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Dynamic behaviour of square tubular T-joints under impact loadings

Pengfei Cui [a], Yanzhi Liu [a,*], Fan Chen [a], Jingsi Huo [b]

[a] College of Civil Engineering, Hunan University, Yuelu Mountain, Changsha 410082, China
[b] College of Civil Engineering, Huaqiao University, Xiamen 361021, China

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ABSTRACT

This paper examines the dynamic behaviour of square tubular T-joints under impact loading by means of experimental, numerical and analytical studies. Firstly, a high-performance drop hammer setup is employed to carry out the impact tests on five hot-rolled square tubular T-joints with different chord thickness and width ratio of brace/chord under three levels of impact height. The dynamic responses of tubular T-joints including the deformation patterns and the development of impact force and displacement are described. Based on the experimental results, the impact load-deformation relationships as well as the energy dissipation are further discussed to reveal the mechanical behaviour of T-joints, with emphasis on the effect of width ratio of brace/chord and impact energy. Complementary finite element model for simulating the tubular T-joints under impact is then proposed and validated against the available test results. Finally, the test results and numerical simulations are utilized to investigate the failure mechanism of T-joints under impact load. In particular, the local and global displacements of square chord are estimated by an equivalent area method, and the impact resistance of impacted joints is examined based on the yield line theory. In general, the investigation in this paper can also offer reliable test data and design suggestions to reasonably evaluate the impact behaviour of square tubular T-joints.

1. Introduction

The architectural and structural advantages of tubular sections have prompted their wide use in industrial building, offshore platform and breakwater. In the tubular structures, the common configuration of tubular joints includes Type T, Type K, Type N etc. During the past decades, a large number of studies have been carried out on the static behavior of tubular truss and directly welded tubular (RHS) joints. For example, Bauer et al. [1] carried out experimental programs on static performance of simplified double-T joints and triangular truss segments with double-K gap joints, Zhao et al. [2] performed a large number of tests on a range of rectangular and square hollow sections subjected to combined actions, and De Matteis et al. [3] numerically investigated the behavior of aluminium alloy T-stub joints subjected to monotonic tensile loads. Moreover, design guides for rectangular tubular joints [4] and circular tubular joints [5] outline the specifications for the design of tubular joints under static loading. However, tubular structures are easily subjected to impact loading, and it is necessary to understand the impact behavior of tubular T-joints.

A number of impact tests were carried out on the steel tube structure over the past years. Oliveira et al. [6] and Ellinas et al. [7] performed the experimental study on the steel tubes clamped at both ends subjected to lateral impact load. Jones and Birch [8] carried out impact tests on 130 steel pipes, while Chen et al. [9] worked on 226 steel pipes under impact loadings, and failure modes of the pipes were identified with different geometries and different impact positions. Zeinoddini et al. [10] described the experimental investigation on the impact behaviour of axially pre-loaded tubes aiming at understanding the dynamic failure of impacted tubes with axial preloads. Meanwhile, Yu et al. [11] and Qu et al. [12,13] performed a series of experimental studies on the dynamic behaviours of circular tubular T/K-joint under different impact loading conditions, and it was shown that the circular tubes of joint experienced the combination of the local indentation and global bending under impact loadings. However, limited experimental studies were conducted on the dynamic behavior of square or rectangular tubular joints. It was found from the studies by Bambach et al. [14] and Liu et al. [15] that the failure mechanism of square or rectangular tubes was different from that of circles. Therefore, it is necessary to characterize the behaviour of square or rectangular tubular joints subjected to impact loadings.

Recently, the numerical simulation of tubular structures subjected to impact loadings was also developed to study their impact resistance. Zeinoddini et al. [16] examined the impact behaviour of axially pre-loaded steel tubes by FE model. A series of numerical studies on the dynamic behaviour of circular tubular T-joint under different impact loading conditions were carried out by Qu et al. [17] to investigate the deformation modes and impact resistance of tubular joints. Wang et al. [18] described numerical studies on the performance of T joints in a jack-up structure under lateral impact loading by. Additionally, Travanca and Hao [19] presented numerical simulation results of ship impacts on offshore platform tubular structures, and proposed a

* Corresponding author.
E-mail address: liuyanzhi@hnu.edu.cn (Y. Liu).

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procedure to develop simplified equivalent systems for efficient structural response analysis. However, there is still lack of numerical investigation on the impact response of square or rectangular tubular joints.

Moreover, some theoretical analysis methods were developed to design the tubular structures under impact. Formisano et al. [20] provided the robustness assessment methods for steel framed buildings under catastrophic events. Jones and Shen [21] carried out a theoretical analysis for a fully clamped ductile pipeline laterally struck by a mass. Cerik et al. [22] proposed a simplified analysis method to evaluate an equivalent circumferential bending strength. Meanwhile, an equal area axis method was introduced by Jones and Birch [23] to estimate the local and global components from the tube total displacement. Qu et al. [17] assessed the impact capacity of circular tubular T-joints through the calculation of plastic hinge lines at the joint zone. On the other hand, several design codes on offshore platform including API R P. 2A-WSD [24], NORSOK Standard N-004 [25], and Recommended practice DNV-RP-C204 [26], provide the design method of steel tubular structure against accidental impacting action, but the specifications of these design codes mainly focus on the design of circular tube structures against accidental impacting action rather than square or rectangular tubes. In addition, it is found that Lu et al. [27] and Zhao [28] provided analytical methods to evaluate the ultimate capacity and deformation limit criterion of circular and rectangular hollow section joints under static loadings. However, limited theoretical study was carried out to examine the deformation patterns and dynamic resistance of square or rectangular tubular T-joints subjected to impact loadings.

To this end, this paper examines the dynamic behaviour of square tubular T-joints under impact loading by means of experimental, numerical and analytical studies. Firstly, a high-performance drop hammer setup is employed to carry out the impact tests on five hot-rolled square tubular T-joints with different chord thickness, width ratio of brace/chord under three levels of impact height. The dynamic responses of tubular T-joints including the deformation patterns and the development of impact force and displacement are described. Complementary finite element model for simulating the tubular T-joints under impact is then proposed and validated against the available test results. Finally, the test results and numerical simulations are utilized to investigate the failure mechanism of T-joints under impact load by an equivalent area method and the yield line theory.

2. Experimental programme

2.1. Specimen details

Five hot-rolled square tubular T-joints were designed to examine their dynamic behaviour under impact loadings by means of experimental investigation. The details of the testing specimens including the component sizes and loading conditions are summarized in Table 1, where the configurations of tubular T-joints are depicted in Fig. 1. For the specimen reference in Table 1, T represents square tubular T-joints. The first Arabic number “6” and “8” denote the chord thickness of 6 mm and 8 mm, respectively, while the followed number “60”, “100” and “150” stand for the brace width of 60 mm, 100 mm and 150 mm, respectively. The last small letter “a”, “b” and “c” represent three different impact heights of 2.3 m, 3.3 m and 3.8 m, respectively. B, T and L represent the width, the thickness and the length of chord, respectively, while b, t and l is the width, the thickness and the length of brace, respectively. Meanwhile, β is defined as the width ratio of brace and chord ($\beta = b/B$), and γ is set as the ratio of chord width to thickness ($\gamma = B/2T$). In addition, H and v represent the impact height and measured velocity of drop hammer, while the hammer weight (M) was kept as 440 kg.

The hot-rolled seamless steel chord and brace of the T-joints were perpendicularly intersected by using partial penetration welds. Additionally, two 30 mm thick steel cover plates were welded to two ends of the chord for the application of boundary conditions, while one 10 mm thick steel plate was welded at the free end of the brace for the application of loadings. In order to avoid the unexpected failure of the chord and brace ends, four wedge stiffeners were welded at the middle of four surfaces at each end, respectively, as shown in Fig. 1. Moreover, the material properties of testing components were obtained and presented in Table 2 according to the coupon tests on the strips cut from the steel tubes.

2.2. Testing setup

The test setup and corresponding details of the impact test are showed in Fig. 2, including the drop hammer facility and a U-shaped rigid base frame. The drop hammer machine has the capacity of up to 10 kN weight load and a maximum impact height of 16 m at the Center for Integrated Protection Research of Engineering Structures (CIPRES) in Hunan University, and the details of this testing machine were described elsewhere [13]. The chord ends were fixed in the rigid base frame. The drop hammer was lifted to a predetermined height and then released to impact the top end of the brace.

In addition, a piezoelectric force transducer installed in the hammer was used to measure the impact force, and several displacement transducers and strain gauges were located around the specimens to record the displacement and strain development of the chord and brace, as depicted in Fig. 1. The displacement transducer (D1) was placed on the bottom of brace end plate to record the vertical displacement of the brace (δ1), which is approximately assumed as the vertical displacement of upper flange in the mid-span section of the chord, while the displacement transducers (D2) was located on the bottom point in the chord mid-span section to record the vertical deformation of bottom flange (δ2). Meanwhile, nine strain gauges were mounted onto the chord upper flange and web around the brace-to-chord intersection zone in order to monitor their strain development during impact loading. As shown in Fig. 1, on the chord upper flange, strain gauges (S1, S2, S3) were mounted along the chord axis direction, while strain gauges (S4 and S5) were located perpendicular to the chord axis direction. On the chord web, strain gauges (S6 and S7) were mounted along the chord axis direction, while strain gauges (S8 and S9) were perpendicularly located. Moreover, a multi-channel high-frequency data acquisition system was employed to record the output signals, and the Lab VIEW visual software was used to output the corresponding data, including the development of impact force, vertical displacement and strain. However, due to the failure of data acquisition, the corresponding results of Specimen T8-100a were not recorded in this research. Therefore, only the deformation pattern and overall residual deflection of Specimen T8-100a are presented in Figs. 3 and 4 in the following descriptions.

Table 1
Details of testing specimens.

Reference	Chord $B \times T \times L$ (mm)	Brace $b \times t \times l$ (mm)	Width ratio of brace and chord β ($= b/B$)	Ratio of chord width to thickness γ ($= B/2T$)	Impact height H (m)	Impact velocity v (m/s)	Impact duration (ms)	Peak impact force (kN)
T8-100a	180 × 8 × 1940	100 × 5 × 500	0.56	11.25	2.3	–	–	–
T8-100c	180 × 8 × 1940	100 × 5 × 500	0.56	11.25	3.8	8.6	20.3	478
T6-60b	180 × 6 × 1940	60 × 5 × 500	0.33	15	3.3	7.8	26.8	323
T6-100b	180 × 6 × 1940	100 × 5 × 500	0.56	15	3.3	7.7	25.0	458
T6-150b	180 × 6 × 1940	150 × 5 × 500	0.83	15	3.3	7.6	18.2	567