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Design of cold-formed stainless steel tubular T- and X-joints

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ABSTRACT

This paper describes the numerical investigation of cold-formed stainless steel tubular T-joints, X-joints and X-joints with chord preload using finite element analysis. The stainless steel joints were fabricated from square hollow section (SHS) and rectangular hollow section (RHS) brace and chord members. The geometric and material nonlinearities of stainless steel tubular joints were carefully incorporated in the finite element models. The joint strengths, failure modes as well as load-deformation curves of stainless steel tubular joints were obtained from the numerical analysis. The nonlinear finite element models were calibrated against experimental results of cold-formed stainless steel SHS and RHS tubular T- and X-joints. Good agreement between the experimental and finite element analysis results was achieved. Therefore, an extensive parametric study of 172 T- and X-joints was then carried out using the verified finite element models to evaluate the effects of the strength and behaviour of cold-formed stainless steel tubular joints. The joint strengths obtained from the parametric study and tests were compared with the current design strengths calculated using the Australian/New Zealand Standard for stainless steel structures, CIDECT and Eurocode design rules for carbon steel tubular structures. Furthermore, design formulae of cold-formed stainless steel tubular T- and X-joints are proposed. A reliability analysis was performed to assess the reliability of the current and proposed design rules. It is shown that the design strengths calculated using the proposed equations are generally more accurate and reliable than those calculated using the current design rules.

1. Introduction

Experimental investigation of cold-formed stainless steel tubular joints was conducted by Rasmussen and Young [1] for SHS X- and K-joints, Rasmussen and Hasham [2] for circular hollow section (CHS) X- and K-joints. In addition, Feng and Young [3,4] conducted a series of tests on cold-formed stainless steel SHS and RHS T- and X-joints. Both high strength stainless steel and normal strength stainless steel specimens were tested. The test strengths were compared with the design strengths calculated using the Australian/New Zealand Standard [5] for stainless steel structures, CIDECT [6] and Eurocode [7] design rules for carbon steel tubular structures. It was shown that the design strengths predicted by the existing design specifications are generally conservative for cold-formed stainless steel tubular T- and X-joints.

The finite element (FE) method is capable of predicting the strength and behaviour of full-scale laboratory structural tests, and it is quite common to use FE method for investigation nowadays. In this study, the FE method is used for the investigation of cold-formed stainless steel tubular connections. The finite element method has been widely used to simulate the behaviour of welded carbon steel tubular joints. Packer et al. [8] described a finite element model of a welded joint in a rectangular hollow section warren truss to study the parameters influencing the flexibility of joint at the serviceability limit state. Zhang et al. [9] developed a suitable nonlinear finite element model incorporated large deflection for elasto-plastic analysis of the ultimate strength of welded RHS joints. The comparison between experimental and numerical results showed good agreement. Moffat et al. [10] carried out nonlinear finite element analysis to assess the static collapse strength of tubular T-joint subjected to compressive brace loading. The static strengths of various FE models produced using the PATRAN mesh generation program were determined by ABAQUS finite element program. Karamanos and Anagnostou [11] presented a nonlinear finite element model to investigate the influence of external hydrostatic pressure on the ultimate capacity of uniplanar welded tubular X- and T-connections under axial and bending loads. Good agreement between the numerical results and test data was found. The finite element method has been used by many other researchers for the modelling of carbon steel tubular joints. It should be noted that the aforementioned finite element analyses were focused on carbon steel tubular joints. However, there are not many researches on the finite element analysis of stainless steel tubular joints.

This paper mainly focuses on the numerical study of cold-formed stainless steel tubular T-joints, X-joints and X-joints with

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Notations

A_0	Cross-sectional area of chord member
A_1	Cross-sectional area of brace member
b_e	Effective width of brace member
b_0	Overall width of chord member
b_1	Overall width of brace member
C_p	Correction factor in reliability analysis
COV	Coefficient of variation
E	Young's modulus of elasticity obtained from longitudinal tensile coupon test
f_k	Chord side wall flexural buckling stress
$f(n)$	Parameters account for the influence of compression chord longitudinal stress
f_{y0}	Yield stress of chord member
F_m	Mean value of fabrication factor
h_0	Overall depth of chord member
h_1	Overall depth of brace member
L_0	Overall length of chord member
L_1	Overall length of brace member
M_m	Mean value of material factor
n	Preload ratio
N_f	Failure load
N_p	Compressive preload applied to chord member
N_1	Design strength calculated using CIDECT rules
N_{1n}	Nominal strength calculated using CIDECT rules
N_{1np}	Nominal strength calculated using proposed design equations
P_{FE}	Joint strength obtained from finite element analysis
P_m	Mean value of tested-to-predicted load ratio
P_{Test}	Joint strength obtained from laboratory test
r_0	Inner corner radius of chord member
r_1	Inner corner radius of brace member
R_i	External corner radius of stainless steel tube
t_0	Overall thickness of chord member
t_1	Overall thickness of brace member
V_F	Coefficient of variation of fabrication factor
V_M	Coefficient of variation of material factor
V_P	Coefficient of variation of tested-to-predicted load ratio
w	Weld size
α_A	Reduction factor for chord face failure
α_B	Reduction factor for chord side wall failure
α_{A+B}	Reduction factor for combination of chord face failure and chord side wall failure
β	Brace to chord width ratio (b_1/b_0)
β_0	Reliability index
β_{01}	Reliability index determined for European Code
β_{02}	Reliability index determined for ASCE Standard
2γ	Chord width to thickness ratio (b_0/t_0)
$\varepsilon_{\ln}^{pl}$	Logarithmic plastic strain converted from measured static strain
η	Brace depth to chord width ratio (h_1/b_0)
θ_1	Inclined angle between brace and chord member
σ_{true}	True stress converted from measured static stress
$\sigma_{0.2}$	Static 0.2% tensile proof stress
τ	Brace to chord thickness ratio (t_1/t_0)
ϕ	Resistance factor

chord preload using the finite element method. The numerical results obtained from the finite element analysis were calibrated against the experimental results obtained by Feng and Young [3,4]. An extensive parametric study was performed on cold-formed stainless steel tubular T- and X-joints. The joint strengths obtained from the parametric study were compared with the design strengths calculated using the current Australian/New Zealand Standard [5] for stainless steel structures, CIDECT [6] and Eurocode [7] design rules for carbon steel tubular structures. Hence, design equations of cold-formed stainless steel tubular T- and X-joints are proposed.

2. Summary of experimental investigation

The experimental investigation of cold-formed stainless steel tubular T-joints, X-joints and X-joints with chord preload performed by Feng and Young [3,4] provided joint strengths, failure modes as well as load–deformation curves of the test specimens. The SHS and RHS were cold-rolled from austenitic stainless steel type AISI 304, high strength austenitic (HSA) and duplex (EN 1.4462) stainless steel sheets. The tubular T- and X-joints were fabricated by welding of SHS and RHS brace and chord members. The 0.2% proof stress of the stainless steel tubes was ranged from 320 to 565 MPa for normal strength material and ranged from 448 to 707 MPa for high strength materials.

The welded tubular joints have the brace width to chord width ratio (β) ranging from 0.5 to 1.0, brace thickness to chord thickness ratio (τ) from 0.5 to 2.0, chord width to chord thickness ratio (2γ) from 10 to 50 as well as the compressive chord preload (N_p) ranging from 10% to 50% of the yield load $(A_0\sigma_{0.2})$ for the X-joints. All specimens were fabricated with brace members fully welded at right angles to the center of the continuous chord members. The welded square and rectangular hollow sections consisted of a large range of section sizes. For the chord members, the tubular hollow sections have nominal overall flange width (b_0) ranging from 40 to 200 mm, nominal overall depth of the web (h_0) from 40 to 200 mm, and nominal thickness (t_0) from 1.5 to 6.0 mm. For the brace members, the tubular hollow sections have nominal overall flange width (b_1) ranging from 40 to 150 mm, nominal overall depth of the web (h_1) from 40 to 200 mm, and nominal thickness (t_1) from 1.5 to 6.0 mm. The length of the brace member (L_1) and chord member (L_0) were chosen as $2.5h_1$ and $5h_0 + h_1$, respectively. The measured cross-section dimensions of the test specimens are detailed in Feng and Young [3,4] for SHS and RHS tubular T- and X-joints, using the nomenclature defined in Figs. 1 and 2.

The test specimens are labeled according to their joint configurations, stainless steel types and cross-section dimensions of chord and brace members. For example, the labels 'TN-C40 × 2-B40 × 2' and 'XD-C50 × 1.5-B40 × 2-P0.1' define the welded tubular T- and X-joints fabricated from normal strength 'N' and duplex 'D' stainless steel materials respectively. If the second letter is 'H', then it refers to high strength austenitic. The third letter 'C' indicates the chord member followed by the nominal overall depths of the web (h_0) of 40 mm and 50 mm, and wall thickness (t_0) of 2 mm and 1.5 mm respectively, the letter 'B' indicates the brace member followed by the nominal overall depths of the web (h_1) of 40 mm and wall thickness (t_1) of 2 mm, the following expression 'P0.1' indicates a 10% of preload applied to the chord member for X-joints only. The overall flange width of both chord (b_0) and brace (b_1) are purposely not shown for simplification.

A 1000 kN capacity servo-controlled hydraulic testing machine was used to apply axial compression force to the test specimens. A special fixed-ended bearing was designed to restrain against both minor and major axes rotations as well as twist rotations and warping to produce uniform axial compression force without any bending moment. Displacement control was used to allow the tests to be continued in the post-ultimate range. The applied loads and readings of displacement transducers were recorded automatically at regular intervals by using a data acquisition system. The experimental investigation of cold-formed stainless steel tubular T- and X-joints is detailed in Feng and Young [3,4].