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Thin circular hollow section-to-plate T-joints: Stress concentration factors and fatigue failure under in-plane bending

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Abstract

Welded thin-walled ($t < 4$ mm) tube-to-plate T-joints made up of cold-formed circular hollow sections welded onto a plate to form a moment resistant connection are used in the road transport and agricultural industry to manufacture equipment and other structural systems. Fatigue design of these joints is not available in current standards. An understanding of the stress concentrations and failure in these connections is therefore necessary as a step towards understanding the fatigue behaviour of these connections. Stress concentration factors (SCFs) of welded thin-walled ($t < 4$ mm) circular hollow section (CHS)-to-plate T-joints are determined at different locations along the weld toes on the tubular brace. The distribution of SCFs along the weld toes shows that the highest SCF occurs at the weld toes in the circular brace at the 0° line. The ratio of the end of test fatigue life (*N*4) to the through-thickness fatigue life (*N*3) in the thin CHS-plate T-joints is found to fall within the range of *N*4/*N*3 found in previous research of both thick and thin-walled joints. Surface crack growth monitoring is used to obtain an approximation of the length of surface crack at the point of occurrence of a through-thickness crack. The relationship between surface crack length and the occurrence of a through-thickness crack is important in that it can be used as a measure of the criticality of a surface crack during structural health monitoring of equipment or structures.

Keywords: Fatigue; Circular hollow section; Hot spots; Stress concentration factor; Failure

1. Introduction

Current fatigue design guidelines such as the Australian Standard AS4100-1998 [1], American Standard [2], European Standard [3], CIDECT design guide no. 8 [4] and International Institute of Welding Recommendations [5–6], do not have fatigue design rules for welded thin-walled ($t < 4$ mm) circular hollow section (CHS)-to-plate T-joints under cyclic in-plane bending. The Canadian Standard CAN/CSA-S16.1-01 [7] however gives guidance for the fatigue design of hollow structural section-to-plate connections made up of square or rectangular hollow sections subjected to cyclic in-plane bending in the tubular brace [8]. For the fatigue design of the hollow structural section-to-plate connections made up of square or rectangular hollow sections subjected to cyclic in-plane bending in the tubular brace, the Canadian Standard CAN/CSA-S16.1-01 [7] recommends the use of an *S–N* curve with a class (stress range at 2 million cycles) of 40 MPa. The differences in shape between the square and circular hollow sections mean that different stress concentrations will occur, causing a difference in fatigue strength between the square hollow section-to-plate T-joints and circular hollow section-to-plate T-joints.

As part of an effort to understand the fatigue behaviour of welded thin-walled CHS–plate T-joints under in-plane bending, this paper investigates the stress concentrations, different stages of fatigue failure such as through-thickness fatigue life and end of test fatigue life and surface crack growth at different stages of fatigue failure.

The circular hollow sections are cold-formed and of grade C350LO which comply with Australian Standard, AS1163-1991 [9]. Grade C350LO steel has a specified minimum yield stress of 350 MPa and a specified minimum ultimate tensile strength of 430 MPa. A circular hollow section tube is welded to a plate of grade 350 using fillet welds, to form a base plate moment connection. The gas metal arc welding method (MIG) is used in fillet-welding the CHS tube to the plate. The circular hollow sections used are of thicknesses equal to 2.0, 2.6 and 3.2 mm. Three different connection series of CHS–plate T-joints, shown in Table 1, made up of tubes of the three

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Notation

CHS circular hollow section
d_1 tube diameter
E Young's modulus
MIG gas metal arc welding method
N number of cycles to failure
$N3$ through-thickness fatigue life
$N4$ end of test fatigue life
PLC programmable logic controller
SCF stress concentration factor
SCF_{ipb_brace} stress concentration factor at weld toes in the tubular brace due to the load 'in-plane bending in the brace'
SCF_{ipb_brace} stress concentration factor at weld toes in the plate due to the load 'in-plane bending in the brace'
T plate thickness
t_1 or t tube wall thickness

Greek letters

ν Poisson's ratio
τ tube wall thickness (t_1) to the plate thickness (T)
σ_{nom} simple beam theory nominal stress
$\sigma_{nom.exp}$ experimental nominal stress
ε_x strain perpendicular to the weld toe
ε_y strain parallel to the weld toe
ε_z strain normal to the x–y plane
σ_x Stress perpendicular to the weld toe

different thicknesses of 2.0, 2.6 and 3.2 mm, are tested under cyclic in-plane bending. The ratio, τ of the tube wall thickness (t_1) to the plate thickness (T) ranges from 0.2 to 0.32. The ratio of the diameter (d_1) to the tube wall thickness (t_1) which reflects the slenderness of the tested circular hollow sections ranges between 15.1 and 21.2.

Strip strain gauges were installed at different weld toe locations on the circular hollows section member in order to determine the location of the 'hot spots' around the thin-walled CHS–plate T-joints subjected to in-plane bending. Stress distributions were derived from the strain measurements and used to estimate the hot spot stresses at locations around the weld toes on the CHS brace to plate interface. Experimental SCFs for the welded thin-walled CHS–plate T-joints under the load 'in-plane bending in the brace' were determined. Nominal stresses applied to the connection during the determination of SCFs have also been verified using individual gauges mounted onto the brace member.

The fatigue life ($N3$) for welded thin-walled CHS–plate T-joints corresponding to the development of a through-thickness crack in the member failing under fatigue loading was determined. For each connection series, two specimens were instrumented for the measurement of through-thickness fatigue life through the pressurisation of the CHS brace member. Through-thickness fatigue life ($N3$) is the commonly accepted fatigue failure mode. In the mining industry for example, critical members of dragline structures are subjected to a detectable air pressure. A sudden drop in air pressure of the pressurised members indicates a through-thickness crack. In offshore rigs, through-thickness cracking is detected by leaking or flooding in those members that are submerged under water.

During the determination of through-thickness fatigue life ($N3$), surface crack growth monitoring was carried out. During this process, the surface crack length at the point of development of a through-thickness crack was recorded. This process allowed a relationship of the extent of surface crack length at a point when a through-thickness crack occurs to be estimated for welded thin-walled CHS–plate T-joints. The knowledge of the crack length at the occurrence of a through-thickness crack is important in that it can be used in structural health monitoring by welding inspection engineers to make decision of the criticality of a crack during the inspection of structures.

2. Stress concentration factors (SCFs)

2.1. General

The hot spot stresses in welded thin-walled CHS–plate T-joints were determined experimentally through the use of strain gauges. Fatigue tests, carried out prior to the measurement of stress distribution at hot spots, showed that the initiation point for fatigue cracks was at the weld toe in the brace, around the 0° line, at the brace-plate interface as shown in Fig. 1(a). Fig. 1(b) is a photograph of the strain-gauged

Table 1
Connection series for CHS–plate T-joints

Connection series	Web/branch member $d_1 t_1$ (mm)	Ratio $(=d_1/t_1)$	Plate LWT (mm)	τ $(=t_1/T)$	R	Lines along which SCFs were determined	Steel grade/ description
C7P	48.3×3.2 CHS	15.1	200×200×10	0.32	0.1	Brace lines 0°, 45° and 60°	C350LO/non-galvanised
C8P	42.4×2.6 CHS	16.3	200×200×10	0.26	0.1		
C9P	42.4×2.0 CHS	21.2	200×200×10	0.20	0.1		