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Hysteretic behaviour of circular tubular T-joints with local chord reinforcement

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Abstract. When a welded circular hollow section (CHS) tubular joint is subjected to brace axial loading, failure position is located usually at the weld toe on the chord surface due to the weak flexural stiffness of the thin-walled chord. The failure mode is local yielding or buckling in most cases for a tubular joint subjected to axial load at the brace end. Especially when a cyclic axial load is applied, fracture failure at the weld toe may occur because both high stress concentration and welding residual stress along the brace/chord intersection cause the material in this region to become brittle. To improve the ductility as well as to increase the static strength, a tubular joint can be reinforced by increasing the chord thickness locally near the brace/chord intersection. Both experimental investigation and finite element analysis have been carried out to study the hysteretic behaviour of the reinforced tubular joint. In the experimental study, the hysteretic performance of two full-scale circular tubular T-joints subjected to cyclic load in the axial direction of the brace was investigated. The two specimens include a reinforced specimen by increasing the wall thickness of the chord locally at the brace/chord intersection and a corresponding un-reinforced specimen. The hysteretic loops are obtained from the measured load-displacement curves. Based on the hysteretic curves, it is found that the reinforced specimen is more ductile than the un-reinforced one because no fracture failure is observed after experiencing similar loading cycles. The area enclosed by the hysteretic curves of the reinforced specimen is much bigger, which shows that more energy can be dissipated by the reinforced specimen to indicate the advantage of the reinforcing method in resisting seismic action. Additionally, finite element analysis is carried out to study the effect of the thickness and the length of the reinforced chord segment on the hysteretic behaviour of CHS tubular T-joints. The optimized reinforcing method is recommended for design purposes.

Keywords: Circular hollow section (CHS) tubular T-joints; hysteretic behaviour; local chord reinforcement; failure mode; energy dissipation

1. Introduction

Welded tubular structures have many advantages such as light weight and high strength, good ductility, ease fabrication, fast construction and aesthetic appearance, and thus they are widely used in the construction of stadium, bridge, airport, railway station and jacket offshore platforms etc. A welded tubular structure is consisted of many steel tubes and joints. A tubular joint is formed by welding one or several tubular members with smaller diameter (braces) directly onto the surface of a tubular member with large diameter (chord). Due to the sharp corner between the weld

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toe and the tube surface in a tubular joint, high stress concentration exists in this region to produce tri-axial stress state along the weld toe. Additionally, tri-axial stress state is also generated by welding process. As steel material in tri-axial stress state tends to be brittle, a welded tubular joint may fail due to fracture when it is subjected to cyclic or seismic loading. Previous studies on the fatigue tests for tubular joints by Shao and Lie (2005) and Chiew *et al*. (2004) showed that crack always initiates at weld toe after some repeated loading cycle. In these studies, the static behaviour as well as the fatigue behaviour of tubular joints has been investigated extensively. However, the seismic behaviour of tubular structures also becomes significant as more and more tubular structures are built in the regions with high risk of earthquake. In addition, some structures such as offshore platforms may face the cyclic action of strong waves induced by tsunami. In such cases, it is more senseful to study the hysteretic behaviour of the tubular joints because cracks are always located at these connections.

A circular hollow section (CHS) tube is weak in resisting external load in its radial direction because it is a thin-walled member and its flexural stiffness is small. Therefore, local yielding or buckling of the chord member is the mostly common failure mode, especially when the thickness of the chord is very small compared to its diameter. The repeated local yielding or buckling in a tubular joint under cyclic load can intensify crack initiation and propagation along the weld toe and reduce the static strength. To improve such deficiency, a tubular joint is strengthened with different measures by increasing the flexural stiffness of the chord at the brace/chord intersection. The reported strengthening methods in the literature include internally and externally stiffened ring reinforcement, doubler- or collar-plate reinforcement, rib plate reinforcement, inner plate reinforcement, and local chord reinforcement etc. For internally ring-stiffened tubular joints, the fatigue behavior (Gandhi *et al*. 2000), the static strength (Lee *et al*. 2004, 2005), the stress concentration factor (Ahmadi *et al*. 2016) and the fire resistance (Chen *et al*. 2015) were investigated in last two decades. Zhu *et al*. (2014, 2016) studied the improvement on the static strength of tubular joints reinforced with external ring stiffeners. For doubler- or collar-plate reinforced tubular joints, the static strength (Fung *et al*. 1999, Hoon *et al*. 2001, Choo *et al*. 2004, 2005, van der Vegte *et al*. 2005), hysteretic behaviour (Yin *et al*. 2009, Shao *et al*. 2011b, Gao *et al*. 2015a) and fire resistance (Gao *et al*. 2015b) were all investigated. Myers *et al*. (2001) studied the effect of rack/rib plate on the stress concentration factors in jack-up chords. As FRP is a material with light weight, small volume and high strength, it was also used to strengthen tubular joints. Lesani *et al*. (2013, 2014) analyzed the static strength of tubular joints reinforced with FRP by using numerical and experimental methods. Aguilera and Fam (2013) investigated on retrofitting tubular joints using bonded FRP plates. For local chord reinforcing method, Shao *et al*. (2010) and Yang *et al*. (2012) investigated the static strength of reinforced tubular T- and Y-joints. Chiew *et al*. (2012) conducted experimental tests and numerical simulations on analyzing the static strength of complex multi-planar DKYY-joints. Shao *et al*. (2011a) studied the hysteretic behavior of square tubular T-joints with local chord reinforcement through experimental tests and numerical analyses.

To evaluate the aseismic performance of welded structures, it is usually to carry out analyses on the hysteretic behaviour because it represents the energy absorption of the structures before failure. For un-reinforced welded tubular joints, some experimental studies on the hysteretic behaviour have been conducted in the past, and the typical work can be referred to Qin *et al*. (2001), Soh *et al*. (2001) and Wang and Chen (2007). It was found from these studies that all tubular joints after some loading cycles failed due to crack propagation along the weld toe although the ductility of these structures was relatively good. Although the static strength of a tubular joint can be generally improved efficiently by using the above introduced method, the effect of the mentioned reinforcing methods on improving the energy dissipating capacity for a tubular joint is still necessary to be studied. Yin *et al*. (2009) conducted experimental tests on the hysteretic behaviour of tubular N-joints with infilled concrete and with doubler-plate reinforcement. It was found that the ductility was deteriorated for the strengthened tubular joints although the static strength was increased. Shao *et al*. (2011b) investigated the hysteretic behavior of collar-plate reinforced tubular T-joints through experimental tests. The results indicated that the strengthened tubular T-joints can dissipate more energy before failure compared to the un-reinforced specimens. Gao *et al*. (2015a) analyzed the hysteretic behaviour of tubular T-joints reinforced with doubler plates after fire exposure. It was also found that the hysteretic curves of the reinforced T-joints were plump, and more energy was dissipated before failure for the reinforced specimens compared to the un-reinforced ones.

For local chord reinforcement in a tubular joint, the chord near the brace/chord intersection is reinforced locally by increasing the tube wall's thickness. Compared to other conventional reinforcing methods, the reinforcing method by increasing the thickness of the chord segment at the brace/chord intersection has the following advantages: (1) Ease construction. It is very convenient to weld two circular segments together by using butt weld. (2) Slight effect on residual stress and residual deformation around brace/chord intersection. (3) Remarkable reinforcing efficiency. The stiffness and the load carrying capacity of a tubular joint can be both improved efficiently. Shao *et al*. (2011b) carried out both experimental and numerical analyses for the hysteretic behaviour of square tubular T-joints with local chord reinforcement. The results indicated that a more ductile failure may occur because the failure mode was changed from cracking along the weld toe for the un-reinforced square T-joints to local yielding at the chord intersection for the reinforced ones. Because the failure mode is changed, the reinforced square T-joints have a better capacity of energy dissipation. The study aims to investigate if local chord reinforcement is still effective to improve the hysteretic performance for circular tubular T-joints through both experimental and numerical investigations.

2. Experimental tests

2.1 Specimens

A typical tubular T-joint reinforced with chord reinforcement is shown in Fig. 1. As local buckling usually occurs on the chord surface near the weld toe, a chord segment in this region is reinforced by increasing the section thickness. The reinforced chord segment has the same outer diameter as that of the un-reinforced one. Full penetration butt weld is used to connect the two chord segments of different thicknesses. Fig. 1 also gives the definition of some commonly used normalized geometrical parameters of tubular joints. The crown and saddle, which are two critical positions, are also marked in Fig. 1 where $T_c = T$ denoted the un-reinforced tubular joint.

The reinforced chord thickness of the T-joint specimen is shown in Figs. 2(a) and (b). For an un-reinforced specimen, the chord member has a constant thickness. A segment of the reinforced chord having same outer diameter and larger thickness is connected to the original chord by using full penetration butt weld. After the chord is reinforced, the brace is welded directly onto the surface of the reinforced chord segment also by using full penetration butt weld. Ultrasonic technique is then used to check the welding quality of the entire specimen, and the quality of all the welds is found to be satisfactory.

Before test, the material property of the steel sections is measured from a standard uni-axial

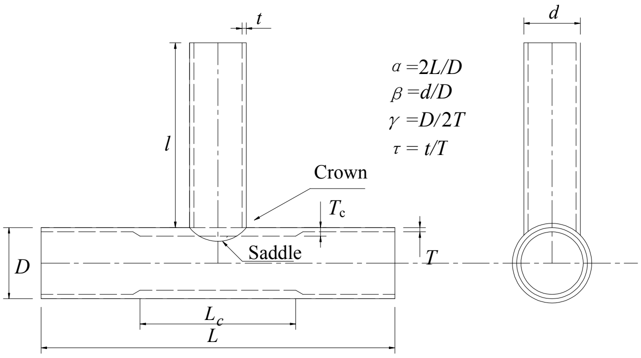


Fig. 1 Geometry of a circular tubular T-joint with chord reinforcement

(a) Outer view (b) Inner view

Fig. 2 View of butt weld

Table 1 Dimensions of the un-stiffened and stiffened tubular T-joint specimens

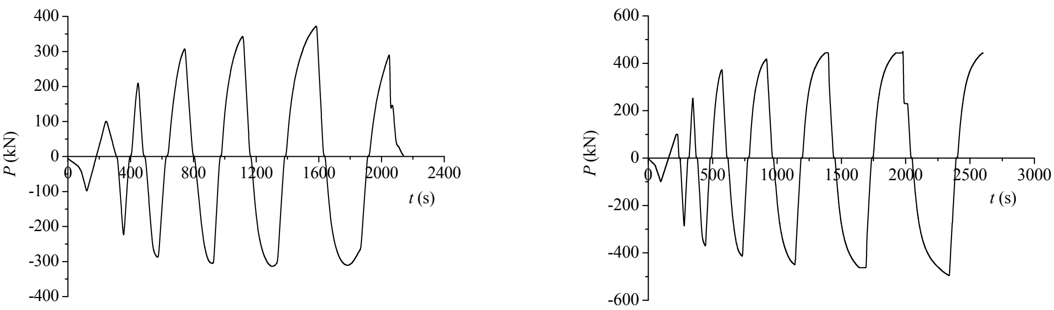
	Un-stiffened	Stiffened
D (mm)	245	245
T (mm)	10	10
d (mm)	102	102
t (mm)	8	8
L (mm)	2400	2400
l (mm)	500	500
T_c (mm)	-	20
L_c (mm)	-	367.5

tensile test. The yield stress and the ultimate stress of the steel are found to be equal to 333 N/mm^2 and 540 N/mm^2 respectively, and the elongation is 20%. The geometry of the un-stiffened and the stiffened T-joint specimens is tabulated in Table 1. For comparison purposes, the reinforced specimen has the same size as that of the un-stiffened one except at the reinforced chord segment.

2.2 Test setup

Both the un-stiffened and the stiffened specimens are pinned at the chord ends in the test frame. As shown in Fig. 3, axial cyclic loading is applied at the brace end. During the test, the applied

Fig. 3 View of test setup



(a) Un-stiffened specimen (b) Stiffened specimen

Fig. 4 Applied cyclic loadings for the specimens

loading and the displacement at brace end are captured using a Digital Data Acquisition System. The cyclic loading is applied by controlling the displacement at the brace end. In each loading step, an axial displacement is applied at the brace, and the corresponding loading is obtained simultaneously from the Digital Data Acquisition System. In the hysteretic test, the applied cyclic loadings for the two specimens are shown in Figs. 4(a) and (b).

2.3 Experimental observations

For the un-stiffened specimen, local buckling occurs at the weld toe at the compressive stage of the third loading cycle, as shown in Fig. 5. Due to the weak stiffness of the chord in radial

Fig. 5 Local buckling of un-stiffened specimen

Fig. 6 View of crack along weld toe

Fig. 7 Failure mode of un-stiffened specimen

Fig. 8 Yielding of the stiffened specimen

Fig. 9 Failure mode of reinforced specimen

direction, local buckling is the most common failure mode for un-stiffened tubular T-joints. At the tensile stage of the third loading cycle, crack initiates at the crown position, and the crack propagates continuously in the following 4^{th} and 5^{th} loading cycles. At this stage, crack has already propagated to the saddle region, as shown in Fig. 6. In the tensile stage of the 6^{th} loading cycle, the chord wall is fractured suddenly with the further crack extension, which can be seen in Fig. 7. At the point of failure, the specimen can't sustain external loading anymore, and the crack is already through the chord wall thickness. It is obvious that brittle fracture failure is the final failure mode for the un-stiffened tubular T-joint under quasi-static cyclic loading.

The failure mode of the specimen with reinforced chord is very different. At the third loading cycle, the specimen begins to yield and plastic deformation is observed as shown in Fig. 8. Due to the reinforcement of the chord, local buckling does not occur at the weld toe. The specimen exhibits a remarkable flexural deformation. Along the chord intersection, plastic yielding can be seen clearly. After the third loading cycle, the plastic deformation continues to increase in the following loading cycles. However, the load capacity in each cycle remains almost same, and it indicates that plastic flow occurs at brace/chord intersections. As no crack initiates, hence brittle fracture failure does not occur, and the test is stopped at the 7^{th} loading cycle. The final failure mode can be seen clearly in Fig. 9. Due to excessive plastic deformation, the specimen final failure mode is very much like a beam.

The different failure modes of the un-reinforced and the reinforced specimens as shown in the above figures can be explained from the following mechanisms: In a CHS tubular T-joint without reinforcement, the peak stress is located at the brace/chord intersection due to high stress concentration at the weld toe. When local chord segment around the intersection is improved, the stress concentration is reduced greatly because the joint's stiffness increases efficiently. Through suitable reinforcement, the peak stress moves from the intersection to the chord segment connection. In the chord segment connection, stress concentration is quite slight. In addition, the un-reinforced chord segment may yield before the failure of the butt weld since the strength of the butt weld is not lower than the yield strength of the tube. Therefore, a more ductile failure may occur in a reinforced joint.

2.4 Experimental results and hysteretic behaviour

The hysteretic behaviour of the two specimens can be evaluated from the applied loading and its corresponding displacement at the brace end. For circular hollow section tubular joints, the ovalization is generally used to express the hysteretic curves. However, the displacement at the brace end is used in this study to plot the hysteretic curves. For the reinforced tubular T-joints, the ovalization at the brace/chord intersection is observed to be very small because the chord stiffness in this region is increased greatly due to the increase of its thickness. Therefore, it is not feasible to assess the hysteretic behaviour of the reinforced specimen by using the ovalization to plot the hysteretic curves. For clear comparison, the applied axial load, P, and the axial displacement at the brace end, u, are used to plot the hysteretic curves.

The hysteretic curves of the un-stiffened and the stiffened specimens are shown in Fig. 10. The experimentally measured hysteretic curves of both specimens are plump, which shows the specimens have good energy dissipation capacity. The hysteretic curves of the stiffened specimen cover more areas compared to those of the un-stiffened specimen. For the un-stiffened tubular T-joint, pinch phenomenon exist in the hysteretic curves which causes the lower energy dissipation capacity. After reinforcing the chord, no pinch phenomenon exists and the plumper curves can absorb more energy to resist earthquake action. It can be found that the load bearing capacity as well as the deformation is increased significantly for the stiffened specimen. Due to this reason, the stiffened specimen is more advantageous in resisting cyclic loading.

The ductility ratio is an important index for assessing the seismic behaviour of any structures. It is defined as the ratio of the ultimate displacement to the yield displacement. If the ductility ratio is denoted by μ, and the ultimate displacement and the yield displacement are denoted by δ_u and δ_y respectively, the ductility ratio is then calculated from the following equation

$$\mu = \delta_u / \delta_y \tag{1}$$

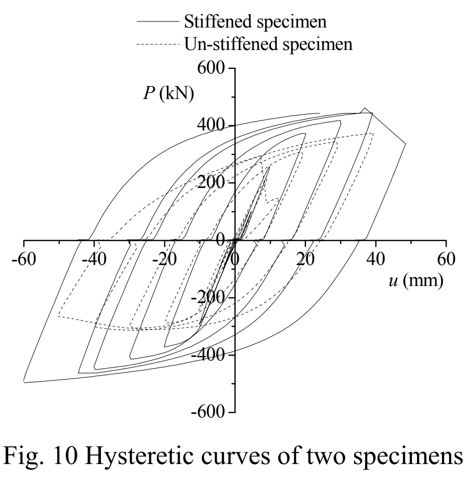


Fig. 10 Hysteretic curves of two specimens

The yield displacement can be determined from the hysteretic curves directly for both un-stiffened and stiffened specimens. As shown in Fig. 10, in the loading cycles, there is linear elastic stage and nonlinear inelastic stage. The displacement at the point connecting the linear straight line and the nonlinear curve is defined as the yield displacement. The ultimate displacement is defined as the displacement at rupture for the un-stiffened specimen. According to the above definition, the ductility ratios of the un-stiffened specimen in compressive and tensile stages are 5.0 and 4.4 respectively. Such values mean the ductile characteristics of the un-stiffened specimen are still good even though it failed by brittle fracture. For the stiffened specimen, it is difficult to define the ultimate displacement because its final failure is yielding and no fracture occurs. As plastic flowing can cause very large deformation to the stiffened specimen, it is reasonable to believe that the ductility ratio of the chord-reinforced specimen is much bigger than that of the un-stiffened specimen.

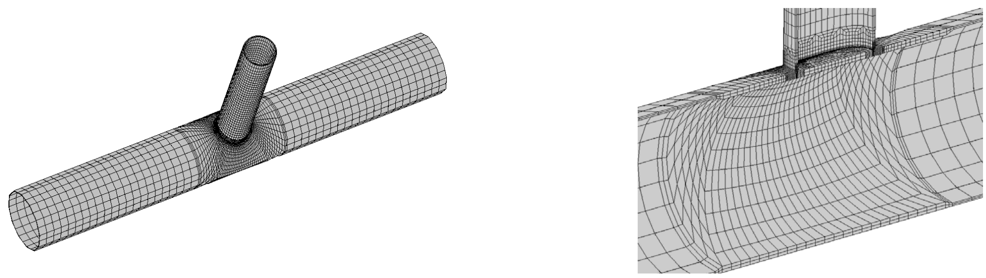
3. Finite element analysis

3.1 Finite element model

Although it is more accurate and reliable to study the hysteretic behaviour of tubular joints from experimental test, this method is very time consuming and expensive. Finite element simulation and analysis, however, is very convenient and efficient once its accuracy is verified from experimental results. As it is necessary to carry out a parametric study on many different stiffened tubular T-joint models to understand the reinforcing efficiency, using numerical technique is quite challenging. In the finite element analysis, the mesh of the structure is critical because a suitable choice of element type and quality have a significant influence on the accuracy of the numerical results.

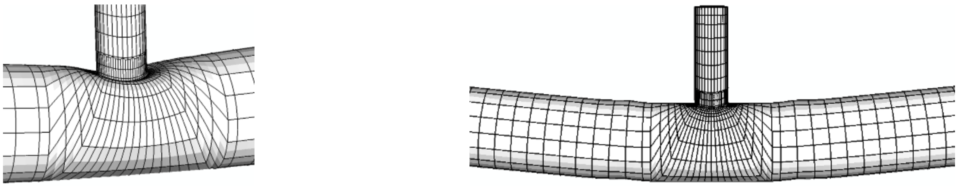
In the choice of element type, 20-node hexahedral elements are used to generate the mesh of the entire structure. The reinforced chord segment is refined in the mesh generation as this region is the possible failure location. The weld is also modeled and the detailed mesh generation scheme is introduced by Shao *et al*. (2010). Using this approach, the generated mesh of the entire structure of a tubular T-joint is shown in Fig. 11(a). Fig. 11(b) shows the close view of the detailed mesh of the reinforced chord segment.

In the finite element analyses for the hysteretic behaviour of chord reinforced CHS T-joints, the stress-strain relationship is defined in accordance to the measured material properties of the steel



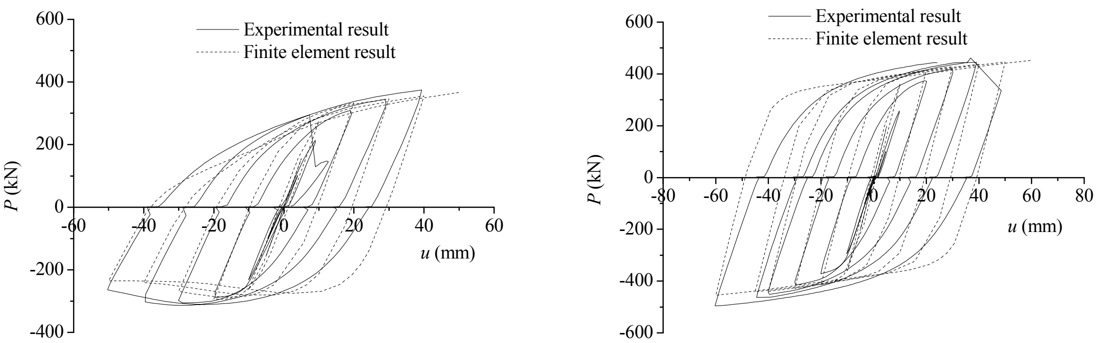
(a) Mesh of entire structure (b) Detailed mesh at chord intersection

Fig. 11 Finite element mesh generation of a chord-reinforced tubular T-joint



(a) Un-stiffened specimen (b) Stiffened specimen

Fig. 12 Failure modes from finite element simulation



(a) Un-stiffened specimen (b) Stiffened specimen

Fig. 13 Hysteretic curves of two specimens

tubes. A bi-linear model is used to simulate the stress-strain relationship: (1) a straight line model in the elastic and linear stage with the slope equal to the elastic modulus; and (2) a straight line passing through the yield stress point and the tensile stress point (hardening stage).

3.2 Finite element analyses

Using the above finite element model, the hysteretic behaviour of both the un-stiffened and stiffened tubular T-joint specimens is analyzed. The deformations of the two specimens in the compressive stage of the loading cycle are shown in Figs. 12(a) and (b). Compared with experimental results shown in Figs. 5 and 9, the numerical results are quite similar.

From finite element analyses, the hysteretic curves of the un-stiffened and the stiffened specimens are obtained, and they are plotted in Figs. 13(a) and (b). It is found that the numerical results agree with the experimental measurements reasonably well. However, the experimental results show that stiffness deterioration after yielding is more severe when more loading cycles are applied. The finite element results do not reflect such deterioration because the stress-strain relationship is linear elastic and plastic model and it does not consider the stiffness deterioration. Generally, the finite element analysis can provide a reliable estimation of the hysteretic behaviour of the two specimens, and thus it can be used to conduct numerical investigation for more reinforced tubular T-joint models.

3.3 Parametric study

To study the reinforcing efficiency on the hysteretic behaviour, a parametric study on tubular T-

Table 2 Geometries of the un-stiffened and stiffened tubular T-joint models

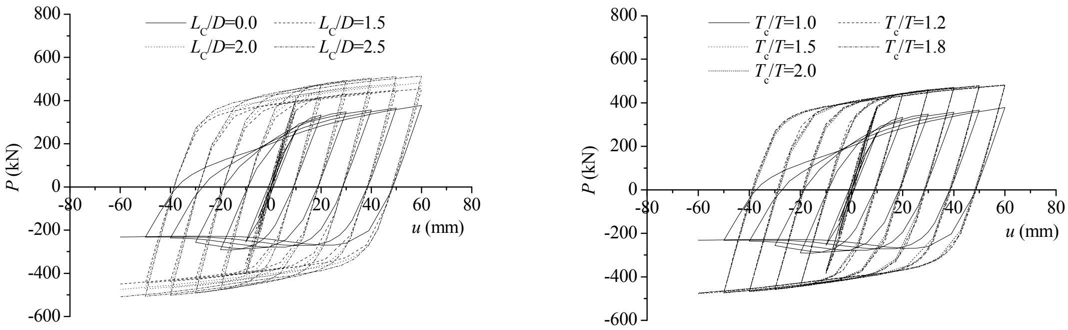
Model	D (mm)	γ	β	τ	L (mm)	l (mm)
I	245	12.5	0.416	0.6	2400	500
II	245	20.4	0.416	1.0	2400	500

joints under axial cyclic loading is carried out. In the parametric study, two typical tubular T-joints are analyzed, and the geometrical parameters of the two models are tabulated in Table 2. For each model, the chord reinforcing parameters are given as follows:

T_c/T: 1.0, 1.2, 1.5, 1.8, 2.0
L_c/D: 0.0, 1.5, 1.8, 2.0, 2.5

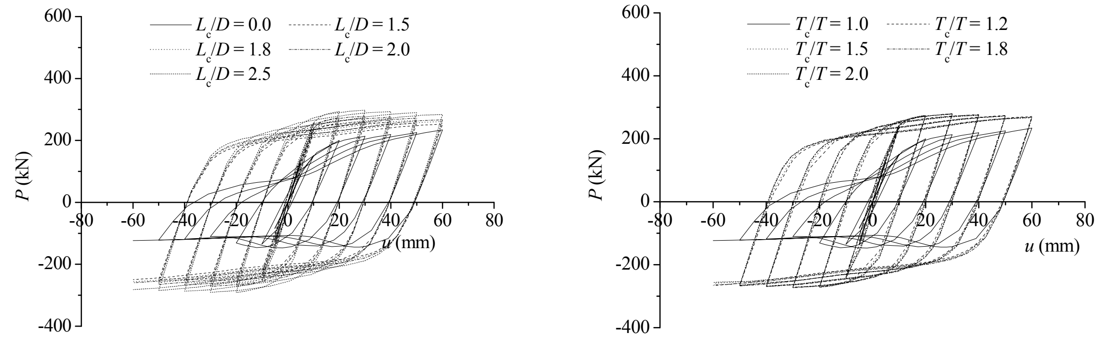
In the case of $T_c/T = 1.0$ and $L_c/D = 0.0$, it means that the T-joint model is not stiffened.

The stress-strain relationship in the finite element analyses is an elastic-perfectly plastic model. This model used to carry out the parametric study because safe and conservative estimation on the energy dissipation of a CHS T-joint is produced by using this model.



(a) $T_c/T = 1.5$ (b) $L_c/L = 2.0$

Fig. 14 Effect of chord reinforcement on hysteretic curves of model I



(a) T_c/T=1.5 (b) L_c/L=2.0

Fig. 15 Effect of chord reinforcement on hysteretic curves of model II

The effect of the chord reinforcement on the hysteretic behaviour of the two models can be seen from Figs. 14(a), (b), 15(a) and (b). Figs. 14(a) and 15(a) show the effect of the reinforcing chord length on the hysteretic behaviour of two models. It can be seen clearly that the T-joint models with chord reinforcement have much plumper curves than that of the un-stiffened one. Although the hysteretic curves cover more areas when the length of the reinforced chord segment is longer, the increased of the enclosed area is not so remarkable, and thus it is suitable and efficient to adopt the value of L_c/D to be 1.5. The effect of the reinforced chord thickness on the hysteretic behaviour of tubular T-joint models is shown in Figs. 14(b) and 15(b). Generally, increasing the chord thickness can still improve the energy dissipation of the models because the hysteretic curves cover more areas. However, it seems that it is not efficient to increase the chord thickness beyond a certain value since the hysteretic curves of the reinforced models with different reinforced thicknesses vary slightly. For the analyzed two models, the thickness ratio of the chord reinforcement is most efficient at T_c/T= 1.2.

4. Conclusions

Based on the experimental tests and finite element analyses, the hysteretic behaviour of both un-stiffened and chord thickness reinforced tubular T-joints under axial quasi-static cyclic loading is investigated. From the investigation, the following conclusions can be made:

(1) Conventional tubular T-joints is weak in resisting cyclic loading because high stress concentration exists at the weld toe, and the final failure usually manifests as a brittle fracture. After reinforcement by increasing the chord thickness at the brace/chord intersecting region, the critical position can move to the chord intersection region, and the failure mode can be changed to ductile yielding.

(2) Local buckling or convexing can occur near the weld toe for the un-stiffened T-joint under cyclic axial loading, which is the main reason to cause crack initiation and propagation. Due to this reason, the hysteretic curves of the un-stiffened tubular T-joints have pinch phenomenon which reduces the energy dissipation capacity of the joints. The chord thickness reinforcement can avoid such local large deformation, and thus the hysteretic curves of the reinforced tubular T-joints are much plumper so as to dissipate much more energy under cyclic loading.

(3) Although it can improve the ductile characteristics of tubular T-joints under cyclic loading by increasing the length and thickness of the reinforced chord, it is not always efficient to expect that the ductility of a tubular T-joint can be greatly improved by increasing the length of the thickness of the reinforced chord to a large value. Based on the parametric studies, it seems that the reinforced chord thickness should not be more than 1.2 times of the original chord thickness, and the reinforced chord length should not be longer than 1.5 times of the chord diameter.

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