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Strength of longitudinal X-type plate-to-circular hollow section (CHS) connections reinforced by external ring stiffeners

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ABSTRACT

This paper presents an experimental test and finite element (FE) study on the ultimate strength of longitudinal X-type plate-to-circular hollow section (CHS) connections reinforced by external ring stiffeners (abbreviated as PCE connections) under in-plane bending moment. Static tests on four large-scale specimens were performed under both symmetrical and anti-symmetrical loadings. Local axial buckling and transverse plastic deformation failures on PCE connections were observed from the test. Further FE analysis reveals that the external ring stiffener can achieve effective strengthening of the connection and the failure modes are affected by the size of the ring. A total of 541 PCE connections with a various range of geometric configurations and chord stress levels were analyzed and the results obtained were transformed into the ultimate strength of "ring models". Based on the regression analysis of numerical simulation database, the current design equations by JSTA were re-assessed and a set of novel design model has been proposed utilizing the mathematic design model for transverse X-type plate-to-CHS connections by CIDECT design guide. The proposed design model tends to have practical significance by offering a design guideline for the similar connections.

1. Introduction

Due to the simplification of fabrication, high efficiency of erection and aesthetically appealing, longitudinal plate-to-circular hollow section (CHS) connections were widely used in steel tubular components for transmission towers, long-span structures and frame structures [1,2]. However, as a result of the imposed deformation limit of 3% for the chord diameter [3] and potential punching shear failures [4,5], the capacity of the connection is not sufficiently utilized. To strengthen such connections, the ring stiffeners are directly welded to the outside of CHS chord at gusset plate edges [1,6]. Comparing with other CHS chord strengthening alternatives [7–9], the external ring stiffener can be conveniently installed even for the chord with small diameters and can also be placed either before or after the construction of connection [10]. Therefore, the external ring stiffeners are commonly used for steel tubular of the transmission towers and frame structures, such as the application for KK connections in diaphragms of towers in Fig. 1(a), connections at the intersections of tower and cross-arm [11] and beam-to-column connections in frame structures of Fig. 1(b) [12,13].

Since the 1960s, extensive studies have been conducted on the mechanical behaviors of unreinforced plate-to-CHS connections [4,14–21]; however, the data was still limited for establishing a rational and explicit design method. Based on these previous researches and the analysis work by Wardenier et al. [22–24], design recommendations for such unreinforced connections were proposed based on the design guidelines for CHS-to-CHS connections by regression analysis [23,25]. These models have been adopted by CIDECT Design Guide No. 1 [6], International Institute of Welding design rules [26] and AISC Steel Design Guide No. 14 [27]. Further, Voth et al. [28–30] modified these formulae by taking account of the thickness, skewed angle and incline angle of branch plate with a wider range of validity. Driven by the needs from practical engineering application, studies were increasingly conducted on reinforced connections. In the early 1970s, Akiyama et al. [15] proposed the design equations for CHS connections reinforced by external ring stiffeners based on elastic-plastic theory and models extrapolated from typical "ring models" with T-shaped section. Fei Xu et al. [31] investigated the mechanical behavior of concrete-filled CHS connections subjected to in-plane bending and put forward design equations based on the punching shear strength. Y.S. Choo et al. [32] conducted the parametric numerical study on the static strength of collar plate reinforced X-joints loaded by in-plane bending and proposed strength equations for such connections. The formulae proposed by Akiyama et al. [15] were specifically for connections of transmission steel tubular towers and adopted by technical guidelines of electric power industry such as the Japanese Steel Tubular Association [33] and Q/GDW 391–2009 [34]. However, further researches on full-scale

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Nomenclature

D	external diameter of CHS chord;
t, t_r, T	thickness of chord wall, ring stiffener, and gusset plate;
l	full-length of the chord;
l_1, l_2, l'	the upper effective chord length, the lower effective chord length, the length of end plates and stiffening plates;
R	width of external ring stiffeners;
w_0	weld leg size along chord;
B_e	effective chord length of "ring model";
B	length of gusset plate;
2γ	chord diameter-to-thickness ratio ($2\gamma = D/t$);
α	effective chord length parameter ($\alpha = 2(l_1+l_2)/D$);
ε	gusset plate thickness-to-chord diameter ratio ($\varepsilon = T/D$);
λ	gusset plate length-to-chord diameter ratio ($\lambda = B/D$);
η	ring stiffener thickness-to-chord diameter ratio ($\eta = t_r/D$);
β	ring stiffener width-to-chord diameter ratio ($\beta = R/D$);
P_a, P_b	symmetrical and anti-symmetrical design load on bracing member;
F_a, F_b	symmetrical and anti-symmetrical design load on H-shaped beam;
H	distance from chord surface to loading point;
M_U	the ultimate moment of PCE connections;
L_o	original gauge length;
L_c	parallel length;
L	the full-length of tensile coupons;
b	the original width of coupons in parallel length;
F_v, F_v'	design axial load on CHS chord in H-shaped beam-to-column connection;
P_v, P_v'	design axial load on CHS chord in KK connection;
f_y, f_u	yield stress, ultimate stress of material;
ν	Poisson ratio;
E, E'	Young's modulus, modulus in strengthening stage;
F	vertical force applied on gusset plate;
δ	vertical displacement of gusset plate;
N, N_A	axial force and applied force in the CHS chord;
F_{JSTA}	design vertical force;
M_P	the ultimate moment based on the proposed functions;
M_c	the resistance moment resulting from the chord wall;
M_A	acting moment on CHS chord;
N_{pl}	chord plastic strength;
M_{pl}	chord plastic moment capacity;
M_e, M	local bending moment, bending moment;
M_{max}	the peak moment of moment-deformation curve;
Q	shear force on CHS chord;
P	horizontal force acting on "ring models";
P_{u1}	chord strength;
P_{u2}	ultimate horizontal force on "ring models";
Δ	horizontal displacement of the point of maximum curvature variation on CHS chord;
R^2	coefficient of multiple determination;

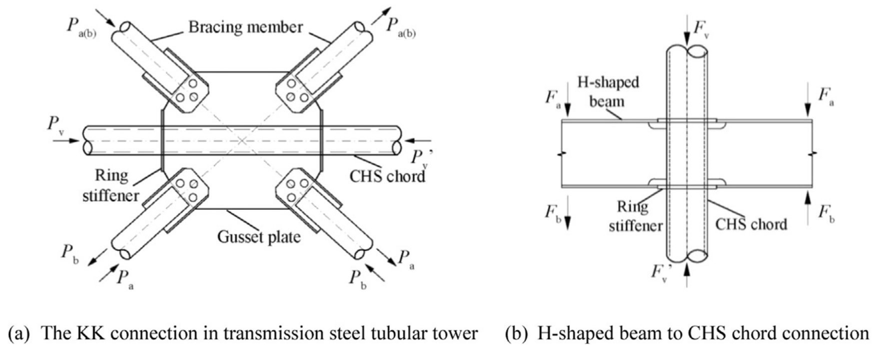

Fig. 1. Typical longitudinal plate-to-CHS connections reinforced by external ring stiffeners.

connections of transmission towers revealed that design by these formulae were excessively conservative [35–37].

This paper investigates the ultimate strength and the design model for longitudinal X-type plate-to-circular hollow section connections reinforced by external ring stiffeners (which is abbreviated as PCE connections in this paper). First, experimental test and numerical analysis were conducted for PCE connections to reveal the general behaviors and failure modes of such connections. Then, further FE

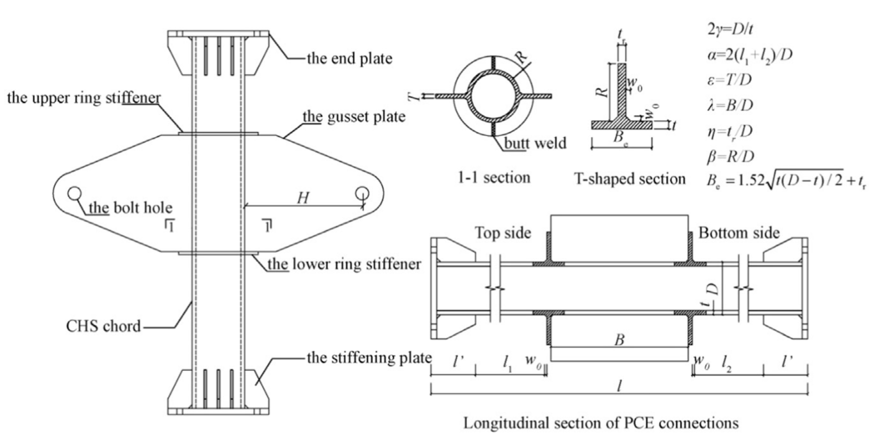

Fig. 2. Geometric configuration and parameters for the PCE connection.