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Structural behavior of cold-formed stainless steel bolted connections

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ABSTRACT

This paper presents a series of tests on cold-formed stainless steel bolted connections. The test specimens were fabricated from three different types of stainless steel, including austenitic stainless steel EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti having small amount of titanium) as well as lean duplex stainless steel EN1.4162 (AISI S32101). The material properties of the three types of stainless steel were determined by tensile coupon tests. Stainless steel single shear and double shear bolted connections with different bolt diameter and bolt arrangement were tested. Two main failure modes were observed in the bolted connection tests, namely the bearing and net section tension failures. The test strengths were compared with the nominal strengths calculated using the American Specification, Australian/New Zealand Standard and European codes for stainless steel structures. It is shown that the nominal strengths predicted by these specifications are generally conservative. Furthermore, the failure modes observed from the tests were also compared with the failure modes predicted by the specifications. It is shown that the failure modes predicted by the European codes are more accurate than the American and Australian/New Zealand predictions.

1. Introduction

The desirable characteristics of stainless steel, such as attractive appearance, corrosion resistance, better fire resistance as compared to carbon steel, low maintenance and so on, can be exploited in a wide range of construction applications [1,2]. A comprehensive discussion of these characteristics and the application of stainless steel in structural design have been reported by Gardner [3]. Bolted connection is one of the common types of connection in cold-formed steel construction. The design rules of stainless steel bolted connections are available in the current design specifications, i.e. the American Specification (ASCE) [4], Australian/New Zealand Standard (AS/NZS) [5] and Eurocode 3 Part 1.4 (EC3-1.4) [6]. However, the design rules in these specifications are mainly based on the rules of carbon steel with small modifications as experimental works of stainless steel bolted connections were relatively limited [7]. Tests of carbon steel bolted connections were conducted by researchers such as Zadanfarrokh [8], Rogers and Hancock [9–11] and Chung [12]. The behavior of austenitic stainless steel type EN1.4306 (AISI 304L) bolted connections was investigated by Bouchaïr et al. [13]. It should be noted that experimental investigation on stainless steel bolted connections is limited so far. Furthermore, the stress–strain behavior of stainless steel is fundamentally different from that of carbon steel [3]. Therefore, it is important to investigate the structural behavior of bolted connections of stainless steel.

In this study, the connection specimens were fabricated from three different types of stainless steel, including austenitic stainless steel EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti, containing 0.34% titanium as specified in the STALA Tube mill certificate) as well as lean duplex stainless steel EN1.4162 (AISI S32101). Lean duplex stainless steel is a relatively new material in the family of stainless steel. It is a high strength material having the nominal yield stress (0.2% proof stress) of 450 MPa. The lean duplex material cost is much lower than the duplex material. Up to date, no test has been reported on lean duplex stainless steel bolted connections. It should be noted that the current design specifications do not cover the design of lean duplex. In this study, the material properties of the three types of stainless steel were determined by tensile coupon tests. Stainless steel single shear and double shear bolted connection tests were conducted on the three types of stainless steel by varying the size of bolt, the number of bolt and the arrangement of bolt. The test strengths were compared with the nominal strengths obtained using the ASCE Specification [4], AS/NZS Standard [5] and Eurocodes [6,14]. In addition, the failure modes observed from the tests were also compared with the failure modes predicted by these specifications.

2. Experimental investigation

2.1. Test specimens

Three types of cold-formed stainless steel were investigated in this study, including austenitic stainless steels EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti having small amount of titanium) as well

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Nomenclature

d	nominal diameter of stainless steel bolt
d_0	nominal diameter of bolt hole
E	initial elastic Young's modulus
e_1	end distance; the end distance from the center of a bolt hole to the adjacent end of any part, in the direction of load transfer
e_2	edge distance; the edge distance from the center of a bolt hole to the adjacent edge of any part, measured at right angles to the direction of load transfer
$F_{b,Rd}$	the design bearing resistance of the connection part from EC3-1.8
F_p	nominal bearing stress from ASCE Specification and AS/NZS Standard
F_t	nominal tension stress from ASCE Specification and AS/NZS Standard
$f_{0.2}$	longitudinal 0.2% proof stress
$f_{0.2,mill}$	longitudinal 0.2% proof stress stated in mill certificate
$f_{0.2,EC}$	longitudinal 0.2% proof stress from EC3-1.4
f_u	longitudinal tensile strength
$f_{u,EC}$	longitudinal tensile strength from EC3-1.4
$f_{u,mill}$	longitudinal 0.2% proof stress stated in mill certificate
$f_{u,red}$	reduced value of bearing strength from EC3-1.4
h	height of lip in the connection specimen
L_1	the length of specimen plate; the length of middle specimen plate for double shear connection
L_2	the length of lip in the specimen plate
$N_{pl,Rd}$	the plastic resistance of the cross-section in connection from EC3-1.4
$N_{u,Rd}$	the ultimate resistance of the cross-section in connection from EC3-1.4
n	exponent in the Ramberg–Osgood expression
P_{ASCE}	nominal strength of bolted connection predicted using ASCE Specification
$P_{AS/NZS}$	nominal strength of bolted connection predicted using AS/NZS Standard
P_{EC}	nominal strength of bolted connection predicted using European Codes
P_{exp}	experimental ultimate load of connection (test strength)
P_s	test shear resistance of stainless steel bolt
$P_{s\text{-}ave}$	average shear resistance of tested stainless steel bolts
p_1	longitudinal spacing; the spacing between centers of bolt holes in a line in the direction of load transfer
p_2	transverse spacing; the spacing measured perpendicular to the load transfer direction between centers of bolt holes
W	nominal width of connection specimen
t	nominal thickness of stainless steel tube
t_m	measured thickness of stainless steel plate
ε	elongation (longitudinal tensile strain) after fracture

as lean duplex stainless steel EN1.4162 (AISI S32101). The austenitic stainless steels have a lower strength than the lean duplex material. The lean duplex stainless steel is considered as high strength material and the austenitic stainless steels as normal strength materials. For simplicity, these three types of stainless steels, EN1.4301 (AISI 304), EN1.4571 (AISI 316Ti) and EN1.4162 (AISI S32101) are labeled as types A, T and L, respectively, in the context of this paper.

The coupon test specimens and connection test specimens were both cut from the same batch of stainless steel rectangular hollow sections. The stainless steel hollow sections were supplied from STALA Tube Finland in uncut lengths of 3000 mm and nominal section size of $20 \times 50 \times 1.5$ mm (width × depth × thickness). The coupon specimens were extracted from the same side of the hollow sections as the connection specimens, which is located at the center of the 50 mm. The single shear and double shear bolted connections were tested with stainless steel washers in both sides of the bolt. The two-bolted test specimens of the assembled connected parts are illustrated in Fig. 1. The single shear connection specimen is bolted with two plates together having one shear plane, while the double shear connection specimen is bolted with three plates having two shear planes. It should be noted that the connection specimens were designed with lips as shown in Figs. 1 and 2. Previous researchers found that standard flat specimens curled out of plane and affected the mode of failure [11] and may not accurately represent the true behavior of profiled structural members, for example channel sections. Therefore, lips of nominal 10 mm height were used in the connection specimens to prevent the out-of-plane curling at the overlapped connection region in this study. The height of lips (h) was determined by 1/5 of the width of the stainless steel connection specimens, which is similar to the carbon steel connection specimens [15,16]. The length (L_2) of the lips was equal to the sum of "$2e_1$"and the length from the center of the most inner bolt hole to the center of end bolt hole in the longitudinal direction in this study. The nominal width and thickness of each connection specimen were 50 mm and 1.5 mm, respectively. They were cut from the stainless steel tubes with a specified length. The length of the specimen plates

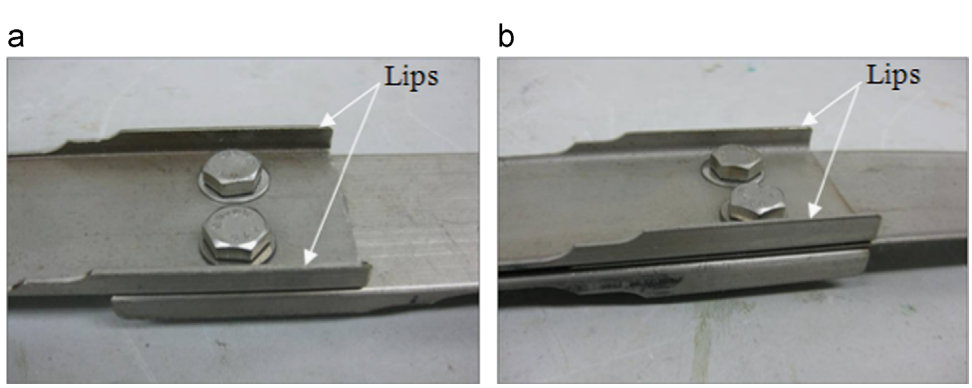

Fig. 1. Test specimens of two-perpendicular bolted connections. (a) Single shear and (b) double shear.