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Punching shear failure of concrete-filled steel tubular CHS connections

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ABSTRACT

Based on the experimental investigation and numerical simulation, the punching shear failure mode of concrete-filled steel tubular CHS (circular hollow section) connections in axial tension was investigated. A finite element model was established using ABAQUS and verified against test results. It is shown that the developed model predicts the ultimate strengths and failure modes of test specimens well. Material properties, sizes of weld and contact interaction between concrete and steel were considered in the developed finite element model. The modified Mohr-Coulomb criterion for ductile fracture was used to define fracture criterion of the steel tube. Distribution of shear stress on the punching shear face was examined and a general equation describing stress distribution was proposed. An equation for equivalent thickness of punching shear failure face was also proposed. Parametric study was performed to determine the parameters in the proposed equations. Finally, design equations for ultimate strengths of concrete-filled steel tubular CHS connections failed in chord punching shear failure were proposed. It is shown that the design predictions agree with the finite element analysis results well.

1. Introduction

With the wide usage of concrete-filled steel tubular structures, concrete-filled steel tubular CHS (circular hollow section) connections are increasingly used in the engineering structures [1]. Previous research indicated that filling the hollow section chord member with concrete could effectively improve the strength of the connections [2–6]. Concrete inside chord could effectively hold the deformation of the steel tube so that chord plastification failure is prevented when the brace in axial tension load. Thus punching shear failure is the dominating failure mode for the chord of concrete-filled steel tubular CHS connections in this case. Test results indicated that the effect of concrete should be taken into consideration in the design and the connections should be designed based on punching shear failure mode [6].

Current AISC [7] standard has the design provisions for punching shear failure of circular section hollow steel tubular connections. However design strength predictions are very conservative for concrete-filled steel tubular CHS connections, when shear yielding stress of the full punching shear failure face is assumed. Averagely design strength is only about 63% of the ultimate strength of test connections. If shear ultimate stress of the full shear failure face is assumed, the design predictions will be unconservative. Averagely design strength is about 121% of the ultimate strength of test specimens [6]. In this case, new design method should be proposed for the punching shear failure of concrete-filled steel tubular CHS connections.

2. Summary of experimental investigation

The test program presented in Xu et al. [6] provided experimental ultimate loads and failure modes of concrete-filled steel tubular CHS connections in tension. The test setup is shown in Fig. 1. The measured geometric sizes of the test specimens are presented in Table 1. The measured steel material properties obtained from the tensile coupon tests are summarized in Table 2. The compressive strength (f_{cu}) and elastic modulus (E_c) obtained on 150-mm cubes at 28 days were 46.9 MPa and 37,420 MPa, respectively. The details of the experimental investigation are presented in Xu et al. [6]. The experimental ultimate loads (F_{Exp}) obtained from the test results are shown in Tables 3. The failure modes of all specimens are punching shear failure of the chord, except for KT type specimens. The test specimens are labeled such that the chord type, outer diameter of chord, thickness of chord, outer diameter of brace and thickness of brace could be identified from the label in this paper.

3. Finite element analysis

3.1. General

The general purpose finite element program ABAQUS/Explicit was used for the numerical modeling of concrete-filled steel tubular CHS

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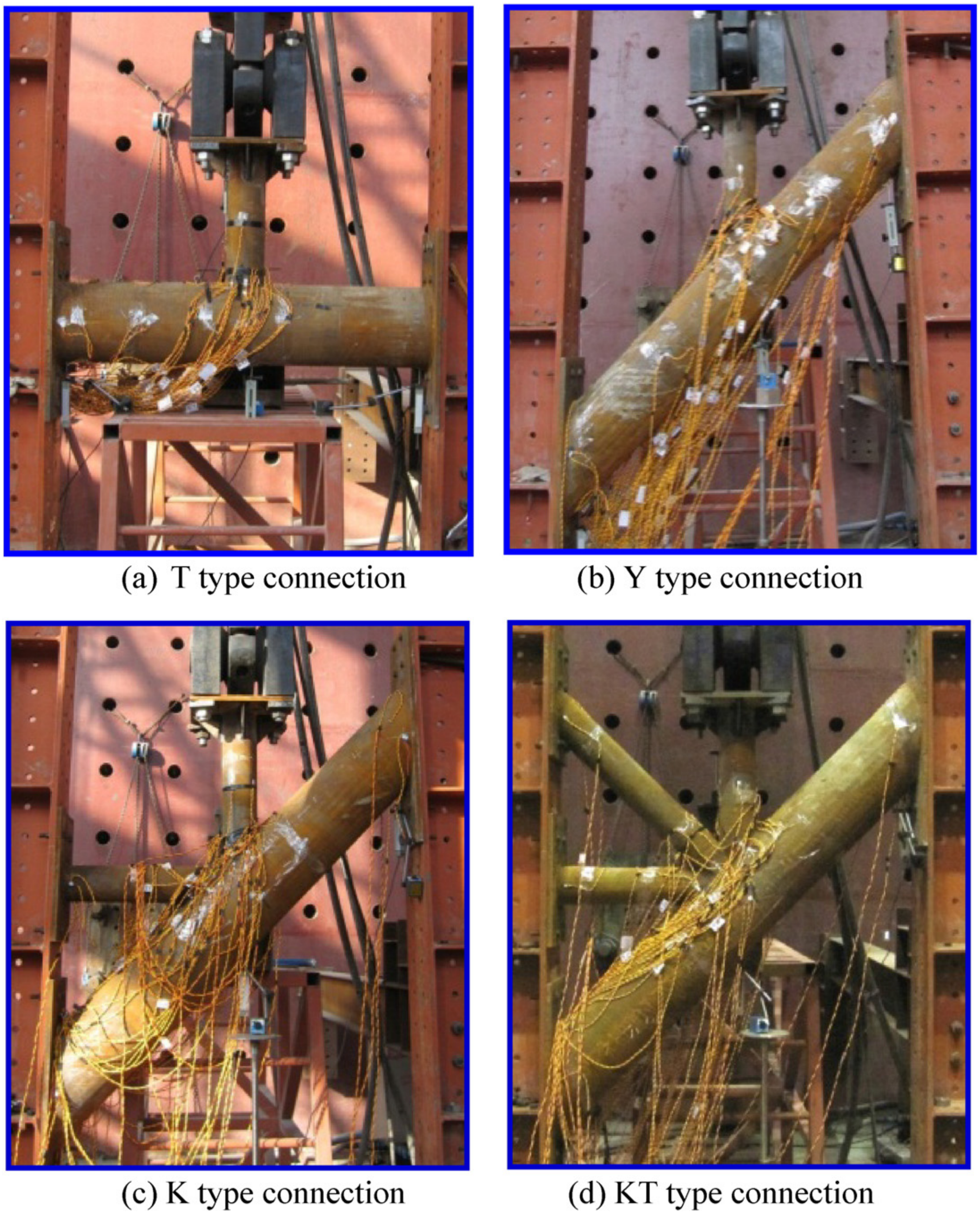

Fig. 1. Test setup [6].

(a) T type connection.
(b) Y type connection.
(c) K type connection.
(d) KT type connection.

connections. The finite element analysis (FEA) included various important factors, such as the modeling of materials and welds, contact interaction between the steel chord and the concrete core, fracture criterion of steel material, as well as loading and boundary conditions. The analysis time was reasonably reduced by introducing fixed mass scaling factor of 10^6 which is defined in ABAQUS [8].

Since there is bending stress in the chord wall, solid element rather than shell element is used to model the steel tube of connection [9,10]. In study, solid element C3D8R was used to model both steel and concrete. The element size near the braces to chord intersection (regions of high stresses) was kept small with aspect ratio as close to unity as possible. However, towards the ends of the braces and chord where the stresses are more uniform, the element size and aspect ratio were increased, as shown in Fig. 2. The weld is simulated as steel material of chord since the failure is not occurred at weld. The measured stress–strain curves of steel tubes were used in the finite element models. Concrete constitutive model is the concrete-damaged plasticity model in ABAQUS [8] and the measured concrete material properties were used in the concrete material model. The interface model to simulate the interaction between steel and concrete in concrete-filled steel tubes is the contact interaction in ABAQUS. Following the testing procedure presented previously [6], the two ends of the chord were fixed against all degrees of freedom. Axial tension load (y direction) was applied on the top surface of the brace by applying a velocity (0.5 mm/min) which is the same as experiments. For K