Stainless Steel Double Shear Bolted Connections under Fire Condition

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Abstract

There is currently no design rule on bolted connections of cold-formed stainless steel structures at elevated temperatures. In this study, 40 double shear bolted connection specimens involving three different grades of stainless steel were conducted by using steady state test method. The bearing failure mode was mainly observed in the connection tests. The test strengths were compared with the nominal strengths calculated from the American Specification, Australian/New Zealand Standard and European Codes for stainless steel structures. In calculating the nominal strengths of the connections, the material properties of stainless steel obtained at elevated temperatures were used. It is shown that the strengths of the double shear bolted connections predicted by the specifications are generally conservative under fire condition. The austenitic stainless steel type EN 1.4571 generally performed better than the other two stainless steel types under fire condition.

Keywords: *Double shear bolted connection; Experimental investigation; Fire condition; Stainless steel; Steady state test.*

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). Bolted connections are one of the common connection types in cold-formed steel structures construction. The design rules of cold-formed stainless steel bolted connections are available in current specifications, i.e. 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 (Salih et al., 2010), despite fundamental differences between the mechanical behavior of stainless steel and carbon steel. Furthermore, the current design rules are applicable at room (ambient) temperature condition only and the application to elevated temperatures is questionable. Therefore, there is a need to investigate the cold-formed stainless steel bolted connections at elevated temperatures.

In this study, a total of 40 double shear bolted connection specimens with three different grades of cold-formed stainless steel were tested by steady state test method. In the steady state tests, the stainless steel bolted connections were investigated in the temperature ranged from 22 to 950 ºC. The three different grades of stainless steels are 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). The investigation of the double shear bolted connections involved different bolt diameters, number of bolts and arrangement of the bolts. A total of 6 series of specimens was considered. The failure modes of the cold-formed stainless steel double shear bolted connections were obtained. The ultimate strengths of stainless steel double shear bolted connection tests at elevated temperatures were compared with the nominal strength calculated from the American Specification, Australian/New Zealand Standard and European Codes for stainless steel structures. The connection strengths of the three different grades of stainless steel at elevated temperatures were compared.

2 Coupon tests

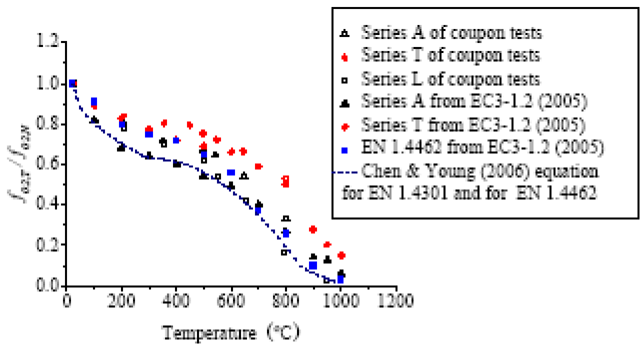
A total of 25 specimens was conducted to obtain the material properties of the stainless steels at both room and elevated temperatures (Cai and Young, 2014a, 2014b). The coupon specimens involved three different grades of stainless steel, namely the austenitic stainless steel EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti having small amount of titanium) as well as the lean duplex stainless steel EN1.4162 (AISI

S32101). The lean duplex stainless steel EN 1.4162 (AISI S32101) is a high strength material and it is a relatively new kind of material in civil engineering construction, thus it is not covered in any current design specifications; while the austenitic stainless steels EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti) have a lower strength than lean duplex material. The type EN1.4571 (AISI 316Ti) contains titanium (element Ti) and has good resistance at high temperature. For simplicity, the three types of stainless steels, EN1.4301 (AISI 304), EN1.4571 (AISI 316Ti) and EN1.4162 (AISI S32101) are labelled as types A, T and L, respectively, in the context of this paper.

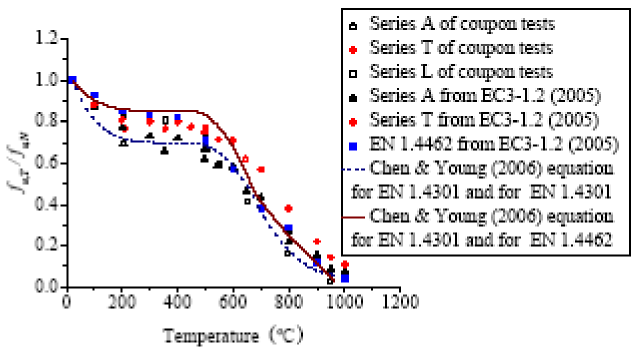
Steady state test method was used for the coupon tests. The tensile coupon tests at elevated temperatures were conducted using an MTS 810 Universal testing machine. The MTS model 653.04 high temperature furnace was used to heat up the specimen to the specified temperature. An external thermal couple was used to measure the actual temperature of the coupon specimen. The external thermal couple was inserted inside the furnace and contacted on the surface of the coupon specimen at mid-length. The temperature obtained from the external thermal couple was recorded as the specimen temperature in this study. 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.

Table 1. Coupon test results at room temperature (Cai and Young, 2014a)

Series	Type	E_N (GPa)	$f_{0.2,N}$ (MPa)	$f_{u,N}$ (MPa)	$\varepsilon_{u,N}$ %	$\varepsilon_{f,N}$ %	n
A	EN1.4301 (AISI 304)	199	474	759	45.2	52.6	5
T	EN1.4571 (AISI 316Ti)	199	463	677	38.8	46.8	7
L	EN1.4162 (AISI S32101)	200	724	862	19.7	36.8	7



(a) 0.2% proof stress



(b) Tensile strength

Figure 1. Comparison of material properties at elevated temperatures (Cai and Young, 2014b)
The mechanical properties of the three types of cold-formed stainless steels obtained at room temperature are
presented in Table 1. The reduction factors $f_{0.2,T}/f_{0.2,N}$ and $f_{u,T}/f_{u,N}$ of the three types of stainless steels versus the specimen temperatures are plotted in Figures 1(a) and 1(b), respectively. The vertical axis of

the graphs is the normalized reduction factors $f_{0.2,T}/f_{0.2,N}$ and $f_{u,T}/f_{u,N}$, while the horizontal axis plotted against the actual specimen temperatures. The symbols employed in Table 1 and Figure 1 are defined as follows: E_N is elastic modulus at room temperature; $f_{0.2,N}$ and $f_{0.2,T}$ is longitudinal 0.2% tensile proof stress at room temperature and elevated temperatures, respectively; $f_{u,N}$ and $f_{u,T}$ is longitudinal tensile strength at room temperature and elevated temperatures, respectively; $\varepsilon_{u,N}$ is ultimate strain at room temperature; $\varepsilon_{f,N}$ is elongation (longitudinal tensile strain) at fracture at room temperature and n is exponent in the Ramberg-Osgood expression. It is shown that the reduction factor $f_{u,T}/f_{u,N}$ dropped rapidly in the temperature ranged from 500 to 950 ºC. Furthermore, the reduction factors $f_{0.2,T}/f_{0.2,N}$ and $f_{u,T}/f_{u,N}$ were compared with those calculated using the equations proposed by Chen and Young (2006) and the factors obtained from EC3-1.2 (2005). It is shown that similar trend of deterioration at elevated temperatures were obtained. The deterioration of different types of stainless steels at elevated temperatures was also compared. It is shown that the austenitic stainless steel type T having a small amount of titanium has better performance in 0.2% proof stress than the lean duplex stainless steel type L and austenitic stainless steel type A in the temperature ranged from 200 to 950 ºC. The stainless steel type T also has a better performance in ultimate strength than the stainless steel types A and L when the temperature exceeded 500 ºC.

3 Double shear bolted connection tests

3.1 Design of bolted connection specimens

The cold-formed stainless steel double shear bolted connection specimens were designed to avoid end-tear out failure and bolt shear failure. The type of stainless steel, the size of bolt as well as the number and arrangement of bolts were considered in the connection specimens. A total of 6 test series of double shear bolted connection specimens were tested at elevated temperatures. Figure 2 shows the detail specimen dimensions of internal plate for each test series. The specimens were cut from stainless steel rectangular hollow sections with a specified length. The stainless steel tubes were supplied from STALA Tube Finland in uncut lengths of 3000 mm and nominal section size 20×50×1.5 mm (width × depth × thickness). The overall length of each part of the specimen was ranged from 391-404 mm, and the total assembled specimen length was maintained at 690 mm for each specimen.

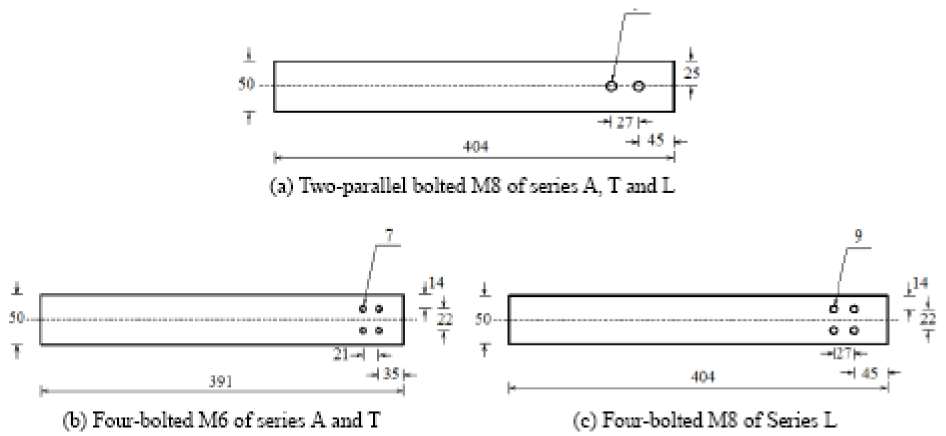


Figure 2. Nominal dimension of double shear (internal plate) bolted connection specimens

The A4 stainless steel bolts M6 and M8 (BS EN ISO 3056-1, 1998) were used in this study. The corresponding size of stainless steel washers and nuts were used. The stainless steel washers were assembled in both sides of the bolt. All bolts were hand-tightened to a torque of approximately 10 Nm, which allowed for slip of the connection after applied a small loading. The specimens are separated into three series according to the stainless steel types, namely A, T and L, respectively. Each specimen was labeled by four segments, for examples “A-D-2Pa-8” and “A-D-4-6”. The first letter “A” indicates the type of stainless steel of which the bolted connection specimen is assembled. The second letter “D” means the double shear bolted connection. The third segment of the label is the number of bolt used in the connection specimen. “Pa” refers to the bolts arranged parallel to the loading direction, and the “2Pa” means there are two-parallel bolts in the specimen. The fourth part of the label means the nominal diameter of the bolt used in the connection. The number “8” represents the bolt diameter of 8 mm, while “6” stands for 6 mm.

3.2 Test set-up and test procedure

The test set-up of stainless steel double shear bolted connections at elevated temperatures is shown in Figure 3. The bolted connection tests were conducted by the same MTS Universal testing machine and furnace as the coupon tests. A total of 40 double shear two-parallel bolted and four-bolted connection specimens including the repeated test specimens were tested in this study under six different elevated temperature levels. In general, it was found that the reduction factors of 0.2% proof stress dropped regularly at elevated temperatures, while the ultimate strength of the three types of stainless steels reduced rapidly when temperature goes beyond 500 ºC as shown in Figure 1. Hence, the nominal temperatures for the connection tests were chosen as 22 (room temperature), 200, 350, 500, 650, 800 and 950 ºC. The connection specimens tested at 22 ºC (room temperature) were reported by Cai and Young (2014a). The test specimen was assembled on a pair of gripping apparatus, which was specially fabricated in order to provide the pin end boundary condition of the test. The test specimen was assembled on a pair of gripping apparatus, which was specially fabricated in order to provide the pin end boundary condition. The details of the gripping apparatus are shown in Cai and Young (2014a). Similar to the coupon tests, an external thermal couple was used to measure the actual temperature of the connection specimen.

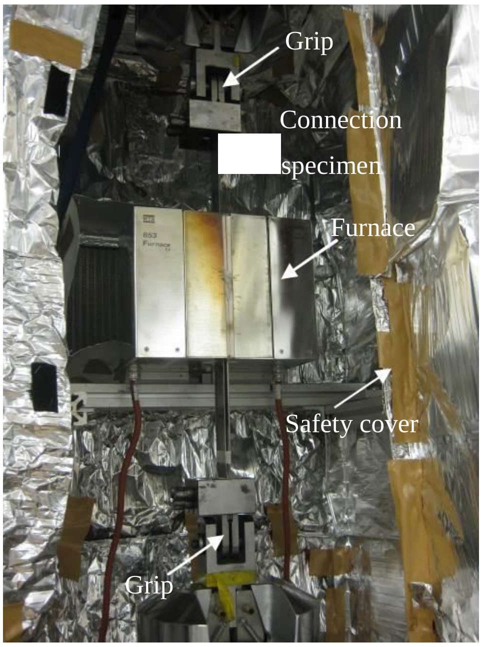


Figure 3. Test set-up of double shear bolted connection at elevated temperatures

Steady state testing method was adopted for the double shear bolted connection tests at elevated temperatures. 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. A data acquisition system was used to record the furnace air temperature, the specimen temperature and the applied load at regular intervals during the test.

3.3 Testing results

The test strengths ($P_{u,N}$ *and* $P_{u,T}$) of the single shear two-parallel bolted and four-bolted connection specimens at elevated temperatures are given in Tables 2 and 3, respectively. The deterioration of the connection strengths at elevated temperatures was plotted in Figure 4. The vertical axis of the graphs show the test strengths normalized with the test strength at room temperature ($P_{u,T}/P_{u,N}$) for each test series, while the horizontal axis plotted against the actual specimen temperatures. The $P_{u,N}$ is ultimate load of bolted connection test at room temperature (Cai and Young, 2014a) while the $P_{u,T}$ is ultimate load of bolted connection test at elevated temperatures. The repeated test results are close to their first test results as shown in Tables 2 and 3, in which the maximum difference of the test strength between the first and repeated test results is 3.4%. The relatively small difference between the first and repeated test values demonstrated the reliability of the tests. It was found that the ultimate strengths of the connections $P_{u,T}$ dropped rapidly when the temperature exceeded 500 ºC. It was also found that the stainless steel type T (EN1.4571 or AISI 316Ti) generally performed better at elevated temperatures compared with the other two types A (EN1.4301 or AISI 304) and L (EN1.4162 or AISI S32101), especially when the temperature exceeded 500 ºC. Furthermore, the stainless steel type A has a slightly better performance than type L for the temperature ranged from 650 to 950 ºC. Figures 5(a) and 5(b) exemplify the test curves of two-parallel bolted and four-bolted connection specimens with series T-D-2Pa-8 and L-D-4-8 at different nominal temperatures, in which "r" represents the repeated test curve. The displacement of bolt slip during the initial loading stage was shifted in all the curves.

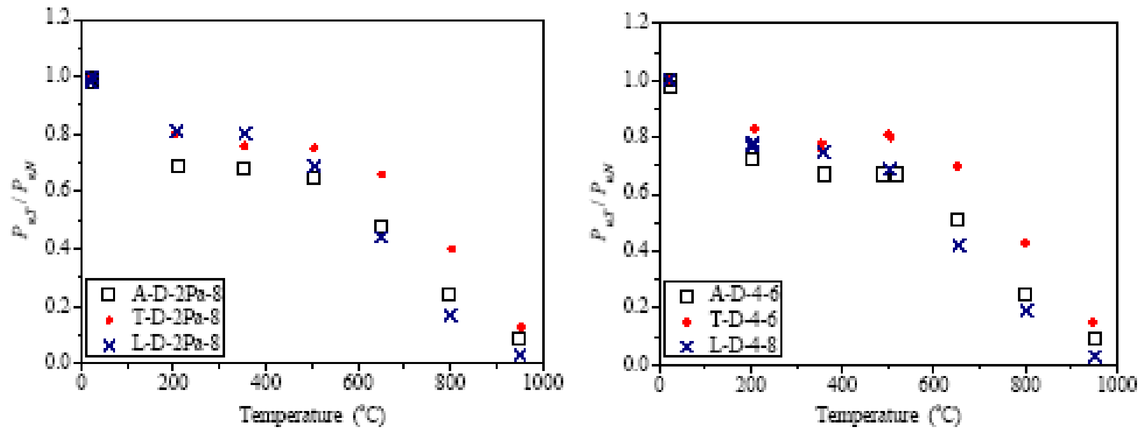
The observed failure modes of each two-parallel bolted and four-bolted connection specimen are listed in Tables 2 and 3. The characteristics of different failure modes of steel bolted connections were detailed in Yan and Young (2011). The specimens were mainly failed by bearing failure (B) based on the experimental observation. The bolt shear failure was deliberately avoided in the design of the test specimens at room temperature. The combined net section tension (NS) and bearing failure (B) were found in specimens A-D-4-6, T-D-4-6 and L-D-4-8 for the temperatures ranged from 22 to 500 ºC. As the temperature increases, only bearing failure mode was found when the temperature exceeded 650 ºC. The bearing failure mode of two-parallel bolted connection specimens at different temperatures is shown in Figure 6. Figure 7 illustrated the failure modes of the four-bolted connection specimens at different temperature levels.

Table 2 Test results and comparisons for double shear two-parallel bolted connections

Specimen series	Temperature (°C)			$P_{u,N}$ or $P_{u,T}$	$P_{u,T}/P_{u,N}$	$P_{u,N}/P_{ASCE}$ or $P_{u,T}/P_{ASCE}$	$P_{u,N}/P_{EC}$ or $P_{u,T}/P_{EC}$	Failure mode		
	Nominal	Coupon	Specimen					ASCE	EC	Test
A-D-2Pa-8	22	22	22	42.1	1.00	1.49	1.23	NS	NS	B
			22	41.4	0.98	1.47	1.20	NS	NS	B
	200	205	209	28.9	0.69	1.26	1.12	---	---	B
	350	351	352	28.5	0.68	1.41	1.19	---	---	B
	500	496	502	27.4	0.65	1.44	1.22	---	---	B
	650	648	649	20.2	0.48	1.31	1.17	---	---	B
	800	800	799	9.9	0.24	1.28	1.24	---	---	B
	950	950	950	3.6	0.09	1.17	1.13	---	---	B
					Mean	1.35	1.19			
					COV	0.085	0.038			
T-D-2Pa-8	22	22	22	39.2	1.00	1.42	1.21	NS	B	B
	200	206	204	31.4	0.80	1.35	1.23	---	---	B
	350	356	354	29.8	0.76	1.34	1.17	---	---	B
	500	498	504	29.3	0.75	1.41	1.20	---	---	B
	650	645	651	25.9	0.66	1.40	1.26	---	---	B
	800	800	803	15.5	0.40	1.27	1.22	---	---	B
	950	950	954	5.0	0.13	1.09	1.05	---	---	B
					Mean	1.33	1.19			
					COV	0.088	0.057			
L-D-2Pa-8	22	22	22	52.2	1.00	1.29	1.24	NS	NS	B
			22	51.3	0.98	1.27	1.22	NS	NS	B
	200	206	207	42.5	0.81	1.27	1.22	---	---	B
	350	356	355	41.9	0.80	1.38	1.23	---	---	B
	500	501	505	35.9	0.69	1.34	1.17	---	---	B
	650	652	648	22.8	0.44	1.35	1.30	---	---	B
	800	795	800	8.7	0.17	1.33	1.28	---	---	B
	950	948	951	1.4	0.03	1.30	1.14	---	---	B
					Mean	1.32	1.23			
					COV	0.030	0.043			

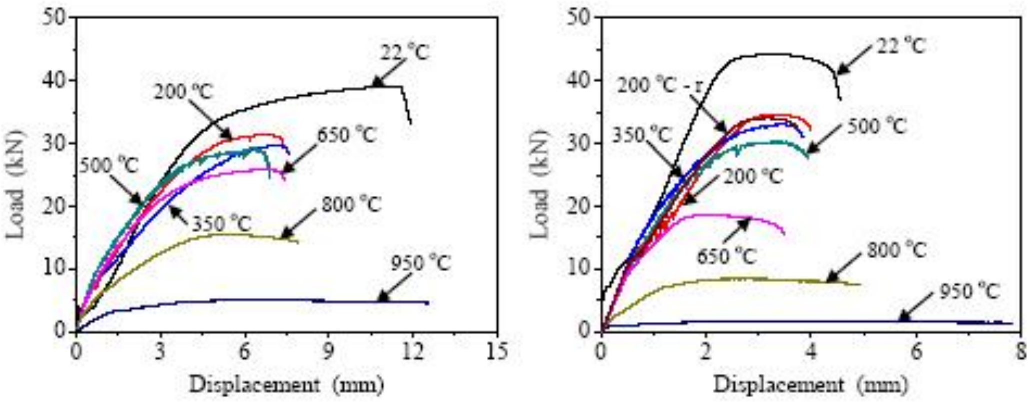
Table 3 Test results and comparisons for double shear four-bolted connections

Specimen series	Temperature (°C)			$P_{u,N}$ or $P_{u,T}$	$P_{u,T}/P_{u,N}$	$P_{u,N}/P_{ASCE}$ or $P_{u,T}/P_{ASCE}$	$P_{u,N}/P_{EC}$ or $P_{u,T}/P_{EC}$	Failure mode		
	Nominal	Coupon	Specimen					ASCE	EC	Test
A-D-4-6	22	22	22	39.5	1.00	1.59	1.14	NS	NS	B+NS
			22	38.7	0.98	1.56	1.13	NS	NS	B+NS
	200	205	202	28.4	0.72	1.41	1.03	---	---	B+NS
	350	351	360	26.4	0.67	1.49	1.07	---	---	B+NS
	500	496	504	26.6	0.67	1.60	1.15	---	---	B+NS
			504	26.6	0.67	1.60	1.15	---	---	B+NS
	650	648	651	20.1	0.51	1.49	1.09	---	---	B
	800	800	801	9.9	0.25	1.21	1.16	---	---	B
	950	950	951	3.4	0.09	1.06	1.00	---	---	B
					Mean	1.45	1.10			
					COV	0.132	0.053			
T-D-4-6	22	22	22	35.3	1.00	1.43	1.03	NS	NS	B+NS
	200	206	207	29.2	0.83	1.43	1.07	---	---	B+NS
	350	356	355	26.7	0.76	1.37	0.98	---	---	B+NS
			354	27.6	0.78	1.41	1.02	---	---	B+NS
	500	498	506	28.3	0.80	1.55	1.11	---	---	B+NS
			499	28.6	0.81	1.56	1.13	---	---	B+NS
	650	645	651	24.6	0.70	1.52	1.11	---	---	B
	800	800	799	15.1	0.43	1.17	1.11	---	---	B
	950	950	949	5.2	0.15	1.06	1.02	---	---	B
					Mean	1.39	1.06			
					COV	0.123	0.050			
L-D-4-8	22	22	22	44.3	1.00	1.32	1.11	NS	NS	B+NS
	200	206	204	34.6	0.78	1.31	1.04	---	---	B+NS
			204	33.9	0.77	1.29	1.02	---	---	B+NS
	350	356	359	33.1	0.75	1.39	1.02	---	---	B+NS
	500	501	504	30.4	0.69	1.45	1.04	---	---	B+NS
	650	652	655	18.6	0.42	1.31	1.11	---	---	B
	800	795	803	8.5	0.19	1.53	1.32	---	---	B
	950	948	952	1.5	0.03	1.79	1.28	---	---	B
					Mean	1.42	1.12			
					COV	0.119	0.106			



(a) Two-parallel bolted connections (b) Four-bolted connections

Figure 4: Comparison of double shear bolted connection test results by steady state test method



(a) Specimen series T-D-2Pa-8 (b) Specimen series L-D-4-8

Figure 5. Load-displacement curves of double shear bolted connection specimens at elevated temperatures

(a) T-D-2Pa-8 at 803 °C (b) L-D-2Pa-8 at 648 °C (c) L-D-2Pa-8 at 951 °C

Figure 6. Failure mode of two-parallel bolted connection specimens at elevated temperatures

(a) A-D-4-6 at 360 °C (b) A-D-4-6 at 951 °C (c) T-D-4-6 at 799 °C

4 Comparison of test strengths with nominal strengths

The nominal strengths (P_{ASCE} and P_{EC}) of the stainless steel double shear two-parallel bolted and four-bolted connections were calculated using the design equations in the current specifications (ASCE, 2002; EC3-1.4, 2006; EC3-1.8, 2005) with consideration of the deterioration of the material properties at elevated temperatures. In the design calculation, the reduced 0.2% proof stress and ultimate strength obtained from the coupon tests at elevated temperatures were used. The measured specimen dimensions were used to calculate the nominal strengths. The design rules for single shear bolted connections in the ASCE Specification (2002) are identical to those in the AS/NZS Standard (2001). Therefore, the predicted values obtained from the two specifications are identical. The comparison of the test results with the predicted values calculated using the ASCE Specification (2002), AS/NZS Standard (2001) and Eurocodes (EC3-1.4, 2006; EC3-1.8, 2005) are shown in Tables 2 and 3. It was found that the predicted strengths (P_{ASCE} and P_{EC}) of the two-parallel bolted and four-bolted connections calculated using the ASCE Specification (2002) and Eurocodes (EC3-1.4, 2006; EC3-1.8, 2005) are conservative at elevated temperatures. The predictions P_{ASCE} were more conservative than the predictions P_{EC} as found in Tables 2 and 3. The current design formulas in these three standards by substituting the reduced material properties at elevated temperatures underestimate the bearing strength of the stainless steel double shear two-parallel bolted and four-bolted connections.

5 Conclusions

An experimental investigation on cold-formed stainless steel double shear two-parallel bolted and four-bolted connections under fire condition has been presented. Three types of cold-formed stainless steels with nominal thickness 1.50 mm were investigated. The three types of stainless steel were 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). A total of 40 two-parallel bolted and four-bolted connection tests was conducted by steady state test method in the temperature ranged from 22 to 950 ^{o}C.

The reduction factor of different types of stainless steel double shear two-parallel bolted and four-bolted connections under fire condition was compared. It is shown that the austenitic stainless steel type EN 1.4571 generally has better performance than the lean duplex stainless steel type EN1.4162 and austenitic stainless steel type EN1.4301 under fire condition, especially when the temperature exceeded 500 ºC. Furthermore, bolted connections of the stainless steel type EN1.4301 has a slightly better performance than type EN1.4162 for the temperature ranged from 650 to 950 ºC.

The test strengths of the double shear two-parallel bolted and four-bolted connections were compared with the nominal strengths calculated from the ASCE Specification, AS/NZS Standard and Eurocodes for cold-formed stainless steel structures by using the reduced material properties due to high temperatures. It was found that the nominal strengths predicted by the ASCE Specification and Eurocodes for the two-parallel bolted and four-bolted connections are conservative under fire condition. The ASCE predictions are more conservative than the Eurocode predictions for the stainless steel two-parallel bolted and four-bolted connections under fire condition.

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