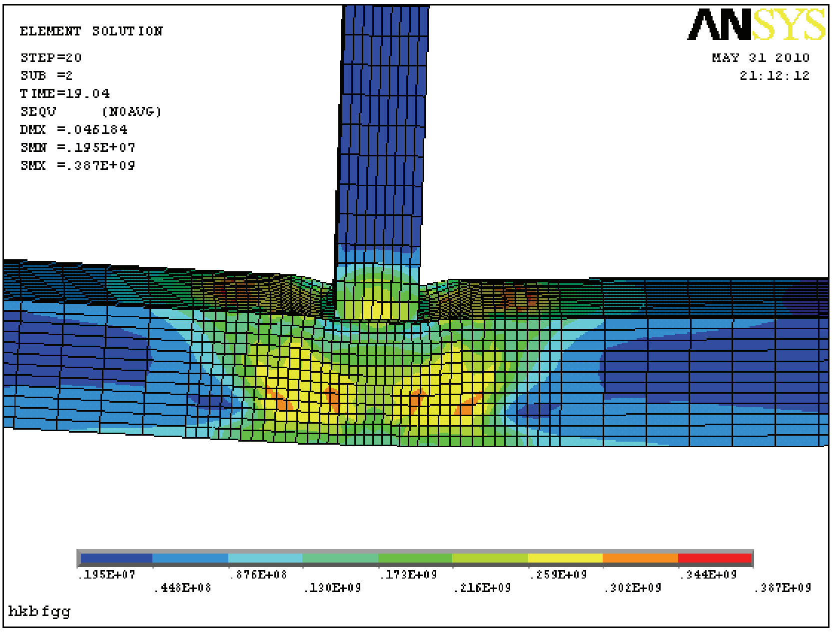


Figure 10: Stress distribution of the reinforced specimen

of the load-displacement curve) in each loading cycle of the reinforced specimen is definitely bigger than that of the un-reinforced one, especially in the compressive stage. For a clear comparison, the hysteretic curves of the un-reinforced model and the reinforced one are plotted together as shown in Fig. 13.

Another point is also provided in Fig. 11 and Fig. 12. The FE simulation can produce reasonably accurate estimation for the hysteretic performance of the T-joint models. Although the FE results seem to cover more areas (calculated from the enclosed curves of the load-displacement relationship), it is easy to explain such difference. In FE analysis, the element connectivity can not be changed in the analyzing process once the mesh is generated. However, crack inititation and propagation after several loading cycles in the hysteretic tests will change the surface (or boundary in a domain), and the FE model can not simulate such boundary variation problem (although extended finite element method can be used for analyzing cracking problem, it is not used in this study). Because of this reason, the FE results overestimate the energy dissipating capacity as they do not consider the deterioration of the stiffness caused by cracking along the weld toe.

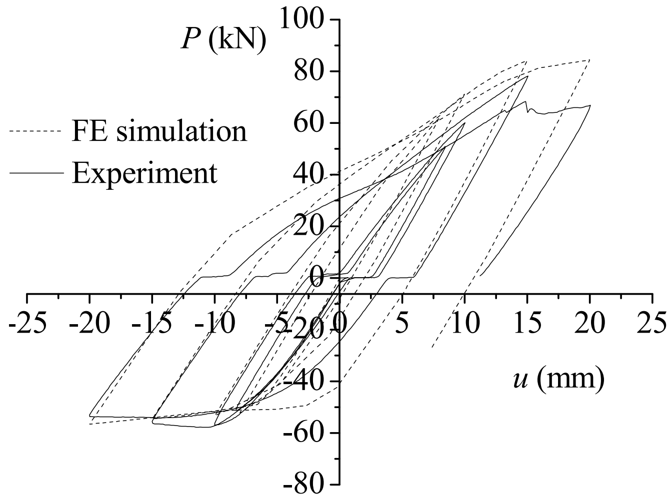


Figure 11: Hysteretic curves of the un-reinforced T-joint

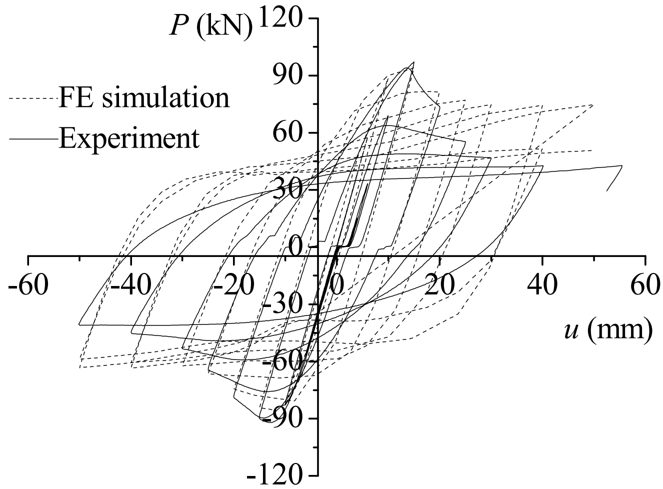


Figure 12: Hysteretic curves of the reinforced T-joint

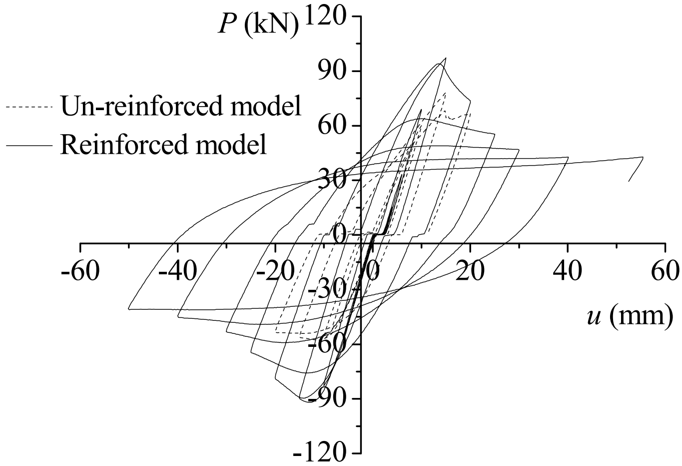


Figure 13: Comparison of the experimental hysteretic curves

4.2 Evaluation of ductility

Ductility is an important index in reflecting the deformed capacity of a member or a structure before failure when it is subjected to earthquake load. Ductility is usually assessed by a ratio of the ultimate displacement to the elastic displacement. Such ratio is called ductility ratio. To calculate the ductility ratio, it is more convenient to plot the skeleton curves from the hysteretic curves as shown in Fig. 13. The skeleton curves are obtained by joining the peak point in each loop of the hysteretic curves together. The skeleton curves can be divided into two stages: linear and elastic stage, and nonlinear and elastic-plastic stage. Accordingly, two critical points can be easily found from the skeleton curves: one point is the limit of the linear and elastic stage, and the other point is at the ultimate displacement. The former point determines the limit of the elastic displacement, or called the plastic displacement, and such displacement is denoted by u_y. The ultimate displacement is located at the fracture point, and it is denoted by u_u. Then the ductility ratio, μ, is defined as follow

$$\mu = \frac{u_u}{u_y} \tag{2}$$

Ductility ratio actually reflects the plastic deformed capacity before the failure of the joint. It is especially important in evaluating the aseismic behaviour of the structure. A bigger value of ductility ratio means marked inelastic deformation

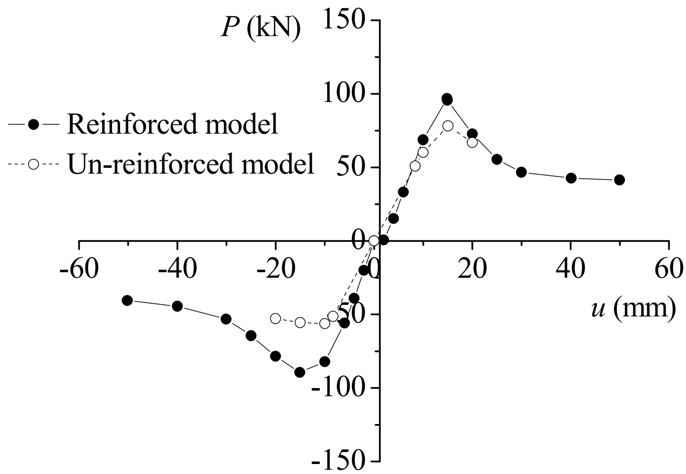


Figure 14: Skeleton curves

can be observed during an earthquake before the collapse of a member or a structure, which is the typical symbol of ductile failure. For the un-reinforced and the collar-plate reinforced square tubular T-joints, Their ductility ratios can be easily estimated from Fig. 14. For the un-reinforced T-joint model, the ductility ratio is about 1.33. However, the ductility ratio of the reinforced T-joint increases to be 3.33. The marked difference between the values shows that the reinforced model can experience more inelastic deformation before brittle fracture failure, and thus it is more capable in resisting earthquake load.

4.3 Evaluation of energy dissipation

The failure mechanism can be also explained from the energy dissipation which can be obtained from the hysteretic curves as shown in Fig. 13. For brevity, an energy dissipation ratio, η, is defined as follow

$$\eta = \sum_{i=1}^{N} \left(E_i^t + E_i^c\right) / E_y \tag{3}$$

where N is the total number of loading cycles, E_i^t and E_i^c are the areas in the tensile stage and in the compressive stage of the i-th enclosed loop. E_y is the elastic energy which is calculated from the product of the peak load in the skeleton curves as shown in Fig. 14 and the corresponding plastic displacement u_y.

The energy dissipation ratio actually reflects the relationship between the total absorbed energy of the T-joint before failure and the elastic energy. When the value of this ratio is much bigger, it means more inelastic energy is dissipated during the cyclic loading. From Eq. (3), the energy dissipation ratios of the un-reinforced and the corresponding reinforced T-joint models are obtained, and they are tabulated in Tab.2.

Table 2: Energy dissipation ratio

Model	$\sum_{i=1}^{N}(E_i^t + E_i^c)$(kN·m)	E_y(kN·m)	η
Un-reinforced	2.62	0.15	17.5
Reinforced	20.02	0.43	46.6

From Tab. 2, it is found that the energy dissipation ratios for both the un-reinforced and the reinforced models are much bigger. Therefore, inelastic deformation is the main mechanism in dissipating the energy caused by earthquake. The T-joint model with collar plate reinforcement has a relatively larger value of η compared to the un-reinforced one, which means the reinforced model can absorb more energy due to its goog capacity of inelastic deformation.

5 Conclusion

Through experimental and numerical analysis on the hysteretic behaviour of square tubular T-joint with and without collar plate reinforcement, the following conclusions can be made

- Collar plate is effective in improving both the load carrying capacity and the plastic deformation.
- The square tubular T-joint with collar plate reinforcement can dissipate more energy before failure compared to the un-reinforced one, and thus it is more capable in resisting earthquake load.
- For both un-reinforced and reinforced T-joints, inelastic deformation is always the main mechanism in dissipating energy caused by earthquake.

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