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Fatigue and residual strength of concrete-filled tubular X-joints with full capacity welds

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ABSTRACT

This paper presents the experimental findings on the fatigue performance and residual strength of the circular hollow section X-joints with a concrete-filled chord. The welding profile along the brace-to-chord intersection employs a recently proposed set of welding details, namely the full capacity tubular joint welds. The experimental investigation focuses on: 1) the stress concentration comparison corresponding to different stages of the specimen preparation, 2) the fatigue crack initiation life and propagation life; and 3) the comparison of the measured fatigue life with respect to the design S-N curves. The experimental measurement reveals that the fatigue crack propagation life contributes to a significant portion of the total fatigue life for both the hollow section tubular joints and the concrete-filled tubular joints. The total fatigue life of the test specimens complies with the life estimation based on the existing design S-N curves, originally developed for tubular joints fabricated using the complete joint penetration welds. The residual strength of the fatigue-cracked tubular joints follows approximately a linear relationship with respect to the percentage of the crack area along the brace-to-chord intersection.

1. Introduction

Concrete-filled steel sections have, over the recent years, become a popular approach to strengthen, reinforce and repair structural components on both onshore and offshore applications [1–7]. Prior research works have led to the development of comprehensive design guidelines [8] for the concrete-filled members focusing on their ultimate capacity under monotonic loading conditions. However, the fatigue failure of these concrete-filled structures, characterized by the initiation and propagation of fatigue cracks in the critical structural components, may impose a potential threat to the safety of these structures experiencing cyclic loadings caused by environmental actions, (e.g., on offshore structures), or traffic conditions, (e.g., on bridges). The fatigue assessment described in existing design guidelines, however, does not provide an explicit S-N curve for the concrete-filled welded tubular joints, due essentially to the lack of experimental data, required for the development of such S-N curves.

The understanding of the fatigue behavior of hollow section tubular joints has grown expansively over the last three decades, driven by extensive experimental works represented for example by the first and second phase of the United Kingdom Offshore Research Project [9,10]. Among the three types of S-N curves, namely the nominal stress S-N curve, the hot-spot stress S-N curve and the notch stress S-N curve, the hot-spot stress based S-N curve has evolved into a widely accepted and convenient approach which agrees closely with the experimental results [11,12]. Recent developments by Dong and his team [13,14] have advanced into a validated, mesh-insensitive structural stress approach to calculate the hot-spot stresses near the weld toe of the tubular joints. Dong's approach simplifies the procedure to calculate the hot-spot stresses in contrast to the conventional extrapolation method recommended in design guidelines [15], and bridges directly with the fracture mechanics assessment under mixed-mode conditions. Other experimentalists have recently uncovered some interesting findings on the fatigue performance of tubular joints. The fatigue tests on the welded tubular joints [16,17] have revealed a size effect on the estimated hot-spot stresses for tubular joints with large wall thicknesses. In contrast, Mashiri et al. [18] discuss the size effect on the fatigue life of thin-walled tubular joints with the wall thickness less than 4 mm. Their study highlights that the conventional S-N approaches may lead to unsafe estimations on the fatigue life for thin-walled tubular joints. In line with the experimentally validated hot-spot stress S-N approach and the fracture mechanics based Paris method [19] to estimate the fatigue life of tubular joints, a number of recent research efforts [20–25] have focused on developing reliable estimations of the stress concentration factors and the stress intensity factors for welded tubular joints. Barter et al. [26] have examined the crack growth behavior for a multi-planar XX-joint. The growing crack size indicates a linear relationship with respect to the number of applied

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Nomenclature

A_{crack}	crack area
E	elastic modulus
E_{con}	elastic modulus of concrete
N	number of cycles
N_i	fatigue crack initiation life
N_p	fatigue crack propagation life
N_t	total fatigue life
P	applied load
P_{max}	maximum load in a load cycle
P_{min}	minimum load in a load cycle
$P_{u,crack}$	ultimate strength of a cracked joint
$P_{u,intact}$	ultimate strength of an intact joint
R	load ratio
Z	loss factor
a	crack depth
d_0	outer diameter of the chord
d_1	outer diameter of the brace
g_{sh}	gap caused by autogenous shrinkage of concrete
r	radius of the burr grinding
t	member thickness
t_0	thickness of the chord
t_1	thickness of the brace
Φ	groove angle for the weld detail
ε_{hs}	hot-spot strain
θ	intersection angle between the brace and chord
ρ	position along the brace-to-chord section
σ_{hs}	hot-spot stress
σ_{nom}	nominal stress
σ_{notch}	notch stress
ψ	local dihedral angle
υ	Poisson ratio
ω	position angle measured in a plane perpendicular to the brace axis

cycles in a log–log scale. In addition to the fatigue performance of the tubular joints, a few other experimental works [27–29] have ascertained the residual strength of the circular hollow section (CHS) joints with a pre-existing surface-breaking or through-thickness crack, in an effort to deliver quantitative assessments on the static strength of cracked joints.

In contrast to the extensive works on the fatigue behavior of hollow section tubular joints, the public literature contains only limited studies on the fatigue performance of tubular connections with a concrete-filled chord member. Wang et al. [30] have concluded, from an experimental investigation of eleven circular hollow section T-joints with a concrete-filled chord, that the presence of the concrete material within the chord member leads to significant reductions in the measured stress concentration factors near the weld toe and therefore enhances the fatigue performance compared to the corresponding hollow section joints. Mashiri and Zhao [31] reported an experimental investigation on the fatigue of square hollow section (SHS) T-joints with a concrete-filled chord under cyclic in-plane bending actions. The concrete-filled SHS joints demonstrate improved fatigue strength compared to the hollow section SHS T-joints. Sakai et al. [32] have reported an experimental study on three fatigue tests of the concrete-filled tubular K-joints and the static tests for six concrete-filled and reinforced tubular K-joints. The presence of the normal strength concrete (with a 14-day compressive strength equal to 31 MPa) decreases significantly the stress concentration factors near the weld toes in the compression brace, but does not cause strong reductions of the SCF values near the weld toes of the tension brace.

More recently, Marshall et al. [33] have proposed a new set of welding details, namely the full capacity tubular joint welds, also known as the welder-optimized complete joint penetration (CJP) welds, to enhance the quality control and workmanship requirement in the otherwise complete joint penetration [34] welds commonly practiced for CHS joints. Qian et al. [35,36] have subsequently confirmed the fatigue performance of the welded circular hollow section X-joints fabricated using the proposed welding details. Qian et al. [37] have also demonstrated that the fracture mechanics based Paris law provides a close estimation of the fatigue crack propagation life compared to the monitored crack growth during the constant amplitude load tests.

This study aims to examine both the fatigue performance and the residual strength of the CHS X-joints with a concrete-filled chord member, fabricated using the full capacity tubular joint welds. The experimental program follows a similar procedure previously reported for the hollow section tubular X-joints [35,36]. This paper compares the fatigue performance of the X-joint with a concrete-filled chord and that of the hollow section X-joint with the design S-N curves originally developed for the hollow section tubular joints fabricated using the CJP welds. The experimental program also investigates the residual capacity of the fatigue cracked tubular joints through a monotonic load test following the constant-amplitude fatigue test.

This paper starts with a brief introduction on the full capacity tubular joint welds. The next section describes the experimental program for the large-scale CHS X-joint with a concrete-filled chord. The following section discusses the experimental findings on the stress concentration factors, the observed crack initiation and propagation in the joint specimen and the comparison with different design S-N curves for the X-joint specimens. The subsequent section presents the residual strength of the fatigue cracked X-joints under the monotonically increasing brace in-plane bending. The last section summarizes the main conclusions drawn from the current study.

2. Full capacity tubular joint welds

Marshall et al. [33] present a new type of welding details for the circular hollow section connections, namely the full capacity tubular joint welds, also known as the welder-optimized CJP-equivalency welds. Fig. 1 illustrates the typical details of the full capacity tubular joint welds for various ranges of the local dihedral angle, ψ, along the brace-to-chord intersection. The local dihedral angle, ψ, refers to the angle formed by the tangent to the outer surface of the brace and that to the outer surface of the chord, intersecting at the weld line, as illustrated in Fig. 1. The full capacity tubular joint welds make use of a part of the brace wall as the inherent backing plate to enhance the quality control at the root of the welds, in contrast to the conventional complete joint penetration welds, which require high-quality workmanship of the welder. The strength requirement on the welds and therefore on the weld volume leads to a large groove angle so as to accommodate sufficient welding deposits in the full capacity tubular joint welds. This large groove angle facilitates the welding procedure especially for brace-to-chord intersections with a small local dihedral angle (ψ in Fig. 1). Previous experimental programs [35,36] have reported the fatigue performance of circular hollow section X-joints with different post-weld treatments subjected to constant-amplitude cyclic actions and overloading conditions. The previous experimental efforts confirm that the toe cracking near the hot-spot locations prevails in the circular hollow section X-joints fabricated with the full capacity tubular joint welds. Root cracking does not initiate unless the post-weld treatment has significantly delayed the initiation of the weld toe cracks.

3. Experimental program and numerical investigation

3.1. Experimental study

The entire experimental program to examine the fatigue performance of the full-capacity tubular joint welds consists of five specimens, as indicated in Table 1. All five specimens have the same chord length and brace