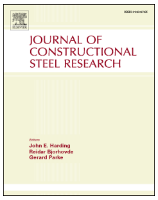
Journal of Constructional Steel Research 145 (2018) 397–413

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Hysteretic behaviour of overlapped tubular k-joints under cyclic loading

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ARTICLE INFO

Article history:
Received 1 July 2017
Received in revised form 13 January 2018
Accepted 25 February 2018
Available online xxxx

Keywords:
Overlapped CHS K-joints
Hidden weld
Cyclic loading
Hysteretic behaviour
Joint ductility
Energy dissipation

ABSTRACT

Overlapped K-joints arise in truss type structures when one diagonal (overlap brace) intersects the other diagonal (through brace). In such joints, part of the through brace is hidden within the overlap brace, and the hidden toe of the through brace may or may not be welded to the chord. This study investigates the hysteretic behaviour of partially overlapped circular hollow section K-joints, with and without hidden welds, under cyclic loading. This study involved nine full-scale specimens, out of which four specimens had hidden welds. One joint was statically loaded and the remaining eight joints were cyclically loaded until failure. Chord plastification, brace local buckling, and cracking of the brace adjacent to welds were observed in these tests. The hysteretic performance indicators, such as ultimate capacity, joint ductility, energy dissipation, ultimate stiffness, etc., were established, which were then used to understand the hysteretic behaviour of overlapped K-joints. Results show that, compared with static loading, brace cracking occurred more easily under cyclic loading with a reduced joint capacity of up to 7% and a severely decreased ductility. Joints with hidden welds may exhibit a higher strength by approximately 10% and an increased hysteretic energy dissipation capacity, but with a reduction in joint ductility. The analysis of strain distributions around the joint zone indicates that, even though the joints with hidden welds experience lower strains, the hidden weld creates an asymmetric strain profile in the joints, which may be a weakness as some locations may become stress raisers leading to crack initiation.

1. Introduction

Hollow structural sections (hollow circular, square or rectangular, elliptical, etc. in shape) are some of the most popular structural members for buildings, bridges, offshore structures, etc. Beneficial properties such as, high strength-to-weight ratio, high axial resistance, high torsional resistance, aesthetic appeal, etc., give inherent advantage for them to be used widely as major structural members such as, beams, columns, truss chords, truss braces (diagonals), etc. Engineers involved with the design and construction of structures consisting of hollow structural sections are fully aware that connections of such members need to be designed with care, and that the connection may be weaker than the members and thus may govern the capacity of the entire structure. The majority of truss connections have one compression diagonal member and one tension diagonal member welded to the chord, forming a joint commonly known as the K-joint. The capacity of a K-joint is influenced by many factors including the geometry of the joint, the member profiles (circular, square or rectangular), the size and thickness of the chord member, the size and thickness of the diagonals (braces), and whether an axial compression is present in the chord. Overlapped K-joints arise when one diagonal (overlap brace) intersects the other diagonal (through brace), requiring a weld between the braces. Furthermore, part of the through brace is hidden within the overlap brace, and the hidden toe of the through brace may or may not be welded to the chord. This study investigates the hysteretic behaviour of partially overlapped tubular (circular hollow section) 60° K-joints, with and without hidden welds, under cyclic loading.

Considerable studies exist on the static behaviour of Circular Hollow Section (CHS) K-joints. Kurobane et al. [1] established a database of experimental results on tubular joints and suggested a unified formula to estimate the ultimate strength of both gap and overlapped CHS K-joints. Zhao et al. [2] had also experimentally investigated the static behaviour of overlapped CHS K-joints and the impact of the hidden weld. They found out that the hidden weld has a limited effect on the static strength of overlapped CHS K-joints, but may influence the failure mode. Dutta et al. [3] suggested that the hidden weld can be neglected if the vertical load components of static load in the two braces do not differ by more than 20%. Dexter and Lee [4,5] presented an extensive finite element study into the static behaviour of CHS K-joints. They also studied the effects of geometric parameters and developed a unified strength formula for gap and overlapped CHS K-joints. Different institutions worldwide have developed design guides for such overlapped K-joints and the design recommendations are not always consistent. The American Petroleum Institute [6] and Eurocode 3 [7] suggested a unified formula

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https://doi.org/10.1016/j.jcsr.2018.02.035
0143-974X/

List of notations

E	Young's modulus
N_{by}	cross-section yielding capacity of the through brace of an overlapped K-joint specimen
N_y	yield strength of an overlapped K-joint specimen
N_u	peak load of an overlapped K-joint specimen
N_{GB}, N_{EC3}, N_{IIW}	Capacity of an overlapped K-joint specimen calculated by GB50013, Eurocode3 or IIW (2012)
Ov	q/p, overlap ratio
d_c	chord diameter
d_T	through/overlap brace diameter
f_y	yield stress
f_u	ultimate stress
k_d	initial stiffness
k_u	ultimate stiffness
l_c	chord length
p	$\sin\theta/d_T$, the projected length of the overlap brace on the chord
q	the length of the projected overlap of the braces onto the chord
t_c	chord wall thickness
t_L	overlap brace wall thickness
t_T	through brace wall thickness
α	$2l_c/d_c$, chord length parameter
β	d_T/d_c, diameter ratio between the braces and chord
γ	$d_c/2t_c$, half diameter to thickness ratio of the chord
δ_y	deformation corresponds to N_y
δ_u	deformation corresponds to N_u
ε_1, ε_2	first and second principal strain components
ε_u	von Mises strain
ε_y	f_y/E, yield strain
μ	δ_u/δ_y, ductility ratio
θ	in-place brace angle
τ_L	t_L/t_c, wall thickness ratio between the through brace and chord
τ_T	t_T/t_c, wall thickness ratio between the overlap brace and chord

for CHS K-joints regardless of their configurations. The International Institute of Welding (IIW) [8] suggested an ultimate strength formula for CHS overlapped K-joints incorporating the local yielding failure of braces, thereby seeming to imply the dominance of the braces on the ultimate strength of overlapped CHS K-joints. The Chinese code GB50017–2003 [9], Packer et al. [10], and the design guides by Dutta et al. [3] and Wardenier et al. [11], may also be consulted. All of the above design guides do not require the hidden weld, thus the hidden seam may be left unwelded for statically loaded braces with substantially balanced loads, provided the remaining welds are designed to develop the capacity of the connected brace walls.

As became evident from the inadequate performance of moment connections of steel building frames during the Northridge earthquake, the hysteretic characteristics of tubular K-joints would be of importance when such joints are located in highly seismic zones. In 2001, Qin et al. [12] conducted cyclic tests on completely overlapped tubular joints. Based on the observation of the failure mode of the joints during these experiments, Qin et al. [12] provided hysteretic curves and established other indicators in order to assess the performance of the joints. Other noteworthy cyclically loaded experimental investigations on tubular T-, N-, X- and KK-joints include Wang and Chen [13], Yin et al. [14], Wang et al. [15,16]. These studies included cyclic axial loads and cyclic bending moments, and these studies noted that the joint cracks always appeared adjacent to intersecting areas. Hitherto, however, there are inadequate studies on the hysteretic behaviour of overlapped K-joints in general, and the influence of hidden welds on the cyclic behaviour of such joints in particular.

While numerical simulations have been used successfully to investigate the static behaviour of joints, such numerical simulations of cyclic behaviour of joints, which involve consideration of damage accumulations and propagations of cracks, are a considerable challenge. The results presented herein are based on an experimental study by Xu [17] and Zhao et al. [18] on the hysteretic behaviour of overlapped CHS K-joints. This study involved nine full-scale overlapped K-joint specimens, out of which four specimens had the hidden seam welded. Even though the hidden seam weld will add to the construction cost, it is of engineering interest to investigate the potential influence of the hidden weld on the structural behaviour and the strength of overlapped K-joints. Based on these cyclic tests, performance indicators, such as ductility ratio, energy dissipation, ultimate stiffness, etc., were established which were then used to understand the hysteretic behaviour of overlapped K-joints. The primary objective of this investigation is to establish the impact of hidden welds in overlapped circular hollow section K-joints on the hysteretic behaviour and the strength of such joints.

2. Experimental study

2.1. The test specimens

Fig. 1 shows the configuration of a typical test specimen, which represents an overlapped CHS K-joint subassembly of a truss structure, consisting of a 1025 mm long through brace and a 1025 mm long overlap brace connected at the centre of a 2650 mm long chord segment. Both braces are considered to be of the same size, whereas the chord size varied. Both braces were oriented such that the angle between the braces and the chord was $\theta = 60°$ and the centrelines met at the node, thereby creating a zero eccentricity. The through brace was first welded only to the chord, with some test specimens having the hidden seam welded and the remaining specimens with no hidden weld. The overlap brace was then welded both to the chord and to the through brace. The experimental investigation presented herein considered a total of nine such CHS K-joints. One test specimen, identified herein as JD1, was subjected to increasing static loading establishing the benchmark results, whereas the remaining eight specimens, identified herein as JD2 thru JD9, were subjected to a cyclic testing protocol. Table 1 shows pertinent geometric details associated with these nine test joints. As shown in Table 1, Column 2, the chord member of the test specimen was either $\phi 203 \times 8$ or $\phi 203 \times 12$. Thus, the outer diameter d_c of the chord members was always 203 mm and the nominal wall thicknesses were 8 mm and 12 mm, respectively. The chord length parameter may be defined as $\alpha = 2l_c/d_c$, where l_c is the test specimen length of the chord and d_c is the diameter of the chord. The chord length parameter for the test specimens under consideration is $\alpha = 26.1$ which, as discussed by Choo, et al. [19], is an appropriate dimension in order to represent real structures and to eliminate the end effects that may arise on the chord. The actual thickness of the chord members was measured and is shown in Table 1, Column 3 as t_c. The geometric parameter of the chord member $\gamma = d_c/2t_c$, which is the nominal radius-to-measured thickness ratio of the chord, is shown in Table 1, Column 4, which ranged between 8.05 and 14.18. Both the through brace and the overlap brace of each test specimen were of same nominal size, and as listed in Table 1, Column 5, three different brace sizes, namely $\phi 168 \times 6$, $\phi 168 \times 10$ and $\phi 133 \times 6$, were used. The amount of overlap between the braces can be quantified through an overlap ratio, $\mathrm{Ov} = q/p$, which is defined [11] as the ratio between the length of the projected overlap of the braces onto the chord (q) and the projected length of the overlap brace on the chord (p). The overlap ratios (Ov) corresponding to these brace-chord combinations are 40% and 24%, for $\phi 168$ and $\phi 133$ braces, respectively. The geometric parameter $\beta = d_T/d_c$, which is the diameter ratio between the braces and chord,