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Bearing resistance design of stainless steel bolted connections at ambient and elevated temperatures

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Abstract. In recent years, significant progress has been made in developing design rules for stainless steel members, while the investigation on bolted connections is relatively limited, in particular at elevated temperatures. In this paper, experimental and numerical investigations on stainless steel bolted connections at ambient and elevated temperatures from the literature were reviewed. Firstly, the research program that focused on structural behavior of cold-formed stainless steel (CFSS) bolted connections at elevated temperatures carried out by the authors were summarized. Over 400 CFSS single shear and double shear bolted connection specimens were tested. The tests were conducted in the temperature ranged from 22 to 950℃ using both steady state and transient state test methods. It is shown that the connection strengths decrease as the temperature increases in the similar manner for the steady state test results and the transient state test results. Generally, the deterioration of the connection strengths showed a similar tendency of reduction to those of the material properties for the same type of stainless steel regardless of different connection types and different configurations. It is also found that the austenitic stainless steel EN 1.4571 generally has better resistance than the stainless steel EN 1.4301 and EN 1.4162 for bolted connections at elevated temperatures. Secondly, extensive parametric studies that included 450 specimens were performed using the verified finite element models. Based on both the experimental and numerical results, bearing factors are proposed for bearing resistances of CFSS single shear and double shear bolted connections that subjected to bearing failure in the temperature ranged from 22 to 950℃. The bearing resistances of bolted connections obtained from the tests and numerical analyses were compared with the nominal strengths calculated from the current international stainless steel specifications, and also compared with the predicted strengths calculated using the proposed design equations. It is shown that the proposed design equations are generally more accurate and reliable than the current design rules in predicting the bearing resistances of CFSS (EN 1.4301, EN 1.4571 and EN 1.4162) bolted connections at elevated temperatures. Lastly, the proposed design rules were further assessed by the available 58 results of stainless steel bolted connections subjected to bearing failure in the literature. It is found that the proposed design rules are also applicable to the bearing resistance design of other stainless steel grades, including austenitic stainless steel (EN 1.4306), ferritic stainless steel (EN 1.4016) and duplex stainless steel (EN 1.4462).

Keywords: bearing strength; bolted connection; cold-formed stainless steel; elevated temperatures; steady state tests; transient state tests

1. Introduction

In recent years, significant progress has been made in developing design rules for stainless steel structures at room temperature, but the performance of fire resistance has received less attention (Gardner and Baddoo 2006). These research works mainly focused on the structural behaviour and design of stainless steel members, e.g., beams (Chang *et al*. 2010, Huang and Young 2014, Theofanous and Gardner 2010) and columns (Ellobody and Young 2007, Theofanous and Gardner 2012, Young and Ellobody 2006). Bolt connection is one of the most commonly used connection types in carbon steel and stainless steel structures. The design rules of stainless steel bolted connections are available in current specifications, such as the American Society of Civil Engineers Specification (ASCE) (2002), Australian/New Zealand Standard (AS/NZS) (2001) and European Code 3 Part 1.4 (EC3-1.4) (2006). However, the stainless steel bolted connection design rules in the current international specifications are mainly based on the rules of carbon steel with small modifications due to the limited investigation (Salih *et al*. 2010), despite the fundamental differences between the mechanical behaviour of stainless steel and carbon steel. It should be noted that these current design rules are applicable at room (ambient) temperature condition only, and the application to elevated temperatures is questionable.

Compared with those of stainless steel, lots of works have been conducted to investigate the structural behaviour of carbon steel bolted connections. The investigations were recently extended to the connection behaviour in composite structures, e.g., bolted connections with concrete-filled steel tubular columns (Beena *et al*. 2017, Agheshlui *et al*. 2017) and bolted connections with end-plate into reinforced concrete columns (Li *et al*. 2018). In the last decade, experimental and numerical investigations on the structural

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behaviour of stainless steel bolted connections have been getting more attention. Kim and Cho (2013) tested the influence of microstructure difference of stainless steels on the behaviour of bolted connections. Cai and Young (2014a) assessed the bolted connection design rules in current stainless steel specifications (ASCE 2002, AS/NZS 2001, EC3-1.4 2006) by conducting a series of tests on cold-formed stainless steel (CFSS) single shear and double shear bolted connections. There are relatively more numerical investigation than experimental investigation on the structural behaviour of stainless steel bolted connections, including the effects of the connection end distances by Bouchaïr *et al*. (2008), the effects of plate curling by Kim and Kuwamura (2007) and by Kim *et al*. (2008), the bearing failure by Kiymaz (2009) and by Salih *et al*. (2011), the net section failure by Salih *et al*. (2010, 2013).

These investigations were mainly focused on the performances of stainless steel bolted connections at room temperature condition, but not at high temperature conditions. It should be noted that fire safety is one of the critical scenarios in the design of carbon and stainless steel structures due to the strength and stiffness deterioration at elevated temperatures. 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 ambient temperature (Leong *et al*. 2016). On the other hand, there is a need to investigate the stainless steel bolted connections at high temperatures and propose design rules.

In this paper, firstly, a research program that focused on the structural behaviour of CFSS bolted connections at ambient and high temperatures carried out by the authors was summarized. Over 400 CFSS bolted connection specimens were tested at both room and elevated temperatures. Both steady state test method and transient state test method were used in the experimental investigation. In addition, 450 numerical results were generated based on the calibrated finite element models that verified again over 200 test results. Based on the experimental and numerical results, the structural performance of CFSS bolted connections at elevated temperatures was investigated. New bearing factors with and without considering bolt hole deformation were proposed for the bearing resistance design of CFSS single shear and double shear bolted connections that subjected to bearing failure at elevated temperatures. Lastly, the proposed design rules (Cai and Young 2016) were further examined by the available results of stainless steel bolted connections subjected to bearing failure from the data in the literature. It should be noted that these results were obtained at ambient temperature condition only. The stainless steel bolted connection results that satisfied the spacing requirements in the proposed design rules (Cai and Young 2016) were used regardless of stainless steel grades and connection plate thickness. It was found that the proposed design rules were generally accurate and reliable for the bearing resistance design of stainless steel bolted connections.

2. Experimental investigation conducted by Cai and Young

2.1 General

Three different grades of CFSS were involved in this study, namely the austenitic stainless steel EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti), as well as the lean duplex stainless steel EN 1.4162 (AISI S32101). The lean duplex stainless steel EN 1.4162 is a relatively new high strength material, while the austenitic stainless steels EN 1.4301 and EN 1.4571 have a lower strength than lean duplex material. The type EN 1.4571 having small amount of titanium has good resistance at high temperature. For simplicity, the three types of stainless steels, EN 1.4301, EN 1.4571 and EN 1.4162 are labeled as types A, T and L, respectively, in the context of this paper.

2.2 Test methods and procedures at elevated temperatures

The steady state test method and transient state test method were adopted for the CFSS single shear and double shear bolted connections at elevated temperatures. For the steady state tests, the specimen was firstly set-up with clamping the top end, while keeping the bottom end free. The external thermal couple was inserted inside the furnace and contacted on the surface of the specimen in the middle of the overlapped part. The temperature obtained from the external thermal couple was recorded as the specimen temperature. The furnace was then closed and the temperature was raised to a pre-selected level. The thermal expansion of the specimen was allowed by the free bottom end of the specimen during the heating process. Once the pre-selected temperature was reached, the temperature was hold for a period of 8 to 15 minutes, such that allows the temperature to stabilize and the heat to transform uniformly in the specimen, and then the bottom end of the specimen was gripped. The bolted connection tests were conducted by displacement control with the loading rate of 1.5 mm/min. For the bolted connections tested at room temperature condition, displacement control with the same loading rate was used, while the furnace was not used. Details of the steady state testing procedure were described in Cai and Young (2014b and 2015)

For the transient state test, the specimen is loaded by a specified constant force in 1-3 min. Hence, the required pre-selected load level on the connection specimen can be obtained. The load was then maintained for approximately 1 min to ensure the load level stabilizes. Once the load on the connection specimen is stabilized, then the temperature rises in accordance with the heating rate following the ISO standard fire curve specified in EC1-1.2 (2002) until the specimen fails. Similar to the steady state tests, the temperature obtained from the external thermal couple that contacted on the surface of the specimen in the middle of the overlapped part was recorded as the specimen temperature. The force control procedure was used during the entire process in order to maintain the load constant. Details of the transient state testing procedure were described in Cai and Young (2014c and 2015)

Table 1 Material properties of CFSS at room temperature (Cai and Young 2014a)

Stainless steel	Grade	E_N	$f_{0.2,N}$	$f_{u,N}$	$\varepsilon_{u,N}$	$\varepsilon_{f,N}$	n
		GPa	MPa	MPa	%	%	
Austenitic	A (EN1.4301)	199	474	759	45.2	52.6	5
	T (EN1.4571)	199	463	677	38.8	46.8	7
Lean duplex	L (EN1.4162)	200	724	862	19.7	36.8	7

2.3 Coupon tests

The coupon test specimens were designed according to the Australian Standard AS-2291 (1979). The dimension of the coupon specimens had 6 mm width and 25 mm gauge length. The coupon test specimens were extracted from the same batch of CFSS tubes as those for connection specimens. The nominal section size of the stainless steel tube is 20 × 50 × 1.5 mm (with × depth × thickness). A total of 25 coupon specimens were conducted to obtain the material properties of CFSS at elevated temperatures using steady state test method. The nominal temperature levels for the coupon tests were 22 (room temperature), 200, 350, 450, 500, 550, 650 800 and 950℃. The MTS model 632.54 F-11 high temperature axial extensometer was used to measure the strain of the middle section of the coupon specimen. The test results of the material properties for the three different types of CFSS at normal room temperature condition were shown in Table 1, including Young's modulus ($E_{,N}$), the 0.2% proof stress ($f_{0.2,N}$), tensile strength ($f_{u,N}$), ultimate strain ($\varepsilon_{u,N}$), fracture strain ($\varepsilon_{f,N}$) of the specimens, as well as Ramberg-Osgood parameter (n) based on the 0.01% and 0.2% proof stresses. The details of the material properties at elevated temperatures were presented in Cai and Young (2014a-b).

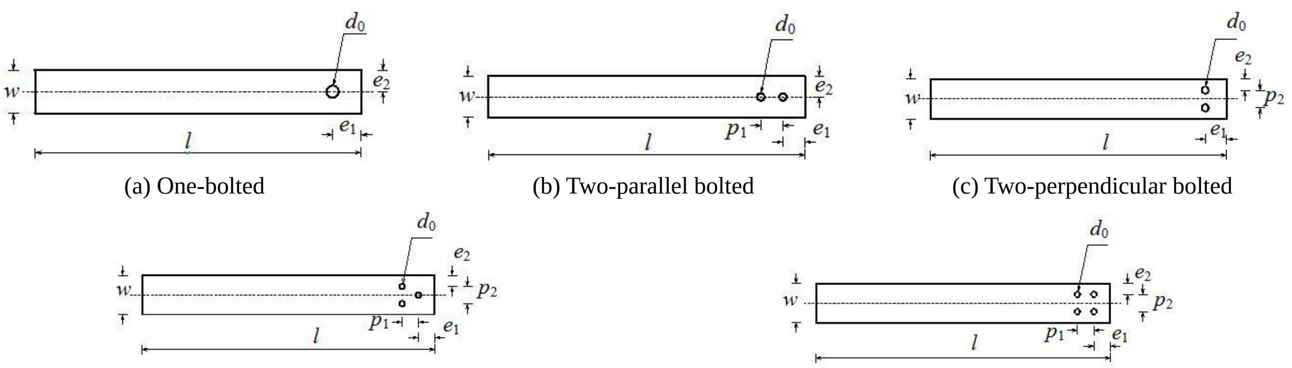
2.4 Bolted connection specimen design

A total of 30 series of CFSS bolted connection specimens were designed. These included two connection types (single shear and double shear), three different types of CFSS (types A, T and L), as well as five different configurations of bolt number and bolt arrangement in the connection specimen, as shown in Fig. 1. The single shear and double shear bolted connections were designed with stainless steel washers in both sides of the bolt. 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. The external plates of double shear bolted connection test specimens are identical to those single shear bolted connection plates for the same bolt configurations. The nominal width (w) and thickness (t) of each connection specimen were 50 mm and 1.5 mm, respectively. They were cut from the CFSS tubes with a specified length (l). The total length of each assembled connection specimen was maintained at approximately 690 mm. The length of the gripping part at each end of the connection specimen was 65 mm.

The A4-80 stainless steel bolts (BS EN ISO 3506-1 1998) were used and assembled in the connection specimens with hand-tightened to a torque of approximately 10 Nm, which allowed slip in the bolt holes of the connection at a small load level. Three different sizes of A4 stainless steel bolts were mainly used. The sizes of the bolts were M6, M8 and M12, and the corresponding sizes of stainless steel washers and nuts were also used. Standard size of bolt holes (d_o) were adopted in accordance with the ASCE (2002) and AS/NZS standards (2001), and the size of bolt hole is 1 mm larger than the nominal bolt diameter (d) if d is smaller than 12 mm, otherwise the d_o is 2 mm larger than d. Generally, the spacing in the connected parts satisfies the minimum requirements of the specifications. The details of the specimen dimensions for single shear and double shear bolted connections were presented in Cai and Young (2014a-b, 2015).

2.5 Bolted connection tests

A total of 430 CFSS single shear and double shear



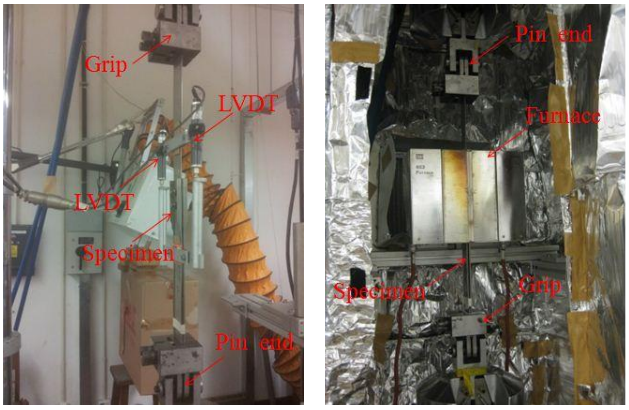
(a) One-bolted (b) Two-parallel bolted (c) Two-perpendicular bolted

(d) Three bolted (e) Four bolted

Fig. 1 Configurations of bolt number and bolt arrangement in the connection specimen

Table 2 Summary of testing on CFSS bolted connections at elevated temperatures

Stainless steel	Connection tests	No. of tests		References
		Single shear	Double shear	
A (EN 1.4301)	Ambient temperature tests	27	22	Cai and Young (2014a)
T (EN 1.4571)	Steady state tests	100	106	Cai and Young (2014b, 2015)
L (EN 1.4162)	Transient state tests	87	88	Cai and Young (2014c, 2015)



(a) Room temperature (b) High temperatures

Fig. 2 Test setup of CFSS bolted connections at elevated temperatures

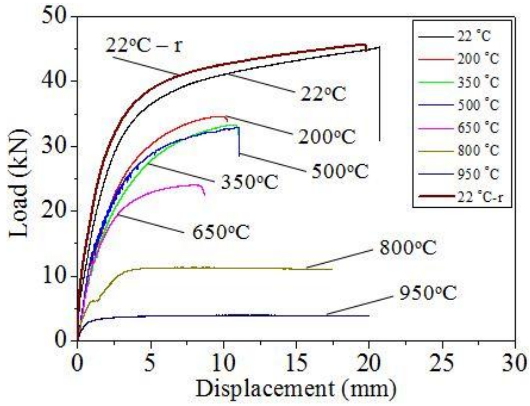


Fig. 3 Load-displacement curves of CFSS (EN 1.4301) single shear four-bolted connections by steady state test method

bolted connection specimens was tested at elevated temperatures, as summarized in Table 2. In which, 49 tests for single shear and double shear bolted connection were conducted at room temperature condition (Cai and Young 2014a); 100 single shear and 106 double shear bolted connections were tested using steady state test method (Cai and Young 2014b, 2015); as well as 87 single shear and 88 double shear bolted connections were tested using transient state test method (Cai and Young 2014c, 2015).

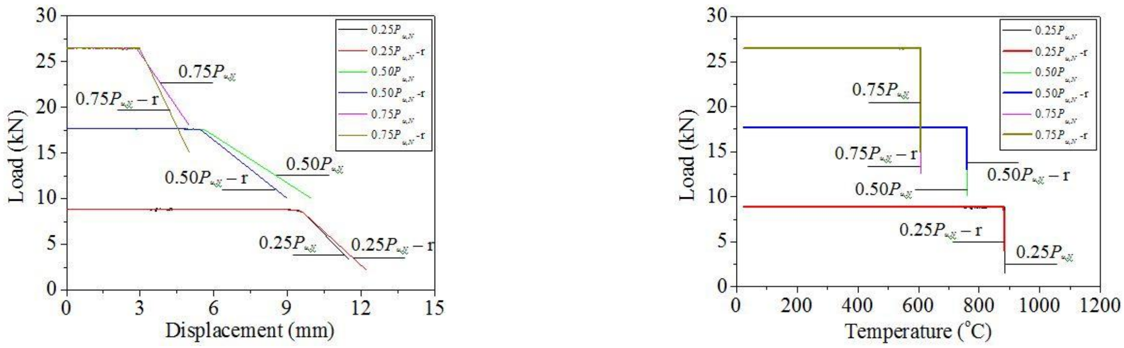
For the steady state tests, six different elevated temperature levels ranged from 200 to 950°C were selected based on the deterioration of the CFSS material properties at elevated temperatures that obtained from the coupon tests. The nominal elevated temperatures for bolted connections were chosen as 200, 350, 500, 650, 800 and 950°C. While for the transient state tests, three different load levels of 0.25, 0.50 and 0.75 of the failure load ($P_{u,N}$) at room temperature condition were adopted for the specimen with the same series. Hence, the applied loads on the CFSS bolted connection specimens were chosen as $0.25P_{u,N}$, $0.50P_{u,N}$, and $0.75P_{u,N}$, respectively.

The bolted connection specimen was assembled in a pair of gripping apparatus, which was specially fabricated in order to provide the pin end boundary conditions of the test. Two calibrated linear variable displacement transducers (LVDTs) were used to measure the elongation of the connections between a distance of 200 mm for normal room temperature (22°C) tests. The tests were conducted using an MTS 810 Universal testing machine. The MTS model 653.04 high temperature furnace was used to raise the temperature inside the furnace for the high temperature tests. The test set-up of CFSS bolted connections at elevated temperatures is illustrated in Figs. 2(a)-(b).

2.6 Test results

Fig. 3 exemplifies the load-displacement curves of CFSS (type A) single shear four-bolted connections at different nominal temperatures using steady state test method; while Figs. 4(a)-(b) illustrate the testing curves of CFSS (type T) double shear four-bolted connections at different pre-load levels ($0.25P_{u,N}$, $0.50P_{u,N}$, and $0.75P_{u,N}$) using transient state test method. The letter "r" in the legend indicates that it is a repeated test. The test ultimate loads at normal room temperature ($P_{u,N}$) and high temperatures ($P_{u,T}$) in the steady state tests, as well as the critical temperatures that the specimens failed in the transient state tests could then be obtained. Figs. 5(a)-(c) show the bearing failure mode of the internal plate of CFSS (type A) double shear one-bolted connections at different temperature levels in steady state tests; while Figs. 6(a)-(b) illustrate the bearing failure mode of CFSS (type T) single shear one-bolted connections at different pre-load levels in transient state tests. The test results were detailed by Cai and Young (2014a-c, 2015).

The deterioration of the material properties and bolted connection strengths at elevated temperatures were compared for the three different types of CFSS, respectively. The deterioration was obtained by normalizing the test results at high temperatures with that at normal room temperature condition, namely $f_{0.2,T}/f_{0.2,N}$, $f_{u,T}/f_{u,N}$ and $P_{u,T}/P_{u,N}$. It was found that the deterioration of the material properties ($f_{0.2,T}/f_{0.2,N}$, $f_{u,T}/f_{u,N}$) and connection strengths ($P_{u,T}/P_{u,N}$) dropped rapidly when the temperature exceeded 500°C. Generally, the deterioration of the connection strengths showed a similar tendency of reduction to those of the material properties for the same type of CFSS regardless



(a) Load-displacement curves (b) Load-temperature curves

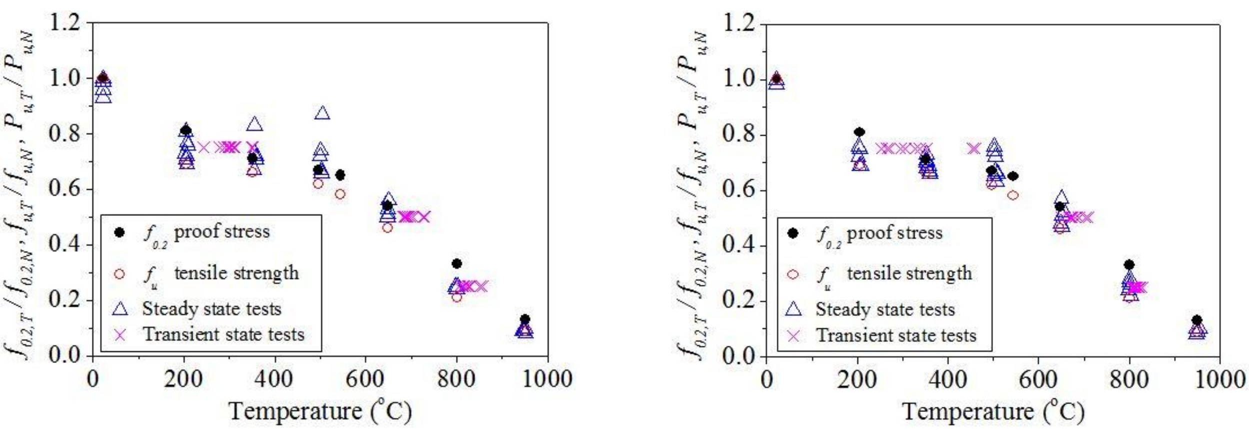
Fig. 4 Testing curves of CFSS (EN 1.4571) double shear four-bolted connections by transient state test method

(a) 200℃ (b) 650℃ (c) 950℃

Fig. 5 Bearing failure mode of CFSS (EN 1.4301) double shear one-bolted connections in steady state tests

(a) $0.25P_{u,N}$ (b) $0.50P_{u,N}$ (c) $0.75P_{u,N}$

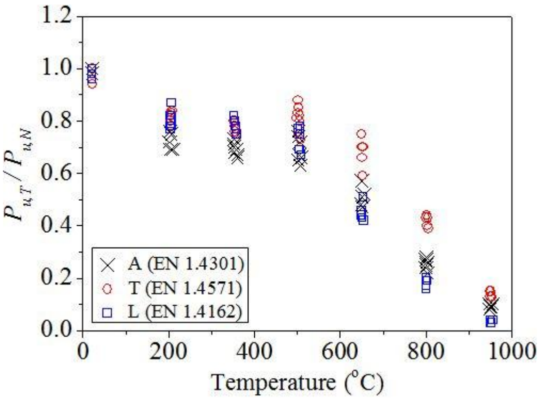
Fig. 6 Bearing failure mode of CFSS (EN 1.4571) single shearone-bolted connections in transient state tests



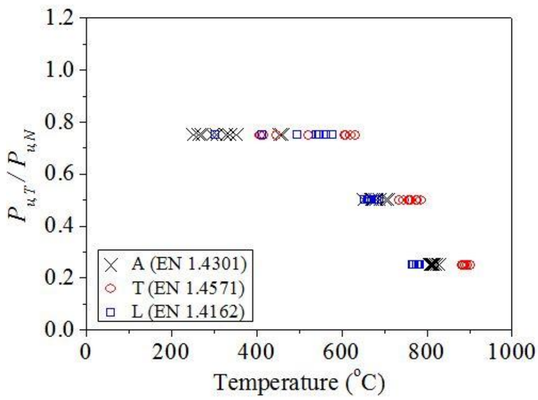
(a) Single shear (b) Double shear

Fig. 7 Comparison of reduction factors for CFSS (EN 1.4301) bolted connections at elevated temperatures

of different connection types and different configurations. Generally, it is shown that the CFSS single shear and double shear bolted connections conducted by transient state tests provide higher critical temperatures when compared with those conducted by steady state tests at the same load levels for the three different grades of CFSS, especially at the load levels of $0.50P_{u,N}$, and $0.75P_{u,N}$. Figs. 7(a)-(b) illustrate the comparison of reduction factors for



(a) Steady state tests



(b) Transient state tests

Fig. 8 Reduction factors for CFSS double shear bolted connections at elevated temperatures

the CFSS (type A) single shear and double shear bolted connections at elevated temperatures, respectively. The vertical axis represents the normalized reduction factors of $f_{0.2,T}/f_{0.2,N}$, $f_{u,T}/f_{u,N}$ and $P_{u,T}/P_{u,N}$, while the horizontal axis plotted against the actual specimen temperatures.

The deterioration of the connection strengths for the three different types of CFSS at elevated temperature was compared. It was also found that the CFSS type T generally performed better than the other two types A and L at elevated temperatures, especially when the temperature exceeded 500℃. Which means that the values of the normalized $P_{u,T}/P_{u,N}$ factors for CFSS type T were generally larger than those for CFSS types A and L at the same temperature levels in the steady state tests, and the critical temperatures of bolted connections for CFSS type T are higher than those for CFSS types A and L at the same pre-load levels in the transient state tests. The critical temperature for bolted connection can be determined by the load-temperature curve for which the load drops 5% of the pre-selected load level (Cai and Young 2014c). Furthermore, it was also found that the connections assembled by CFSS type L generally have a better performance than those assembled by CFSS type A in the temperature ranged from 200 to 500℃; however, the connections assembled by CFSS type A generally have a better performance than those assembled by CFSS type L in the temperature ranged from 650 to 950℃. Figs. 8(a)-(b) illustrate the comparison of reduction factors ($P_{u,T}/P_{u,N}$) for the three different types of CFSS double shear bolted connections at elevated temperatures tested using steady state test method and transient state test method, respectively.

Two main failure modes were observed in the CFSS single shear and double shear bolted connection tests at elevated temperatures, namely the bearing failure and the combination of bearing and net section tension failure. The test strengths were compared with the nominal strengths predicted from the American Specification (2002), Australian/New Zealand Standard (2001) and European Codes (EC3-1.4 2006, EC3-1.8 2005) for stainless steel structures. It should be noted that the predicted values

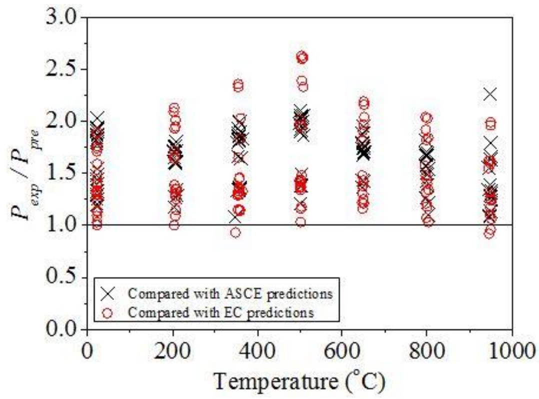


Fig. 9 Comparison of test strength with predicted strength for CFSS single shear bolted connections at elevated temperatures

obtained from the ASCE Specification (2002) and AS/NZS Standard (2001) are identical as the design rules for stainless steel bolted connections in these two specifications are identical. In calculating the nominal strengths of the bolted connections, the reduced material properties of CFSS obtained from the coupon tests at elevated temperatures were used. It is shown that the nominal strengths predicted by the specifications are generally conservative for both single shear and double shear bolted connections at elevated temperatures. The nominal strengths predicted by the current stainless steel design specifications generally under estimate the CFSS bolted connection strengths at elevated temperatures. Comparisons of the test strengths with the nominal strengths predicted by the current stainless steel specifications for single shear and double shear bolted connections at elevated temperatures were detailed in Cai and Young (2014a-b, 2015). Fig. 9 illustrates the comparison of test strengths (P_{exp}) at elevated temperatures, P_{exp} including $P_{u,T}$ and $P_{u,N}$, with the predicted strengths (P_{pre}) for the three different grades of CFSS single shear bolted connections at elevated temperatures.

Table 3 Summary of numerical investigations on CFSS bolted connections at elevated temperatures

Stainless steel	Connection type	Number		References
		Verification	Parametric study	
A (EN 1.4301) T (EN 1.4571) L (EN 1.4162)	Singe shear	103	225	Cai and Young (2018)
	Double shear	128	225	Cai and Young (2016)

3. Numerical investigation performed by Cai and Young

3.1 General

Non-linear finite element models were developed and calibrated with over 200 CFSS single shear and double bolted connections at elevated temperatures that were conducted using steady state test method. The verified finite element models were further used to perform parametric study. A total of 450 single shear and double shear bolted connection specimens at elevated temperatures was designed and performed in the parametric study to study the bearing resistance of CFSS bolted connections at elevated temperatures. The general information of the numerical investigations on CFSS bolted connections at elevated temperatures were summarized in Table 3 of this paper, and detailed in Cai and Young (2016, 2018).

3.2 Development of FEM

The test results of CFSS single shear and double shear bolted connections conducted using steady state test method (Cai and Young 2014b, 2015) were simulated using finite element program ABAQUS (2010). Three main components were carefully considered in developing the finite element model (FEM), and these components are the stainless steel plates, bolts and interfaces between the stainless steel plates and the bolts. Half of the connection was modeled by using appropriate symmetric geometrical boundary conditions in the symmetric plane. Two reference nodes were set in the two bolt holes for the bolt hole deformation measurement. The material properties obtained from the tensile coupon tests at elevated temperatures using steady state test method were used. The bolted connection strength was defined and studied by the equivalent plastic strain of elements around the bolt hole in the finite element analysis (FEA). The development of the FEM and the definition of connection strength were detailed in Cai and Young (2016).

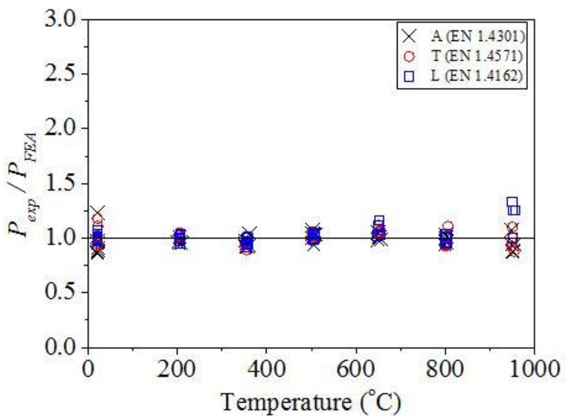


Fig. 10 FEA verification of CFSS double shear bolted connections at elevated temperatures

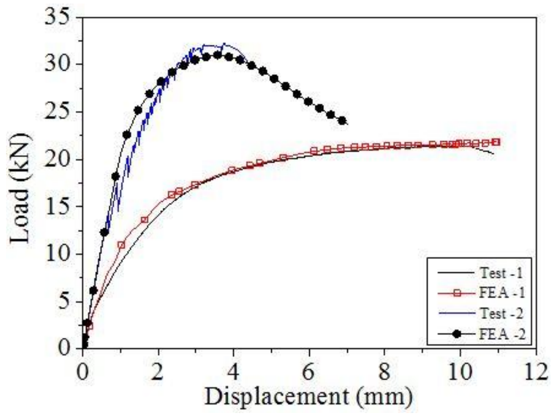


Fig. 11 Comparison of load-displacement curves from tests and FEA

3.3 Verification of FEM

In verifying the FEM, a total of 103 single shear and 128 double shear bolted connections of CFSS at elevated temperatures was analyzed. The experimental results were compared with the numerical results, in which all the connection specimens that having different bolt diameter, bolt number and bolt arrangement tested at different temperature levels were included in the comparison. Generally, it is found that the results predicted from FEA are in good agreement with the test results for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures. Fig. 10 shows the strength comparison (P_{exp}/P_{FEA}) of the 128 CFSS double shear bolted connections at elevated temperatures, with the P_{exp} including $P_{u,T}$ and $P_{u,N}$. Fig. 11 illustrates the comparison of load-displacement curves obtained from tests and FEA. A typical bearing failure mode obtained from the test and predicted by FEA is shown in Fig. 12. The details of the numerical verification were described in Cai and Young (2016, 2018).

3.4 Parametric study

The verified FEM was used for an extensive parametric study that focused on the bearing strengths of CFSS single shear and double shear bolted connections at elevated

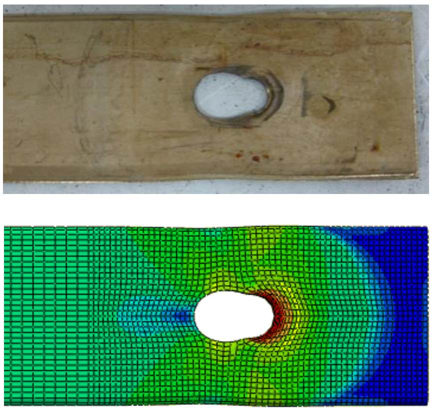


Fig. 12 Comparison of bearing failure mode obtained from test and predicted by FEA (Cai and Young 2016)

temperatures. The effects of end distance (e_1), edge distance (e_2) and bolt spacing (p_2) on the bearing strength of the CFSS bolted connections were investigated before carrying out the parametric study, to ensure the bearing failure of CFSS single shear and double shear bolted connections can be achieved. The spacing requirements in CFSS single shear ($e_1/d \geq 3$, $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$) and double shear ($e_1/d \geq 4$, $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$) bolted connections were determined to study the bearing strength at elevated temperatures (Cai and Young 2016, 2018).

A total of 90 series of CFSS bolted connections that including 450 specimens at elevated temperatures was designed and performed in the parametric study. These included two connection types (single shear and double shear), three different types of CFSS (types A, T and L), three different connection plate thickness (1.5, 3.0 and 4.5 mm), as well as five different configurations that are identical to those configurations shown in Fig. 1 of this paper. In addition, five nominal elevated temperature levels were selected in the parametric study, namely, 22, 200, 500, 650 and 950℃. The details of the parameters for the parametric study were fully presented in Cai and Young (2016, 2018).

4. Bearing resistance design at ambient and elevated temperatures proposed by Cai and Young

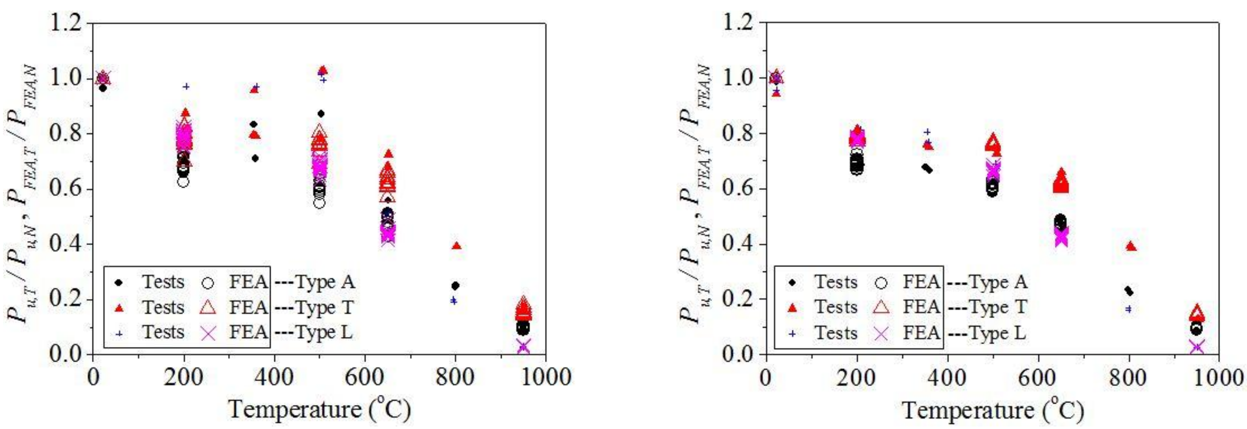
4.1 General

The design rules for CFSS bolted connections in this study are based on the following specifications, including the ASCE Specification (2002), AS/NZS Standard (2001) and Eurocode 3 (EC3-1.4 2006; EC3-1.8 2005). It should be noted that the design equations for CFSS bolted connections in the ASCE Specification (2002) and AS/NZS Standard (2001) are identical. The design equations for determining the bearing resistance of CFSS bolted connections are given in Clause 5.3.3 of the ASCE Specification (2002), in Clause 5.3.6 of the AS/NZS Standard (2001), and in Table 3.4 of the EC3-1.8 (2005). It should be noted that the provisions given in EC3-1.8 (2005) should be used for stainless steel bolted connections, except the modified or superseded provisions in EC3-1.4 (2006).

The differences of nominal bearing strength (P_n) per bolt for CFSS stainless steel bolted connections in the current specifications (ASCE 2002, AS/NZS 2001, EC3-1.4 2006, EC3-1.8 2005) were discussed in Cai and Young (2016). The nominal bearing strength per bolt in the connection is re-written as follows

$$P_n = C\, d\, t\, f_u \tag{1}$$

where C is the bearing factor, d is nominal diameter of bolt, t is thickness of the connection plate and f_u is the longitudinal tensile strength of the connection plate. The parameter C is a constant value of 2.00 and 2.75 for single shear and double shear bolted connections with washers under both bolt head and nut (ASCE 2002, AS/NZS 2001). While the parameter C is consisted of factors that considering the effect of end distance (e_1), edge distance (e_2) and spacing of bolt holes (p_1 and p_2) in EC3-1.8 (2005). It should be noted that Eq. (1) is for the case of plate bearing failure in bolted connection, but not for bolt bearing failure. In addition, Eq. (1) is only applicable for the design in room temperature condition only, but not for high



(a) Single shear (b) Double shear

Fig. 13 Test and parametric results of CFSS bolted connections at elevated temperatures

temperatures (ASCE 2002, AS/NZS 2001, EC3-1.4 2006, EC3-1.8 2005). Hence, the reduced material properties that obtained from the coupon tests were used in calculating the nominal bearing strengths at elevated temperatures in this study.

4.2 Bearing strength without considering bolt hole deformation

Bearing factors (C) for the plate bearing failure were proposed for calculating the bearing strengths of CFSS single shear and double shear bolted connections at elevated temperatures. Two design methods were considered, in which the first design method do not consider the bolt hole deformation, while the second design method considered the bolt hole deformation in the connection. The test results at elevated temperatures that satisfied the spacing requirements in the single shear ($e_1/d \geq 3$, $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$) and the double shear ($e_1/d \geq 4$, $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$) bolted connections, as well as the FEA parametric study results were used to investigate the bearing factors at elevated temperatures in Eq. (1). Both the test results and numerical results that satisfy these spacing requirements for CFSS single shear and double shear bolted connections were shown in Figs. 13(a)-(b), respectively. These results were used to proposed the bearing factors without considering bolt hole deformation in this study. In Figs. 13(a)-(b), the test results and numerical results ($P_{u,N}$ and $P_{FEA,N}$) at normal room temperature condition were normalized by those at elevated temperatures ($P_{u,T}$ and $P_{FEA,T}$) as shown in the vertical axis such that the strength reduction ($P_{u,T}/P_{u,N}$ and $P_{FEA,T}$ /$P_{FEA,N}$) of the bolted connections at elevated temperatures were presented, while the horizontal axis plots the actual specimen temperatures of the tests and FEA.

The proposed bearing factors of CFSS single shear and double shear bolted connections are based on the same approach as the current design rules, as shown in Equation (1), except that the elevated temperatures are taken into consideration. The proposed bearing factors (C) were calibrated with the bearing strengths obtained from the tests ($P_{u,N}$ and $P_{u,T}$) and the parametric study ($P_{FEA,N}$ and $P_{FEA,T}$). It is shown that a constant value of bearing factor of C = 2.65 and C = 2.80 can be used for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures, respectively. Therefore, bearing factors of 2.65 and 2.80 without considering bolt hole deformation are proposed for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures, respectively. Tables 4(a)-(b) shows the comparison of test and numerical results with predictions for bearing strength (P_{P1}) of CFSS single shear and double shear bolted connections at elevated temperatures without considering bolt hole deformation, respectively. Note that P_{exp} and P_{FEA} include bearing strengths obtained from the tests ($P_{u,N}$ and $P_{u,T}$) and the numerical study ($P_{FEA,N}$ and $P_{FEA,T}$) at elevated temperatures, respectively. It is shown that the mean ratios of FEA and tested-to-predicted strength using the proposed bearing factors (C = 2.65 and C = 2.80) were obviously improved in approaching to 1.00 with smaller values of coefficients of variation (COV), when compared with those using ASCE Specification (2002) and European codes (EC3-1.4 2006, EC3-1.8 2005). Furthermore, it is demonstrated that the design equation with the proposed bearing factors is reliable with the reliability index (β) greater than the target value of 3.5. Details of the comparison of FEA and tested-to-predicted strengths were fully presented in Cai and Young (2016, 2018). Fig. 14 illustrates the comparisons of FEA and tested-to-predicted strength for bearing strength of CFSS (type A) single shear bolted connections at elevated temperatures without considering bolt hole deformation.

4.3 Bearing strength with considering bolt hole deformation

The serviceability limit state may be a problem for stainless steel structures as excessive deformations may occur at the ultimate limit state, due to the fact that the high ratio between the ultimate strength and the 0.2% proof stress of the material. The design criterion for steel bolted shear connections by limiting deformations has been studied and proposed in the literature (Salih *et al*. 2011, Yan and Young 2012). However, there is no consensus about whether to limit the permanent or the total elongation, nor on the value to adopt as a suitable deformation limit (Salih *et al*. 2011). The load corresponding to the bolt hole deformation of 6.35 mm (one-quarter inch) is specified in design guidance for carbon steel connections in the AISI (2016), such bolt hole deformation criterion was adopted by Yan and Young (2012) for carbon steel single shear bolted connections at elevated temperatures. Design provisions for stainless steel bolted connections at room temperature were developed based on a 3.0 mm deformation limit under ultimate conditions in the SCI/Euro Inox (2006), while 1.0 mm deformation limit was suggested under service conditions by Salih *et al*. (2011) at room temperature condition.

In this study, the bolt hole deformation obtained from the FEA for the CFSS single shear and double shear bolted connections at elevated temperatures was investigated. The bolt hole deformation-based bearing strengths ($P_{FEA,bh}$)

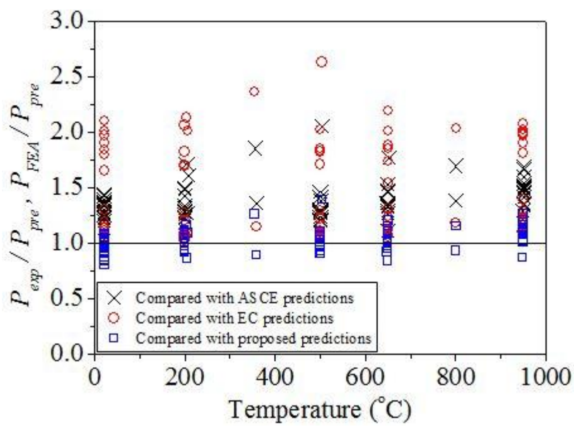


Fig. 14 Comparison of test and numerical results with predictions for CFSS (EN 1.4301) single shear bolted connections at elevated temperatures without considering bolt hole deformation

corresponding to the deformations of 1.0 mm, 3.0 mm and 6.4 mm were obtained from the load and bolt hole deformation curves in the FEA at elevated temperatures. The bearing strengths ($P_{FEA,bh}$) with considering bolt hole deformation were compared with the bearing strengths (P_{FEA}) obtained that do not consider bolt hole deformation. The bearing strengths ($P_{FEA,bh}$) corresponding to different bolt hole deformations compared with the connection bearing strength (P_{FEA}) without considering bolt hole deformation in the percentage ($P_{FEA,bh}/P_{FEA}$) were studied and discussed in Cai and Young (2016, 2018). It is found that the values of $P_{FEA,bh}/P_{FEA}$ for the CFSS bolted connections are generally in the range of 70~90% for single shear with bolt hole deformation of 6.4 mm (Cai and Young 2018), and in the range of 60~80% for double shear with bolt hole deformation of 3.0 mm (Cai and Young 2016). Therefore, when bolt hole deformation in the connection was considered, the deformations of 6.4 mm and 3.0 mm were set for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures, respectively.

It is shown that a constant value of 2.0 for the bearing factor (C) can be used for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures when bolt hole deformations are considered in the connection. Therefore, the bearing factor of 2.00 (C = 2.00) is proposed for the three different grades of CFSS sing shear and double shear bolted connections at elevated temperatures when bolt hole deformations are considered. Table 5 shows the comparison of numerical results with predictions ($P_{FEA,bh}/P_{P2}$) for bearing strength of CFSS bolted connections at elevated temperatures with

Table 4 Comparison of test and numerical results with predictions for bearing strength of CFSS bolted connections at elevated temperatures without considering bolt hole deformation

(a) Single shear

Specimen series	Number			P_{exp}/P_{ASCE} or P_{FEA}/P_{ASCE}	P_{exp}/P_{EC} or P_{FEA}/P_{EC}	P_{exp}/P_{P1} or P_{FEA}/P_{P1}
	Test	FEA				
A (EN 1.4301)	16	75	Mean, P_m	1.38	1.47	1.02
			COV, V_p	0.113	0.281	0.103
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	5.07	2.99	3.93
T (EN 1.4571)	15	75	Mean, P_m	1.36	1.44	1.00
			COV, V_p	0.124	0.276	0.100
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	4.90	2.97	3.89
L (EN 1.4162)	11	75	Mean, P_m	1.34	1.41	1.00
			COV, V_p	0.116	0.271	0.096
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	4.92	2.95	3.89

(b) Double shear

Specimen series	Number			P_{exp}/P_{ASCE} or P_{FEA}/P_{ASCE}	P_{exp}/P_{EC} or P_{FEA}/P_{EC}	P_{exp}/P_{P1} or P_{FEA}/P_{P1}
	Test	FEA				
A (EN 1.4301)	15	75	Mean, P_m	1.07	1.19	1.00
			COV, V_p	0.133	0.045	0.066
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	3.94	3.86	4.06
T (EN 1.4571)	15	75	Mean, P_m	1.06	1.15	0.99
			COV, V_p	0.133	0.079	0.051
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	3.89	3.55	4.09
L (EN 1.4162)	16	75	Mean, P_m	1.06	1.17	0.99
			COV, V_p	0.118	0.065	0.063
			Resistance factor, ϕ	0.65	0.80	0.65
			Reliability index, β	3.98	3.70	4.06

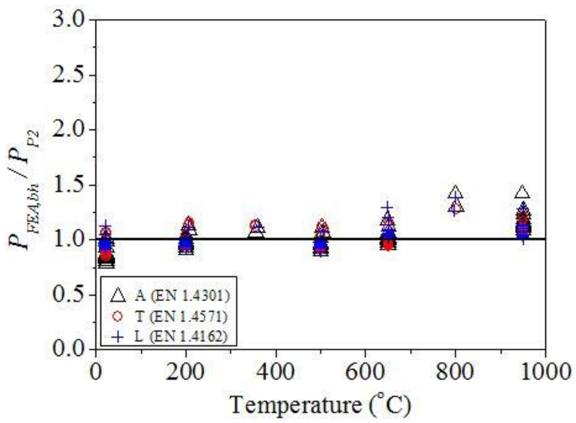


Fig. 15 Cormparison of numerical results with the proposed predictions for bearing strength of CFSS single shear bolted connections at elevated temperatures with considering 6.4 mm bolt hole deformation

considering bolt hole deformations. It is shown that the mean ratios of FEA-to-predicted strength ($P_{FEA,bh}/P_{P2}$) using the proposed bearing factor were around 1.01 for the three different grades of CFSS single shear and double shear bolted connections at elevated temperatures. Furthermore, it is demonstrated that the design equation with the proposed proposed bearing factor is reliable with the reliability index (β) greater than the target value of 3.5. Details of the comparison of FEA-to-predicted strengths are fully presented in Cai and Young (2016, 2018). Fig. 15 illustrates the comparison of numerical results of bearing strength with bolt hole deformation ($P_{FEA,bh}$) with the proposed predictions (P_{P2}) using bearing factor C = 2.00 for CFSS single shear bolted connections at elevated temperatures with considering 6.4 mm bolt hole deformation.

5. Assessment of proposed design rules using results from literature

The proposed design rules (Cai and Young 2016, 2018) were shown to be more accurate and reliable than the current international stainless steel specifications (ASCE 2002, AS/NZS 2001, EC3-1.4 2006) in predicting the bearing resistance of CFSS bolted connections at elevated temperatures. In this study, the proposed design rules were further assessed by the available results of stainless steel bolted connections that subjected to bearing failure from the data in the literature. The numerical results of stainless steel bolted connections investigated by Kiymaz (2009) and Salih *et al.* (2011) that failed in bearing failure and satisfied the spacing requirements in the proposed design rules were

Table 5 Comparison of numerical results with predictions for bearing strength of CFSS bolted connections at elevated temperatures with considering bolt hole deformation

Specimen series		Single shear		Double shear	
		$P_{FEA,bh}/P_{P2}$	No. of FEA	$P_{FEA,bh}/P_{P2}$	No. of FEA
A (EN 1.4301)	Mean, P_m	1.01	89	1.01	89
	COV, V_p	0.127		0.139	
	Resistance factor, ϕ	0.65		0.65	
	Reliability index, β	3.72		3.65	
T (EN 1.4571)	Mean, P_m	1.00	87	1.01	89
	COV, V_p	0.087		0.102	
	Resistance factor, ϕ	0.65		0.65	
	Reliability index, β	3.96		3.91	
L (EN 1.4162)	Mean, P_m	1.02	85	1.03	89
	COV, V_p	0.089		0.082	
	Resistance factor, ϕ	0.65		0.65	
	Reliability index, β	4.04		4.14	

Table 6 Proposed bearing factors for CFSS bolted connections at elevated temperatures

Stainless steel	Temperature (℃)	Connection type	Bearing factor (C)	
			Without considering bolt hole deformation	With considering bolt hole deformation
A (EN 1.4301) T (EN 1.4571) L (EN 1.4162)	22 to 950	Single shear	2.65	2.00
		Double shear	2.80	

* Notes: the bearing factors apply when $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$; $e_1/d \geq 3$ for single shear and $e_1/d \geq 4$ for double shear

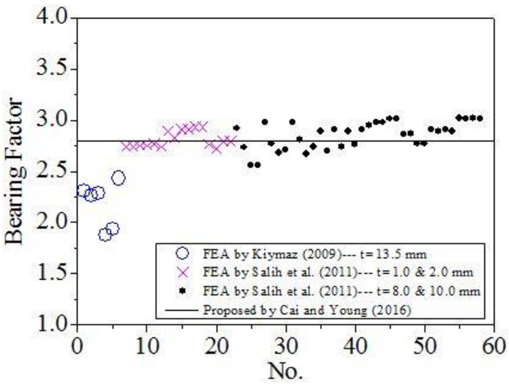


Fig. 16 Comparison of the proposed bearing factor with those from the literature

used regardless of stainless steel grades and connection plate thickness. This is because of the bolted connection failure modes were mainly governed by the spacing (e_1, e_2, p_1 and p_2) in the connection. It should be noted that the bolted connections in Kiymaz (2009) and in Salih *et al*. (2011) were investigated at ambient temperature condition only. There is currently no other results of stainless steel bolted connections at high temperatures. The bolted connections in Kiymaz (2009) and in Salih *et al*. (2011) were categorized as double shear. Therefore, the connection results that satisfied the spacing requirements of $e_2/d \geq 2$, $p_1/d \geq 3$ and $p_2/d \geq 4$ in the proposed double shear bolted connection design rules (Cai and Young 2016) were used, but $e_1/d \geq 3$ instead of $e_1/d \geq 4$ was used. These results are summarized in Table 7.

The bearing factors were obtained directly from Kiymaz (2009) and Salih *et al*. (2011), or otherwise calculated by using Eq. (1) in this paper, where the corresponding material properties, bolt diameter and connection plate thickness in Kiymaz (2009) and Salih *et al*. (2011) were used. The bearing factors obtained from the finite element results were compared with the proposed bearing factor of 2.80 as shown in Fig. 16. It should be noted that the duplex stainless steel (EN 1.4462) with thickness of 13.5 mm in Kiymaz (2009), and the austenitic stainless steel (EN 1.4306) and ferritic stainless steel (EN 1.4016) with thickness of 8.0 and 10.0 mm in Salih *et al*. (2011), were not covered in the proposed design rules by Cai and Young (2016). The comparison of the bearing strengths (P_{lit}) by Kiymaz (2009) and Salih *et al*. (2011), and the proposed bearing strengths (P_{P3}) by using Eq. (1) with the proposed bearing factor of 2.80 (Cai and Young 2016) was shown in Table 7. It is shown that the mean value of (P_{lit}/P_{P3}) is 0.99 with the corresponding COV of 0.087, which means that the predicted strengths by using the bearing factor of 2.80 proposed by Cai and Young (2016) averagely have 1% difference with those bearing strengths from the literature (Kiymaz 2009, Salih *et al*. 2011). Furthermore, reliability analysis was performed by the same method as that used in Cai and Young (2016). It is found that the predicted bearing resistances with the resistance factor of 0.65 are reliable as the reliability index (β) of 3.71 is greater than the target value of 3.5 (Cai and Young 2016). Therefore, it was shown that the proposed design rules by Cai and Young (2016) are generally accurate and reliable for the predictions of stainless steel bolted connections that subjected to bearing failure in the literature (Kiymaz 2009), Salih *et al*. 2011), as shown in Table 7. The proposed design rules (Cai and Young 2016) are also applicable for the bearing resistance design of other stainless steel grades, including austenitic stainless steel (EN 1.4306) and ferritic stainless steel (EN 1.4016), with the connection plate thickness up to 10 mm.

6. Conclusions

Experimental and numerical investigations on cold-formed stainless steel (CFSS) bolted connections at ambient and high temperatures from the literature were reviewed in this paper. Firstly, the test program performed by the authors of this paper was summarized. Three different grades of stainless steel were investigated, 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). A total of 25 CFSS coupon test specimens were tested using steady state test method in the temperature ranged from 22 to 950℃. Totally 430 CFSS bolted connection tests at ambient and elevated temperatures were performed using both steady state and transient state test methods. In the steady state tests, the CFSS bolted

Table 7 Comparison of stainless steel bolted connection strengths from literature and design predictions

References	Stainless steel	Grade	Connection plate thickness (mm)	Spacing	Number	P_{lit}/P_{P3}
Kiymaz (2009)	Austenitic	EN 1.4301	13.5	$e_1/d \geq 3$, $e_2/d \geq 2$, $p_2/d \geq 4$,	3	0.78
	Duplex	EN 1.4462			3	
Salih *et al*. (2011)	Austenitic	EN 1.4306	1.0, 2.0, 8.0, 10.0	$e_1/d \geq 3$, $e_2/d \geq 2$	26	1.01
	Ferritic	EN 1.4016			26	
					Mean, P_m	0.99
					COV, V_p	0.087
					Resistance factor, ϕ	0.65
					Reliability index, β	3.71

connections were investigated in the temperature levels of 22 (ambient temperature), 200, 350, 500, 650, 800 and 950℃, while in the transient state tests, the connections were tested under three different load levels, namely 0.25, 0.50 and 0.75 of the failure load at normal room temperature condition.

The bearing failure and the combination of bearing and net section tension failure were mainly observed from the CFSS bolted connection tests at elevated temperatures. It is found that the deterioration of the material properties and connection strengths of CFSS dropped rapidly when the temperature exceeded 500℃. It is shown that the connection strengths decrease as the temperature increases in the similar manner for the steady state tests and the transient state tests. Generally, the deterioration of the connection strengths showed a similar tendency of reduction to those of the material properties at elevated temperatures for the same grade of CFSS regardless of different connection types and different configurations. It is also found that the austenitic stainless steel EN 1.4571 generally has better resistance than the stainless steel EN 1.4301 and EN 1.4162 for bolted connections at elevated temperatures.

The test strengths were compared with the nominal strengths predicted by the American Specification, Australian/New Zealand Standard and European codes for stainless steel bolted connections. The reduced material properties due to elevated temperatures were used in the calculation in the calculations. It was found that the current design formulas in these three specifications by substituting the reduced material properties at elevated temperatures generally underestimate the connection strengths of the CFSS single shear and double shear bolted connections at elevated temperatures.

Secondly, numerical study on the CFSS bolted connections at elevated temperatures performed by the authors of this paper was summarized. Non-linear finite element models were developed and verified with over 200 CFSS bolted connections at elevated temperatures. Extensive parametric studies focused on the bearing failure of CFSS bolted connections that included 450 specimens were performed using the verified finite element models. Based on both the experimental and numerical results, two sets of bearing factors that with considering and without considering bolt hole deformations in the connections, were proposed for the bearing strength design of CFSS single shear and double shear bolted connections in the temperature ranged from 22 to 950℃.

The bearing resistances of CFSS single shear and double bolted connections obtained from the tests and numerical analyses were compared with the nominal strengths calculated from the current international stainless steel specifications, and also compared with the predicted strengths calculated using the proposed bearing factors. It is shown that the proposed bearing factors for the design equations are generally more accurate and reliable than the current design rules in predicting the bearing resistances of CFSS (EN 1.4301, EN 1.4571 and EN 1.4162) bolted connections at elevated temperatures. The maximum thickness of the connection plate is 4.5 mm.

Lastly, the proposed design rules were assessed by the 58 available results of stainless steel single shear bolted connections subjected to bearing failure in the literature. The connections assembled by austenitic stainless steel (EN 1.4306), ferritic stainless steel (EN 1.4016) and duplex stainless steel (EN 1.4462) with the plate thickness up to 13.5 mm were also used. It is found that the proposed design rules were generally accurate and reliable by comparing the design strengths and results from the literature, except for the numerical results obtained by Kiymaz (2009). Therefore, the proposed design rules are also applicable for the bearing resistance design of single shear bolted connections assembled by austenitic stainless steel EN 1.4306 and ferritic stainless steel EN 1.4016 with plate thickness up to 10 mm by Salih *et al*. (2011).

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