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Fire resistance of stainless steel single shear bolted connections

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ABSTRACT

This paper presents a numerical investigation on single shear bolted connections of cold-formed stainless steel (CFSS) at elevated temperatures. A finite element model (FEM) is developed and verified against the existing single shear bolted connection tests. It is shown that the FEM is able to predict the test strengths and failure modes of the bolted connections. Therefore, the verified FEM was used to perform a parametric study of 225 CFSS single shear bolted connections at 5 different temperature levels. Based on both the test and numerical results, two sets of bearing factors are proposed for the bearing strengths of CFSS single shear bolted connections at elevated temperatures by considering the equivalent plastic strains in the bolt hole and the bolt hole deformation. The connection bearing strengths obtained from the tests and numerical analyses were compared with the nominal strengths calculated using the current international stainless steel specifications. In this study, modified design rules are proposed. In calculating the nominal strengths of the bolted connections, the reduced material properties of CFSS were used due to the effects of elevated temperatures. It is shown that the predictions provided by the modified design rules are more accurate than the predictions provided by the current design rules for bearing strengths of CFSS single shear bolted connections at elevated temperatures. Reliability analysis was also performed to assess the reliability of the current and modified design rule.

1. Introduction

In recent years, significant progress has been made in developing design rules for stainless steel structures at room (ambient) temperature, but the performance of fire resistance has received less attention [1]. Bolting is commonly used in assembling carbon steel and stainless steel members in construction. The current stainless steel design specifications, such as the American Society of Civil Engineers Specification [2], Australian/New Zealand Standard [3] and European Code 3 Part 1.4 (EC3-1.4) [4] provide design rules for bolted connections. However, these current design rules are mainly based on the design rules of carbon steel with small modifications [5], despite fundamental differences between the mechanical behavior of stainless steel and carbon steel. Furthermore, the current design rules are only applicable at room temperature condition but not for elevated temperature.

Structural behavior of stainless steel bolted connections have recently been tested by Kim and Cho [6], Lim et al. [7], Cai and Young [8] and numerically investigated by Kim and Kuwamura [9], Bouchaïr et al. [10], Kim et al. [11], Kiymaz [12], Salih et al. [5], Kim and Kuwamura [13], Salih et al. [14,15], Kim and Lim [16]. These investigations were focused on the performances of stainless steel bolted connections at ambient temperature (room temperature) condition only. Furthermore, a recent review on carbon steel bolted connections to tubular columns showed that studies on bolted connections at elevated temperatures are limited compared with those at room temperature [17]. Hundreds of cold-formed stainless steel (CFSS) single shear and double shear bolted connections were tested at elevated temperatures using steady state test method and transient state test method by Cai and Young [18–20]. It is found that the bolted connection strengths predicted by the current stainless steel design rules [2–4] generally underestimate the bearing strengths at elevated temperatures, despite of using the reduced material properties of stainless steel due to high temperatures. The bearing factors for double shear bolted connections of cold-formed stainless steel at elevated temperatures have been proposed by Cai and Young [21] based on the test and numerical results. However, there is presently no design rule of CFSS single shear bolted connections at elevated temperatures. Therefore, an investigation on the CFSS single shear bolted connections at elevated temperatures was performed with aiming to propose design rules in this study.

In this study, the appropriateness of the current design rules is investigated for the bearing strengths of CFSS single shear bolted connections at elevated temperatures. A finite element model (FEM) using the static analysis in ABAQUS program [22] for CFSS single shear bolted connections was developed and verified against existing connection test results at elevated temperatures. An extensive parametric study was carried out to investigate the structural behavior of CFSS

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Notation

The following symbols are used in this paper:

C	bearing factor;
DL	dead load;
d_0	nominal diameter of bolt hole;
d	nominal diameter of bolt;
E_N	elastic modulus;
e_1	end distance that is the end distance from the centre of a bolt hole to the adjacent end of any part in the direction of load transfer;
e_2	edge distance that is the edge distance from the centre of a bolt hole to the adjacent edge of any part that measured at right angles to the direction of load transfer;
$f_{0.2}$	longitudinal 0.2% tensile proof stress;
F_m	mean value of fabrication factor;
f_u	longitudinal tensile strength;
$f_{u,red}$	reduced ultimate tensile strength;
K	strength constant;
LL	live load;
l	length of specimen plate;
m	strain hardening exponent;
P	bearing strength corresponding to critical end displacement predicted from FEA;
P_{ASCE}	nominal strength of bolted connection based on ASCE Specification;
P_b	defined bearing strength predicted from FEA;
$P_{FEA,bh}$	bolt hole deformation-based bearing strength of connection predicted from FEA;
P_{EC}	nominal strength of bolted connection based on Eurocodes;
$P_{FEA,sb}$	bolt hole strain-based bearing strength of connection predicted from FEA;
P_m	mean value of variation of FEA and tested-to-predicted strength ratio;
P_{max}	maximum connection strength of connection predicted from FEA;
P_n	nominal bearing strength of bolted connection;
P_{p1}	predicted bearing strength calculated using proposed bearing factor based on true plastic strains in the bolt hole;
P_{p2}	predicted bearing strength calculated using proposed bearing factor with considering 6.4 mm bolt hole deformation;
P_t	ultimate strength of connection obtained from test result;
p_1	longitudinal spacing that is the spacing between centers of bolt holes inline with the direction of load transfer;
p_2	transverse spacing that is the spacing measured perpendicular to the load transfer direction between centers of bolt holes;
t	thickness of the connection plate;
w	nominal width of specimen plate;
M_m	mean value of material factor;
V_M	coefficient of variation of material factor;
V_F	coefficient of variation of fabrication factor;
V_P	coefficient of variation of FEA and tested-to-predicted strength ratio;
α	reference element in the bolt hole of FEM;
β	reliability index;
β_1	reliability index determined using ϕ_1;
β_2	reliability index determined using ϕ_2;
Δ_{bh}	bolt hole deformation;
ε	engineering strain;
ε_{ep}	equivalent plastic strain of the element;
$\varepsilon_{ep,max}$	maximum equivalent plastic strain of the element;
ε_{true}^{pl}	true plastic strain;
δ_{cr}	critical end displacement of bolted connection;
δ_{max}	end displacement of bolted connection at ultimate strength predicted from FEA;
σ	engineering stress;
σ_{true}	true stress;
$\sigma_{u,true}$	true ultimate stress;
ϕ	resistance (capacity) factor;
ϕ_1	resistance (capacity) factor specified in the current specifications;
ϕ_2	resistance (capacity) factor specified in this study (ϕ_2 = 0.70).
γ_{m2}	partial resistance (safety) factor in Eurocodes.

single shear bolted connections by using the verified FEM. Bearing factors were proposed for the bearing strengths of CFSS single shear bolted connections at elevated temperatures based on both the test results and numerical results. In this study, two sets of bearing factors are proposed based on the equivalent plastic strains in the bolt hole and the bolt hole deformation of the connections. Reliability analysis was also performed to examine the reliability of the current and modified design rules for CFSS single shear bolted connections.

2. Summary of test program

The test program of CFSS single shear bolted connections conducted by Cai and Young [8] at room temperature and Cai and Young [18,19] at elevated temperatures provided the experimental ultimate strengths and failure modes of the bolted connections. The specimens were fabricated from three different grades of CFSS, namely the austenitic stainless steel EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti having small amount of titanium) as well as lean duplex stainless steel EN 1.4162 (AISI S32101). For simplicity, the three types of CFSS, EN 1.4301 (AISI 304), EN 1.4571 (AISI 316Ti) and EN 1.4162 (AISI S32101) are labelled as types A, T and L, respectively, in the context of this paper. The material properties were determined by tensile coupon tests from room temperature of 22 °C to high temperature of 950 °C. The coupon tests were conducted under steady state test method. Table 1

Table 1
Material properties for different grades of stainless steel [21].

Series	Temperature (°C)	E (GPa)	$f_{0.2}$ (MPa)	f_u (MPa)	K (MPa)	m
A	22	199	474	759	1760	0.47
	205	190	382	526	909	0.21
	351	184	338	499	900	0.23
	496	177	317	470	808	0.21
	648	146	257	351	619	0.22
	800	115	156	163	243	0.08
	950	64	61	65	87	0.05
T	22	199	463	677	1319	0.30
	206	189	388	520	910	0.22
	356	188	372	519	997	0.27
	498	181	348	506	944	0.25
	645	165	308	420	675	0.17
	800	113	246	258	413	0.10
	950	72.4	94	97	116	0.03
L	22	200	724	862	1623	0.26
	206	190	564	710	1122	0.16
	356	183	508	696	1176	0.18
	501	169	448	627	976	0.15
	652	160	304	358	589	0.17
	795	60.4	119	138	255	0.14
	948	13.5	18	25	35	0.09

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