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An out-of-plane bending hysteretic model for multi-planar CHS X-connections

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ABSTRACT

The multi-planar circular hollow section (CHS) X-connection is one of common configurations in single layered lattice steel tubular structures. A hysteretic model, including the skeleton model and restoring force model is proposed to simulate the hysteretic performance of X-connections under cyclic out-of-plane bending moments (OPB) generated by vertical seismic action. Exponential function is adopted in the skeleton model and the Ramberg-Osgood function is adopted in the restoring force model. The parameters in the hysteretic model are determined by finite element (FE) analysis and nonlinear regression. Additionally, an improved out-of-plane bending hysteretic model considering the influence of brace axial stress and chord normal stress is developed to simulate the seismic performance of X-connections in engineering practice. The proposed hysteric model is verified by experimental and FE results and the improved hysteretic model can consider the effect of strength degradation.

1. Introduction

Due to the aesthetic appeal and structural advantages, circular hollow section (CHS) tubes are widely used as main structural members in various types of civil infrastructures, such as buildings and offshore platforms. In practice, the brace members are often directly welded to the surface of the chord members, in which these unstiffened X-connections are one of common CHS tubular connection types employed in single-layer reticulated shell structures with large spans. In these reticulated structures, the distributed load on the CHS members can generate significant out-of-plane bending moments (OPB) in the X-connections under vertical excitations in the event of earthquake or wind suction, meanwhile brace axial force and chord stress (produced by bending moment and axial force) are not be ignored. Therefore, it is necessary to consider the effect of brace axial force and chord stress on the OPB seismic performance of CHS X-connections.

Existing studies of tubular connections are mainly focused on static strength and appropriate strengthening techniques. Lu et al. [1] suggested a deformation limit to determine the strength of tubular joints where the load corresponding to a deformation of 3% of the chord diameter is regarded as the ultimate strength of the tubular joints without show a pronounced peak load. Choo et al. [2] proposed a new method to determine the static strength of thick-walled CHS X-connections under brace axial loading. The research results showed that the strength of the X-connections determined by this method is close to the strength defined by [1]. Mashiri et al [3] carried out experimental tests on thin-walled T-joints fabricated by CHS braces and square hollow section (SHS) chords under in-plane bending moment (IPB). Based on deformation characteristic of the chord, the authors proposed a yield line model to derive the ultimate bending bearing capacity formula for CHS-SHS T-joints, and the formula predicts well with test results. Iskander et al. [4] performed experimental tests and Finite Element (FE) study on the through-bolts strengthened CHS T-joints under brace compression. The results showed that the ultimate capacity is increased by 35% using only one bolt. Wang and Chen [5,6] performed experimental tests and FE study on the flexural capacity of doubler-plate reinforced SHS X-joints. On the basis of the formula of unreinforced SHS X-joints provided in the EC 3 [7], the authors proposed equations to determine the ultimate capacities of doubler-plate reinforced SHS X-joints under in-plane and out-of-plane bending moment, and the proposed formulas are verified by FE and test results.

Apart from the static response, the hysteretic performance of the tubular connections has also received attention. Qin et al. [8] studied the hysteretic behavior of completely overlapped tubular joints with cyclic brace axial loading. The authors found that the main energy dissipation is contributed by local buckling at intersection area. Shao

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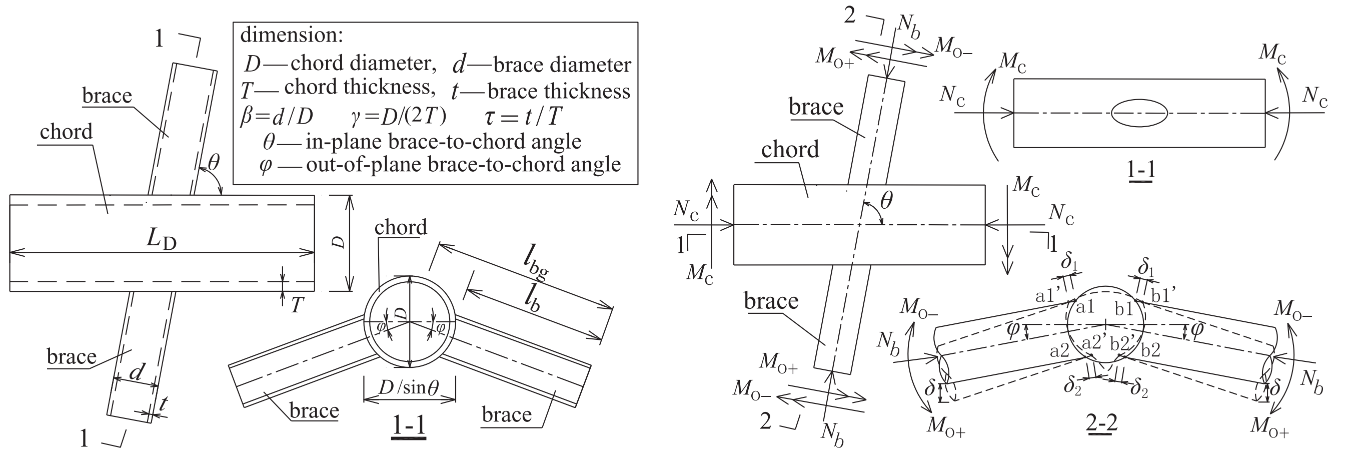

(a) Dimension of the CHS X-connections (b) Loading schematic for the CHS X-connections

Fig. 1. Geometric parameters and loading diagram of multi-planar CHS X-connections.

et al. [9] carried out experimental tests and FE studies on reinforced (increased the chord thickness locally at the brace/chord intersection) and un-reinforced CHS tubular T-joints subjected to cyclic brace axial loading. It was found that increasing the chord local thickness can effectively improve the energy dissipation capacity, ductility and the ultimate capacity of the joints. Xia et al. [10] studied the hysteretic behavior of doubler-plate reinforced SHS T-joints. It was found that doubler-plate reinforcement can enhance the strength of the joints remarkably while decrease the energy dissipation capacity and ductility. Xing et al. [11] found that the ultimate capacity and ductility of cruciform diaphragm joints under axial compressive load and cyclic IPB would be decreased by increasing the axial compressive ratio. Zhao et al. [12] conducted cyclic brace axial loading tests on overlapped CHS K-joints. It was found that using hidden welds could improve the joint capacity and energy dissipation capacity while decrease the joint ductility. Wang et al. [13] carried out OPB cyclic loading tests on three thick-walled CHS X-connections. Research results showed that the brace-to-chord diameter ratio β significantly influence the ductility and energy dissipation capacity of the connections, and the current design specifications [7] cannot accurately predict the out-of-plane bending capacity of these X-connections. Wang et al. [14] investigate the seismic behavior of thin-walled CHS KK-connections under different OPB loading patterns. It was found that the KK-connections under alternate opening and closing out-of-plane bending (AOCO) provide better ductility and energy dissipation than that under alternate clockwise aligned and counterclockwise aligned out-of-plane bending (ACCO). Zhao et al. [15] carried out experimental test and FE analysis to investigate the hysteretic behavior of thin-walled CHS X-connections under cyclic OPB. The research results showed that decreasing the in-plane brace-to-chord angle can help improve the energy dissipation capability, ultimate flexural capacity and ductility ratio.

Though numerous hysteretic models have been proposed for beam-to-column connections, there are relatively few available for unstiffened tubular connections. Meng et al. [16] proposed a hysteretic model for the CHS X-connections under cyclic OPB using Menegotto-Pinto equations and kinematic hardening models. However, the parameters in the skeleton curve model of [16] have no clear physical meaning (i.e., initial stiffness), and the kinematic hardening model cannot accurately reflect restoring force curves of the hysteretic curves. Moreover, the model in [16] does not consider the influence of brace axial force and chord stress on the out-of-plane bending hysteretic behavior of the X-connections. In order to overcome the above flaws, Zhao and Chen [17] proposed a four-spring assembling model for simulation of the hysteretic behavior of CHS X-connections. The four-spring model can consider the influence of brace axial force and agree well with the restoring force curves. However, the skeleton curve in [17] is not a smooth nonlinear curve due to the piecewise linear force–deformation relationship adopted by the springs. Moreover, there are some other limitations in [17] including too many assumptions (e.g., locations of the springs), too many parameters (sixteen) and not considering the influence of chord stress (caused by the bending and axial force). Furthermore, the four-spring model is only applicable to uniplanar CHS X-connections, while there are many multi-planar CHS X-connections that are used in practice.

In order to overcome the limitations of existing hysteretic models, the present paper, based on the experimental data from [13] and [15], aims to establish an out-of-plane bending hysteretic model for unstiffened multi-planar CHS X-connections subjected to cyclic OPB, brace axial force and chord stress. Based on the characteristics of moment-rotation (M_o-ψ_o) hysteretic curves from existing test results and numerical simulation results, an exponential function and Ramberg-Osgood function are adopted to describe the skeleton curve and restoring force curve in this hysteretic model. Then, FE parametric analysis is carried out to study the effect of geometrical parameters (β,etc.) on the behavior of M_o-ψ_o skeleton curve. Based on the FE results, the formulae of the parameters in the hysteretic model are established. Finally, experimental tests and FE results are used to verify the proposed hysteretic model.

2. FE models of multi-planar CHS X-connections and verification

2.1. Geometric parameters and loading pattern of multi-planar CHS X-connections

Fig. 1 presents the geometry and loading diagram of these X-connections, where the dimensions are noted in Fig. 1a, and the dash (in Fig. 1b) express the deformation of the X-connections. For multi-planar CHS X-connections in a single-layer latticed structure, braces at both sides of the chord are identical and subjected to the same loading. In practice, vertical excitations of earthquake or wind suction will cause downward (sagging moment M_{o+}) and upward (hogging moment M_{o-}) OPB. The brace axial force (N_b), chord moment (M_c) and chord axial force (N_c) will influence the out-of-plane bending hysteretic behavior of the X-connections.

2.2. Finite element (FE) model and verification

The software package ABAQUS is used to carry out the parameters analysis in this study. In the FE model, the length of chord (L_D) is taken as 12 times of the chord diameter D, and the length of brace (l_{bg}) is 5