Structural Behaviour of Cold-formed Stainless Steel Bolted Connections at Post-fire Condition

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Abstract

This paper presents an experimental investigation on cold-formed stainless steel single shear and double shear bolted connections at post-fire condition. The connection specimens were fabricated by three different grades of stainless steel. The three different grades of stainless steel are austenitic stainless steels EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti) as well as lean duplex stainless steel EN 1.4162 (AISI S32101). The post-fire connection specimens were heated to different nominal temperatures of 350, 650 and 950 ℃, respectively, and then cooled down to room (ambient) temperature condition. A total of 82 new connection tests was conducted. The test results of post-fire specimens were compared with those tested without post-fire condition for the same specimen series. Generally, it is found that the single shear and double shear bolted connection specimens cooled down from the nominal temperatures of 350 and 650 ℃ had higher ultimate strengths than those specimens without expose to high temperatures for all three different grades of stainless steel. The specimens cooled down from 950 ℃ generally had lower ultimate strengths than the aforementioned specimens. It is also found that the failure modes of cold-formed stainless steel bolted connection specimens at post-fire condition are similar to those tested without post-fire condition. Finally, design rules are proposed for cold-formed stainless steel bolted connections at post-fire condition for temperature up to 950 ℃.

Keywords

Bolted connection; Cold-formed stainless steel; Experimental investigation; Post-fire test; Ultimate strength.

1 Introduction

The desirable characteristics of stainless steel as compared to carbon steel including attractive appearance, corrosion resistance, ductility excellence, better fire resistance and life-cycle cost savings, can be exploited in a wide range of construction applications [1-2]. The usages of stainless steel are found in high-rise buildings (i.e. The Cheung Kong Center, Hong Kong), bridges (i.e. Helix Bridge in Singapore) and other structural applications. New opportunities for stainless steel are arising from the pursuit of sustainable development, such as nuclear power generation, solar power generation, biofuel power generation, sustainable building envelopes and renovation [2]. Investigations on the performances of stainless steels at room (ambient) temperature have been carried out in recent years, such as material properties [3-4], beams [5-6], columns [7-8] and bolted connections [9-11]. The structural behaviours of stainless steels at high temperatures were also investigated, including structural members [12-14] and bolted connections [15-17].

Fire safety is one of the critical scenarios in the design of steel structures due to the strength and stiffness deterioration at elevated temperatures. The full process of fire development can be assumed as four stages: incipient, growth, burning after flashover, and decay [18]. Structural members will cool down along with the decreasing atmosphere temperature in the last stage. It is cost-consuming and time-consuming if all the structures exposed to fire are dismantled and replaced by new alternates, i.e. steel members; while safety is concerned if structures are directly reused or reinforced after exposed to fire. Therefore, the performance of structures after exposed to fire need to be assessed. The post-fire behaviour of concrete-filled steel tubular columns [19] and steel beam to concrete-filled steel tubular column connections have been investigated [20]. Tests on the post-fire mechanical properties of high strength structural steels S460 and S690 showed that mechanical properties are not affected until they are exposed to fire temperatures above 600 ℃ [21]. Bolted connections are commonly used in carbon steel and stainless steel structures. However, it should be noted that there is presently no research work on the post-fire behaviour of stainless steel bolted connections. Therefore, an experimental investigation on the structural behaviour of cold-formed stainless steel bolted connections at post-fire condition was carried out.

A series of cold-formed stainless steel bolted connections have been tested at elevated temperatures by steady state test method and transient state test method [15-17]. The connection specimens in this study were fabricated from the same batch of cold-formed stainless steel as those tested in [11, 15-17]. The three different grades of stainless steel are 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 cold-formed stainless steel bolted connection specimens were designed by varying the size of bolt, the number of bolt and the arrangement of bolt. The connection specimens were heated to different nominal temperatures of 350, 650 and 950 ℃, respectively, and then cooled down to room (ambient) temperature. A total of 82 new connection tests was conducted in this study. The test results were compared with those obtained from room temperature tests without exposing to high temperatures for the same specimen series, including connection strengths and failure modes. In addition, the micro structures of the stainless steel at post-fire condition and without post-fire condition were also investigated. Finally, design rules are proposed for cold-formed stainless steel bolted connection specimens at post-fire condition for temperature up to 950 ℃.

2 Experimental Investigation

2.1 Test specimens

The bolted connection specimens were fabricated from three different grades of cold-formed stainless steel, including austenitic stainless steels 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 austenitic stainless steels have lower strengths 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 in this study. For simplicity, these 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.

The bolted connection specimens were cut from the 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 20×50×1.5 mm (width × depth × thickness). The single shear and double shear bolted connections were tested with stainless steel washers in both sides of the bolt. The single shear connection specimen is bolted with two plates having one shear plane, while the double shear connection specimen is bolted with three plates having two shear planes. 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 were ranged from 381-404 mm such that 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.

Three types of connection plates with different bolt numbers and bolt configurations were designed for the single shear and double shear bolted connection specimens, as shown in Fig. 1. Lips were designed for the connection plates except for the middle plate of the double shear bolted connections. The nominal dimensions of the plates for single shear and double shear (middle plates) bolted connection specimens are presented in Table 1. The dimensions of the specimens were the same as those tested by Cai and Young [11]. Two different sizes of A4 stainless steel bolts [22] of grade 8.8 were used, namely M8 bolt and M12 bolt. Standard size of bolt holes (d_o) were adopted in accordance with the ASCE [23] and AS/NZS standards [24], 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, except for the case when there are three bolt holes in the plate, as shown in Fig. 1(c). In this case, the perpendicular spacing between the centres of two bolt holes is 22 mm for M8 bolts, which could still follow the requirements of EC3-1.8 [25], but 2 mm less than the minimum requirements of 24 mm in the ASCE Specification [23] and AS/NZS Standard [24].

2.2 Specimen labelling

The specimens are mainly separated into two groups according to the connection types, namely the single shear and double shear bolted connections, respectively. Each group of connection contains three different configurations based on the number of bolt and arrangement of the bolts. Each specimen is generally labelled by four segments in order to identify the grade of stainless steel, the connection type, bolt number and bolt arrangement as well as the bolt size. For examples, the labels "A-S-2Pa-8" and "T-D-3-8" define the following specimens:

- The first letter indicates the type of stainless steel, where A = EN 1.4301 (AISI 304) and T = EN 1.4571 (AISI 316Ti).
- The second letter stands for the connection type, where "S" represents single shear bolted connection and "D" represents double shear bolted connection.
- The third segment of the label defines the number of bolt and bolt arrangement. If the specimen is assembled by two bolts, then the letters "Pa" mean the bolts arranged parallel to the loading direction. The "2Pa" means there are two-parallel bolts in the specimen, while "3" indicates that there are three bolts used 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.

2.3 Test rig and operation

The MTS model 653.04 high temperature furnace was used to heat up the specimen to the specified temperature as shown in Fig. 2. The heating device contains three independent-controlled heating chambers with a maximum temperature up to 1400 ℃. Inside each heating chamber, an internal thermal couple was used to measure the air temperature in the furnace. Due to the distance between the internal thermal couples and the coupon specimen, the temperature obtained from the internal thermal couples could be slightly different from the temperature of the connection specimen. Hence, an external thermal couple was used to measure the actual temperature of the bolted connection specimen in the overlap section. The external thermal couple was inserted inside the furnace and contacted on the surface of the connection specimen at mid-length. The temperature obtained from the external thermal couple was recorded as the specimen temperature in this study. The heating rate of the furnace for the coupon tests was approximately 40-60 ℃/min, depending on the specified temperature level. Higher heating rate was used for the higher temperature levels.

The connection specimen was firstly set-up with clamping the top end, while keeping the bottom end free in the MTS 810 Universal testing machine. The furnace was then closed and the temperature inside the furnace was raised to a pre-selected level, namely, 350, 650 or 950 ℃. 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 level was reached, the temperature was hold for a couple of minutes until it became stable. After the specimen temperature was stabilised, the furnace was switched off and thus the specimen temperature was cooled down to room temperature. The set up for heating the specimen in the furnace is illustrated in Fig. 2.

The typical temperature-time curves of connection specimens cooled down from different stabilised temperature levels are shown in Fig. 3. Previous study has shown that the different cooling rate has very limited effects on the residual tensile strength of steel A325 bolts, of which the bolts were cooled down in room air, ice water and furnace [26]. The connection specimen was placed in room air condition for one day after completing the heating and cooling stage. The specimen was then tested in the MTS 810 Universal testing machine with the same testing procedure as the cold-formed stainless steel bolted connection tests at room temperature reported by Cai and Young [11]. Two displacement transducers (LVDTs) were set-up to measure the elongation of the connection part over a distance of 200 mm. Each end of the specimen is joined by a gripping apparatus which are free to rotate in one direction through pin-ends. The gripping apparatus are fixed to the grips of the MTS machine. The testing procedure of single shear and double shear stainless steel bolted connections were detailed in Cai and Young [11]. The tests were conducted by displacement control with the loading rate of 1.5 mm/min. The use of displacement control allowed the tests to be continued in the post-ultimate range. A data acquisition system was used to record the applied load and the readings of displacement transducers at regular intervals during the tests. A typical test set-up of stainless steel single shear two-parallel bolted connections in post-fire condition is shown in Fig. 4.

3 Post-fire Test Results

The ultimate loads ($P_{u,P}$) and failure modes of the cold-formed stainless steel single shear and double shear bolted connection specimens at post-fire condition are shown in Tables 2 and 3, respectively. A total of 82 bolted connection tests were conducted in this study. The repeated test results are close to their first test results. The maximum difference between the first and repeated test results is 4.8%. The load-displacement test curves for specimens in Series A-D-3-8, T-D-3-8 and L-D-3-8 are shown in Figs. 5(a), 5(b) and 5(c), respectively, in which "R" represents the repeated test. The same series of specimens without exposing to high temperatures were also tested and included as 22 ℃ in these figures. The horizontal axis plots the displacement of the specimens obtained from the two transducers, while the vertical axis represents the applied load on the specimens. The temperature in the figure indicates the maximum nominal temperature of which the specimen was exposed. The displacement was obtained from the average readings of the two transducers that measured the elongation of the connections between a distance of 200 mm. The bolt slip is expected at small load level during the tests, and the slip displacement was shifted in all the test curves.

The failure modes at ultimate load of the cold-formed stainless steel single shear and double shear bolted connection tests involved bearing failure (B), net section tension failure (NS) and bolt shear failure (BS), as shown in Tables 2 and 3. The failure modes were determined by observation of the deformed test specimens at the ultimate load. The characteristics of different failure modes for bolted connections were illustrated in Yan and Young [27]. For single shear bolted connections, all the one-bolted and two-parallel bolted connection specimens were failed in bearing failure except for specimen Series L-S-2Pa-8 which failed by combination of bearing and bolt shear failures. Both the bearing and net section tension failure modes were observed for all the three-bolted connection specimens. In particular, it should be noted that tilting of bolts together with the bolt hole elongation were observed in all single shear connection specimens. While for double shear bolted connections, the bolt shear failure mode was not found in any specimens. All the one-bolted and two-parallel bolted connection specimens were failed in bearing failure. Similar to the single shear bolted connections, the combination of bearing and net section tension failures were found in the three-bolted connections for the three different types of stainless steel. The bearing failure mode of specimen Series T-S-1-12 is illustrated in Fig. 6.

4 Analysis of Test Results

The ultimate loads ($P_{u,P}$) of connection specimens at post-fire condition were compared with those test specimens ($P_{u,N}$) without exposing to high temperatures. The strengths ($P_{u,N}$) obtained from tests without exposing to high temperatures were detailed in Cai and Young [11]. The comparisons of the ultimate loads for cold-formed stainless steel single shear and double shear bolted connections were plotted in Figs. 7(a) and 7(b), respectively. The vertical axis represents the normalized values of $P_{u,P}/P_{u,N}$, in which, $P_{u,N}$ is the average value if there were repeated tests; while the horizontal axis plotted against the measured maximum temperatures to which the specimen was exposed. Generally, it is found that the stainless steel single shear and double shear bolted connections cooled down from nominal temperatures of 350 and 650 ℃ had the ultimate strengths higher than those specimens without expose to high temperatures for the three different grades of stainless steels, as the normalized values ($P_{u,P}/P_{u,N}$) are generally greater than 1.0 as shown in Fig. 7(a) and 7(b), respectively. This may be due to the residual stresses caused by cold-forming were released after exposing to high temperatures. Such benefit to cold-formed lean duplex stainless steel (Type L) is relatively more obvious than the cold-formed austenitic stainless steels (Type A & Type T) in the pure bearing failure of connection plate of the single shear bolted connections, for example, $P_{u,P}/P_{u,N}$ is 1.38 and 1.41 for L-S-1-12 cooled down from nominal temperatures of 350 and 650 ℃, respectively; while a similar case, such $P_{u,P}/P_{u,N}$ is 1.10 and 1.13 for A-S-1-12, as well as 1.11 and 1.19 for T-S-1-12. This is because Type L is a relatively high strength material and its residual stress due to cold forming is relatively higher. The normalised values of $P_{u,P}/P_{u,N}$ for specimens cooled down from nominal temperature of 950 ℃ are scattered and approximately for the value of 1.0 for single shear bolted connections, but the values of $P_{u,P}/P_{u,N}$ are smaller than 1.0 for all the double shear bolted connections. The reduced strengths may be due to the changed grains in the microstructure of the material after exposed to temperature of 950 ℃, as detailed in Section 5 of this paper.

The failure modes of single shear and double shear bolted connections in post-fire condition are shown in Tables 2 and 3, respectively. The failure modes obtained from the specimens without exposing to high temperatures [11] for the same series of specimens are also included in the tables. It is found that the failure modes of the single shear and double shear bolted connection specimens at post-fire condition are similar to the failure modes of those test specimens without exposing to high temperatures for the same specimen series, which means that the post-fire condition has little effects on the failure modes of the bolted connection specimens for the three different grades of cold-formed stainless steel. The failure mode of specimen T-S-1-12 without exposing to high temperatures is also illustrated in Fig. 6.

5 Microstructure of Material

In order to understand the characteristics of the tested cold-formed stainless steel bolted connections at post-fire condition, the microstructure of a few selected bolted connection specimens were examined by scanning electron microscope (SEM). The sample (10×10 mm) was taken from middle plate of the double shear one-bolted connection specimens, which located in the vicinity of the bolt hole in the direction of bolt intrusion, as shown in Fig. 8. The samples were cut from the tested specimens at room temperature without exposing to high temperatures as well as those at post-fire condition. The sample was ground with silicon carbide grinding papers from 240 to 1200 grit, and then polished on nylon cloth with 1.0 μm and 0.5 μm diamond compounds, until a good quality was achieved from the smooth polished surface. Finally, the sample was electrolytically etched with solution of perchloric acid (70%) and ethanol (100%) by 1:4. The samples for SEM examination are shown in Fig. 9.

The samples were investigated by SEM to obtain the images for the three different grades of stainless steel without and with post-fire conditions. The corresponding images were illustrated in Fig. 10. The samples from the same types of stainless steel without and with post-fire condition were compared. The differences of the grains of the tested specimens for stainless steel types A, T and L are illustrated in Figures 10(a), 10(b) and 10(c), respectively. Furthermore, the chemical compositions obtained from the mill certificates and those obtained from the SEM energy-dispersive X-ray (EDX) spectrum for specimens without post-fire condition are also compared as shown in Table 4. It is found that the chemical composition percentages are close for the same types of cold-formed stainless steel, except for element *Si* of stainless steel Type A were 0.40% and 0.32% from mill certificates and SEM EDX spectrum, respectively; and element *Ti* of stainless steel Type T were 0.34% and 0.26% from mill certificates and SEM EDX spectrum, respectively.

6 Proposed Design Rules at Post-fire Condition

The ultimate loads ($P_{u,P}$), namely the residual strength, of the cold-formed stainless steel single shear and double shear bolted connections at post-fire condition are presented in Tables 2 and 3, respectively. The strength residual factors of the bolted connections after cooled down from high temperatures were calculated as the ratio of residual strength ($P_{u,P}$) at post-fire condition to that of specimens at 22 ℃ ($P_{u,N}$) without exposing to high temperatures, as detailed in Tables 2 and 3. The deterioration of residual strengths, as reflected by the values of strength residual factor ($P_{u,P}/P_{u,N}$), are plotted in Figs. 7(a) and 7(b), as mentioned in Section 4 of this paper. Generally, it is found that the residual strengths of cold-formed stainless steel single shear and double shear bolted connections are not affected until they exposed to high temperatures above 650 ℃, as the strength residual factor $P_{u,P}/P_{u,N} \geq 1.0$. Based on the investigation in this study, both cold-formed austenitic and lean duplex stainless steel bolted connections can regain their original strength if they are exposed to high temperatures not greater than 650 ℃. Therefore, it could be concluded that if bolted connections assembled by cold-formed stainless steel (Types A, T and L) subjected to shear loading that exposed to high temperature not greater than 650 ℃, their connection strengths are not affected.

When the bolted connection specimens cooled down from nominal high temperature of 950 ℃, for single shear bolted connections, the cold-formed austenitic stainless steel and lean duplex stainless steel regained minimum of 88% and 85% of their strength at room temperature condition without exposed to high temperatures, respectively; while for double shear bolted connections, the austenitic stainless steel and lean duplex stainless steel regain minimum of 86% and 87% of their strength at room temperature condition without exposed to high temperatures, respectively. Generally, the test results obtained from this study showed little difference of the post-fire residual strengths for the single shear and double shear bolted connections in terms of the minimum strength residual factor, for the connections assembled by the three different grades of cold-formed stainless steel (Types A, T and L). Hence, an empirical equation is proposed for the residual strength of the three different grades of cold-formed stainless steel single shear and double shear bolted connections at post-fire condition.

As temperature is the main reason causing the deterioration of the bolted connection strength of cold-formed stainless steel, the equation was developed as a function of the temperature. For safe consideration, the strength residual factor ($P_{u,P}/P_{u,N}$) for both single shear and double shear bolted connections is set to 1.0 for connections exposed to high temperatures not beyond 650 ℃, as shown in Eq. 1. Otherwise, the strength residual factor ($P_{u,P}/P_{u,N}$) could be calculated based on a linear curve for the temperature ranged from 650 ℃ to 950 ℃. The strength residual factors obtained from the tests are compared with the predictions using Eq. (1) for single shear and double shear bolted connections, as shown in Figs. 7(a) and 7(b), respectively.

$$\frac{P_{u,P}}{P_{u,N}} = \begin{cases} 1.0 & for \quad 22 \leq T \leq 650\,℃ \\ -0.0005T + 1.325 & for \quad 650 < T \leq 950\,℃ \end{cases} \qquad (1)$$

7 Conclusions

A total of 82 cold-formed stainless steel single shear and double shear bolted connection specimens were tested at post-fire condition in this study. The connection specimens were fabricated by austenitic stainless steel EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti) as well as lean duplex stainless steel EN 1.4162 (AISI S32101). The stainless steel bolted connection specimens were designed by varying the size of bolt, the number of bolt and the arrangement of bolt. The post-fire specimens were prepared by cooled down the specimens from nominal high temperatures of 350, 650 and 950 ℃.

The post-fire test results were compared with those specimens tested without expose to high temperatures for the same specimen series. It is shown that the ultimate strengths of single shear and double shear bolted connection specimens cooled down from the nominal temperatures of 350 and 650 ℃ had higher ultimate strengths than those specimens without post-fire condition for all three different grades of stainless steel. This may be due to the residual stresses caused by cold-forming were released after exposing to high temperatures. However, it is found that the specimens cooled down from 950 ℃ generally had lower ultimate strengths than those specimens with post-fire condition cooled down from 350 and 650 ℃ and specimens without post-fire condition. This may be due to the change of grains in the microstructure of the material after exposing to high temperature of 950 ℃. Furthermore, the failure modes of bolted connection specimens at post-fire condition are similar to those specimens tested without post-fire condition for the same specimen series.

The characteristics of tested stainless steel bolted connections at post-fire condition and without post-fire condition were examined by scanning electron microscope (SEM) by taking samples from the failed specimens. Different grains of the tested specimens at post-fire condition were found for the same grade of stainless steel. An empirical equation is proposed for the residual strength prediction of the three different grades of cold-formed stainless steel single shear and double shear bolted connections at post-fire condition. The proposed equation is suitable for cold-formed stainless steel single shear and double shear bolted connections exposed to high temperatures up to 950 ℃.

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References

[1] Gardner, L. The use of stainless steel in structures. Prog. Struct. Engng Mater. 2005; 7: 45-55.

[2] Baddoo, N.R., Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research, 2008; 64: 1199-1206.

[3] Rasmussen K.J.R. Full range stress–strain curves for stainless steel alloys. Journal of Constructional Steel Research 2003; 59: 47-61.

[4] Gardner L and Nethercot D.A. Experiments on stainless steel hollow sections Part 1: Material and cross-sectional behaviour. Journal of Constructional Steel Research, 2004; 60(9): 1291-1318.

[5] Mirambell E. and Real E. On the calculation of deflections in structural stainless steel beams: An experimental and numerical investigation. Journal of Constructional Steel Research, 2000; 54(1):109-33.

[6] Theofanous, M. and Gardner L. Experimental and numerical studies of lean duplex stainless steel beams. Journal of Constructional Steel Research, 2010; 66: 816-825.

[7] Theofanous M. and Gardner L. Testing and numerical modelling of lean duplex stainless steel hollow section columns. Engineering Structures, 2009; 31: 3047-3058.

[8] Huang, Y. and Young B. Tests of pin-ended cold-formed lean duplex stainless steel columns, Journal of Constructional Steel Research, 2013; 82: 203-215.

[9] Bouchaïr, A., Averseng, J., and Abidelah, A. Analysis of the behaviour of stainless steel bolted connections, Journal of Constructional Steel Research, 2008; 64(11): 1264-1274.

[10] Salih E.L., Gardner L., and Nethercot D.A. Bearing failure in stainless steel bolted connections. Engineering Structure, 2011; 33(2): 549-562.

[11] Cai Y. and Young B. Structural behavior of cold-formed stainless steel bolted connections. Thin-Walled Structures, 2014; 83: 147-156.

[12] Baddoo, N.R. and Burgan, B.A. “Fire resistant design of austenitic structural stainless steel”, Journal of Constructional Steel Research, 1998; 46(1-3), 458-459, paper number 243.

[13] Gardner, L. and Ng, K.T. “Temperature development in structural stainless steel sections exposed to fire”, Fire Safety Journal. 2006; 41(3): 185-203.

[14] Ng, K.T. and Gardner, L. “Buckling of stainless steel columns and beams in fire”, Engineering Structures, 2007; 29(5): 717-730.

[15] Cai Y. and Young B. Behaviour of cold-formed stainless steel single shear bolted connections at elevated temperatures. Thin-Walled Structures, 2014; 75: 63-75.

[16] Cai Y. and Young B. Transient state tests of cold-formed stainless steel single shear bolted connections. Engineering Structures, 2014; 81: 1-9.

[17] Cai Y. and Young B. High temperature tests of cold-formed stainless steel double shear bolted connections. Journal of Constructional Steel Research, 2015; 104: 49-63.

[18] Buchanan, A. H. Structural design for fire safety, John Wiley & Sons Ltd., West Sussex, 2001.

[19] Yang H. , Han L. and Wang Y. Effects of heating and loading histories on post-fire cooling behaviour of concrete-filled steel tubular columns. Journal of Constructional Steel Research, 2008; 64: 556–570.

[20] Han L., Huo J. and Wang Y. Behavior of steel beam to concrete-filled steel tubular column connections after exposure to fire. Journal of Structural Engineering, ASCE, 2007; 800-814.

[21] Qiang X., Bijlaard, F.S.K. and Kolstein H. Post-fire mechanical properties of high strength structural steels S460 and S690. Engineering Structures, 2012; 35: 1-10.

[22] BS EN ISO 3506-1. Mechanical properties of corrosion-resistant stainless steel fasteners - Part 1: Bolts, screws and studs; BS EN ISO 3506-1: 1998.

[23] American Society of Civil Engineers (ASCE). Specification for the design of cold-formed stainless steel structural members. ASCE Standard, SEI/ASCE-8-02, Reston, Virginia, 2002.

[24] Australian/New Zealand Standard (AS/NZS). Cold-formed stainless steel structures. AS/NZS 4673:2001, Standards Australia, Sydney, Australia, 2001.

[25] EC3-1.8. Eurocode 3: Design of steel structures—Part 1.8: Design of joints. European Committee for Standardization, BS EN 1993-1-8:2005, Brussels, 2005.

[26] Liang, Y. Behavior of bolted connections during and after a Fire. PhD thesis, University of Texas, Austin, 2006.

[27] Yan, S. and Young, B. Tests of single shear bolted connections of thin sheet steels at elevated temperatures - Part I: Steady state tests. Thin-Walled Structures, 2011; 49(10): 1320-1333.

Notation

W nominal width of connection specimen;

t nominal thickness of stainless steel tube;

d nominal diameter of stainless steel bolt;

d_0 nominal diameter of bolt hole;

h height of lip in the connection specimen;

e_1 end distance; 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; the edge distance from the centre of a bolt hole to the adjacent edge of any part, measured at right angles to the direction of load transfer;

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 centres of bolt holes;

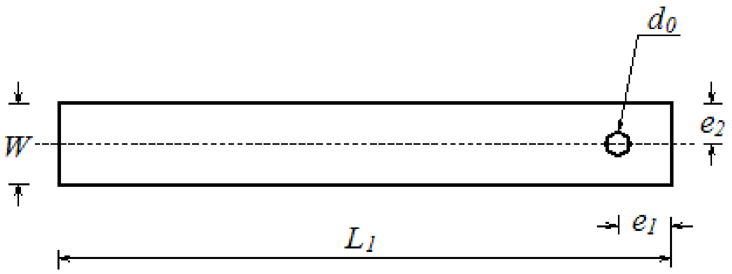
L_1 the length of specimen plate; the length of middle specimen plate for double shear connection;

L_2 the length of lip in the specimen plate;

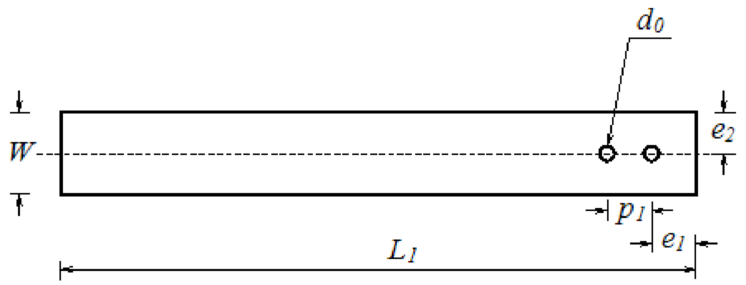
$P_{u,N}$ experimental ultimate load of bolted connection for specimens without expose to high temperatures;

$P_{u,P}$ experimental ultimate load of bolted connection for specimens at post-fire condition.

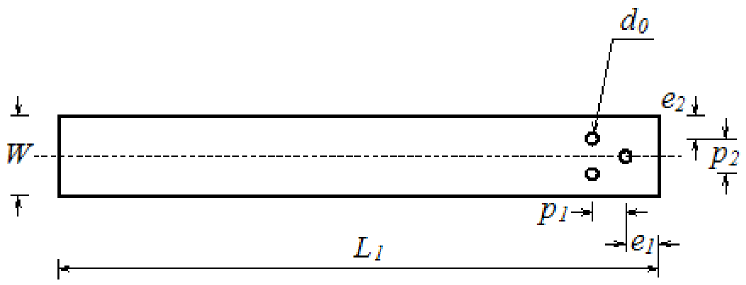
8 Figures



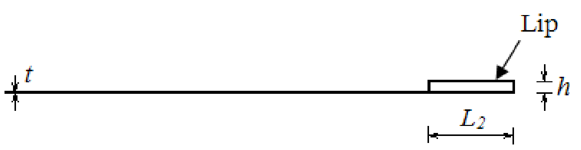
(a) Plate with one bolt hole



(b) Plate with two-parallel bolt holes



(c) Plate with three bolt holes



(d) Lip in the single shear connection plates

Fig. 1 Configuration of connection specimens

Fig. 2 Heating up of connection specimen inside the furnace

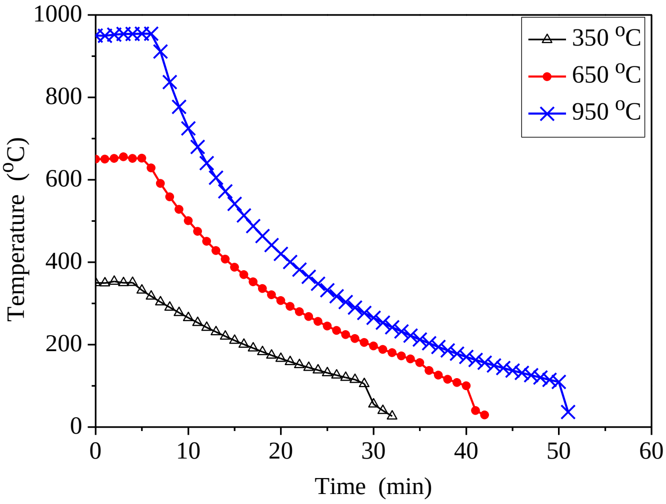


Fig. 3 Typical temperature-time records of specimens cooled down from nominal high temperatures

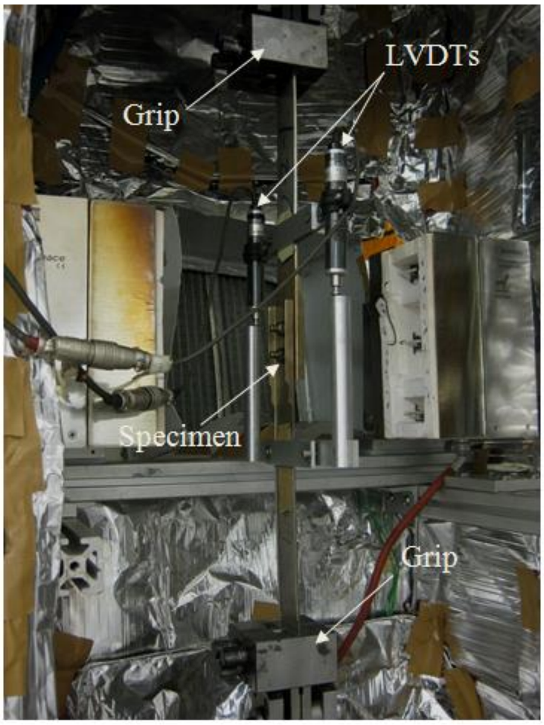
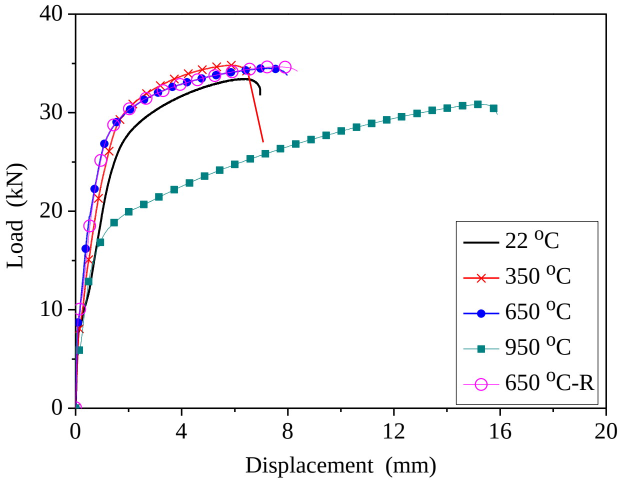
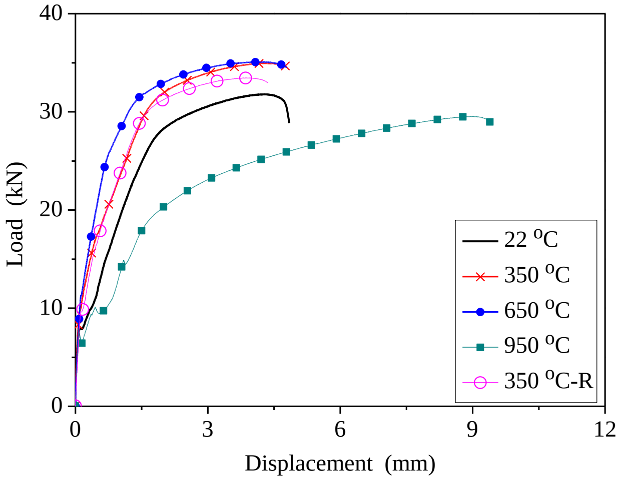


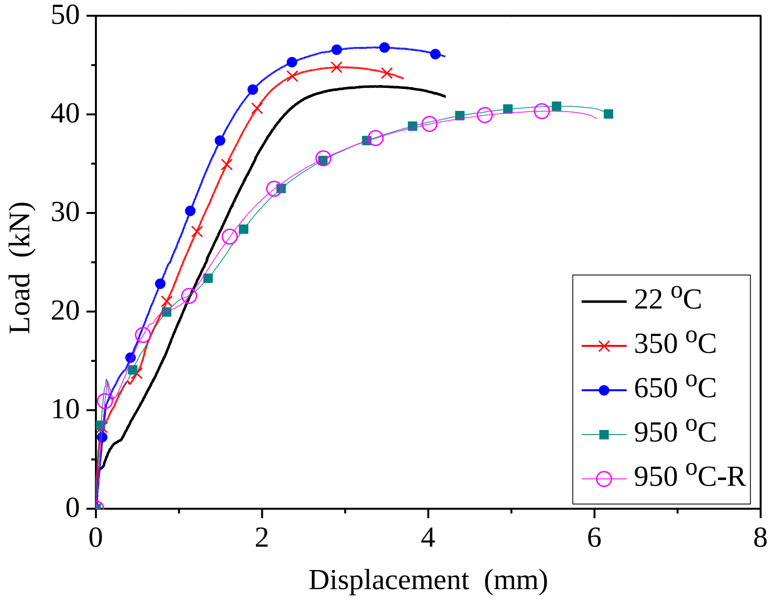
Fig. 4 Test set-up of the single shear two-parallel bolted connection specimen at post-fire condition



(a) Series A-D-3

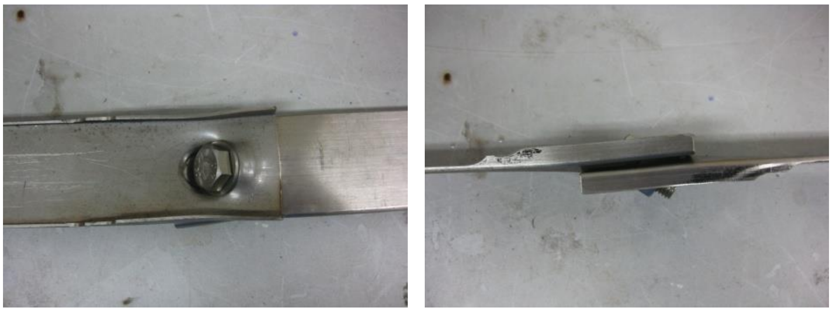


(b) Series T-D-3

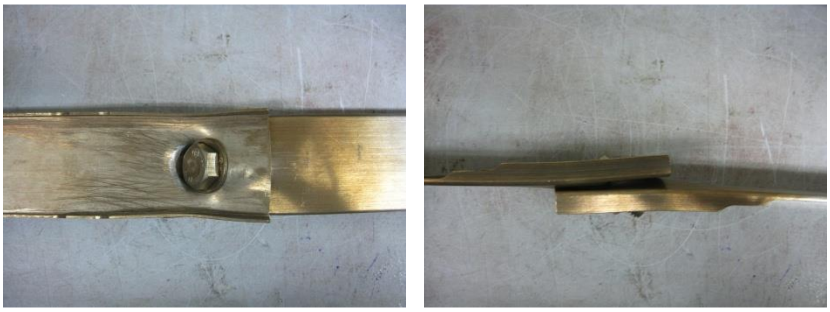


(c) Series L-D-3

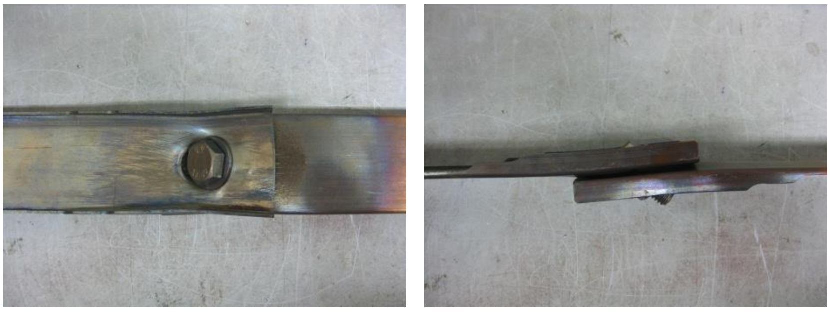
Fig. 5 Load-displacement curves of connection specimens with and without post-fire conditions



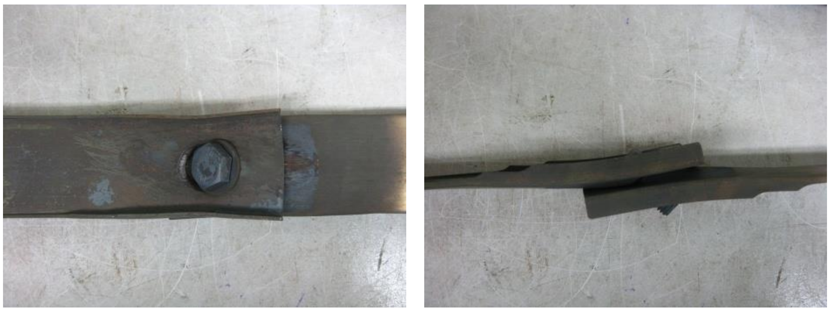
(a) 22 ℃



(b) 353 ℃

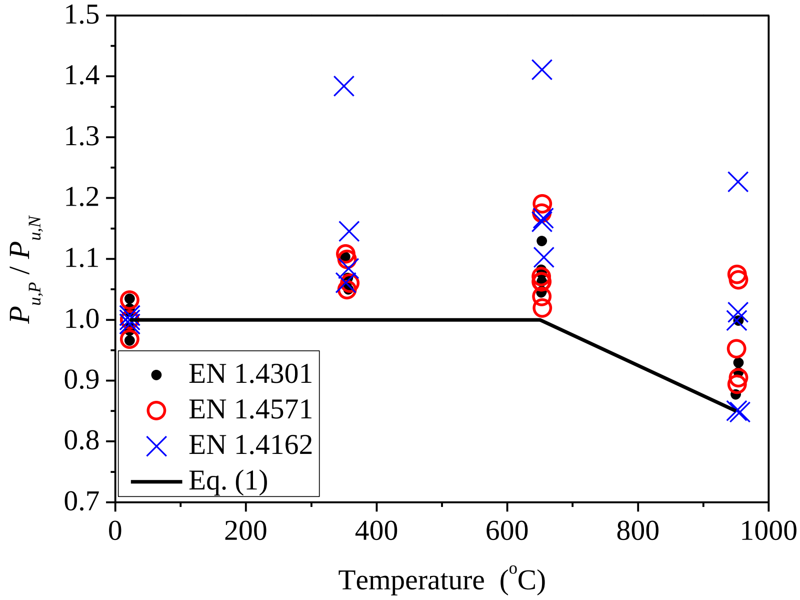


(c) 654 ℃

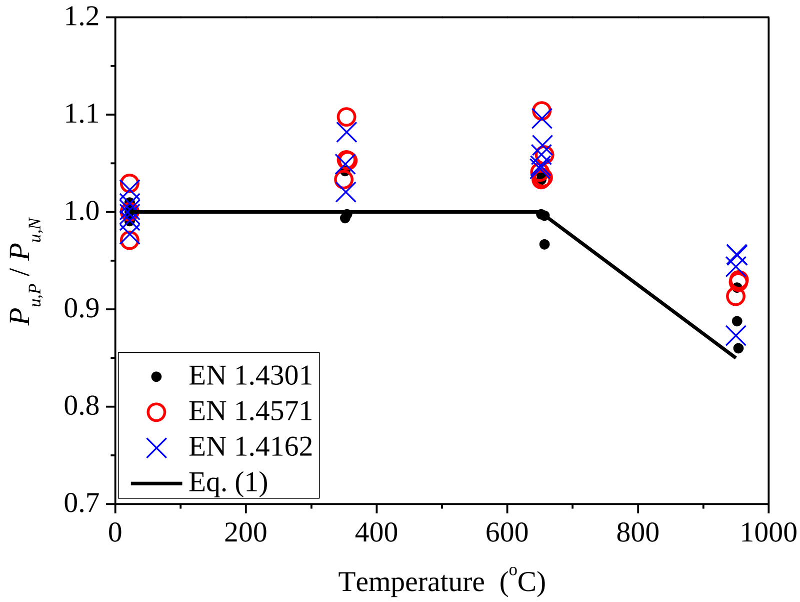


(d) 952 ℃

Fig. 6 Failure mode of specimens T-S-1-12 with and without post-fire conditions



(a) Single shear



(b) Double shear

Fig. 7 Comparison of test strengths for specimens with and without post-fire conditions

Fig. 8 Location of sample taken from tested stainless steel bolted connection specimens

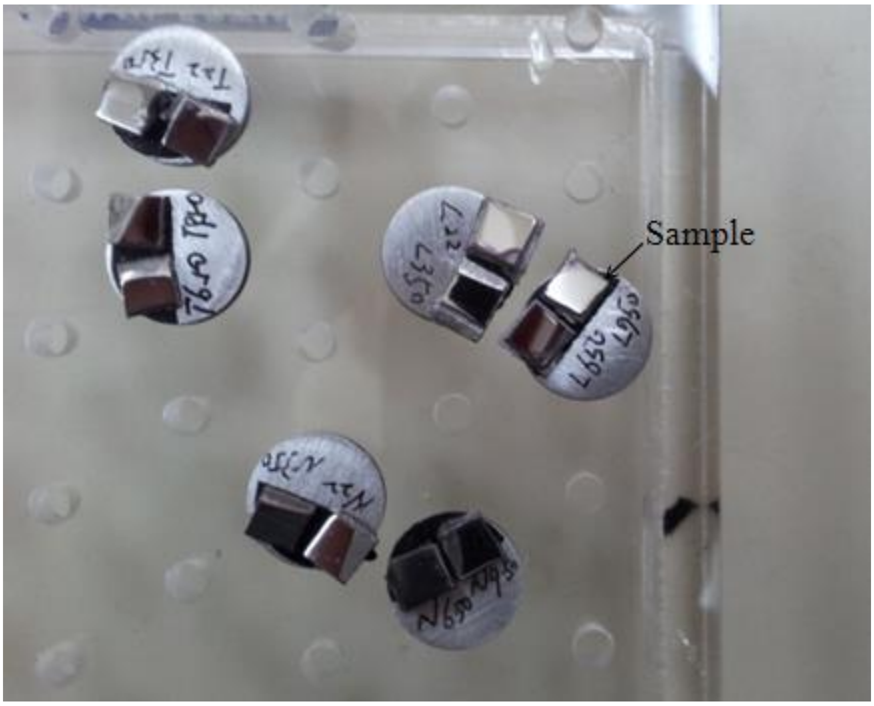
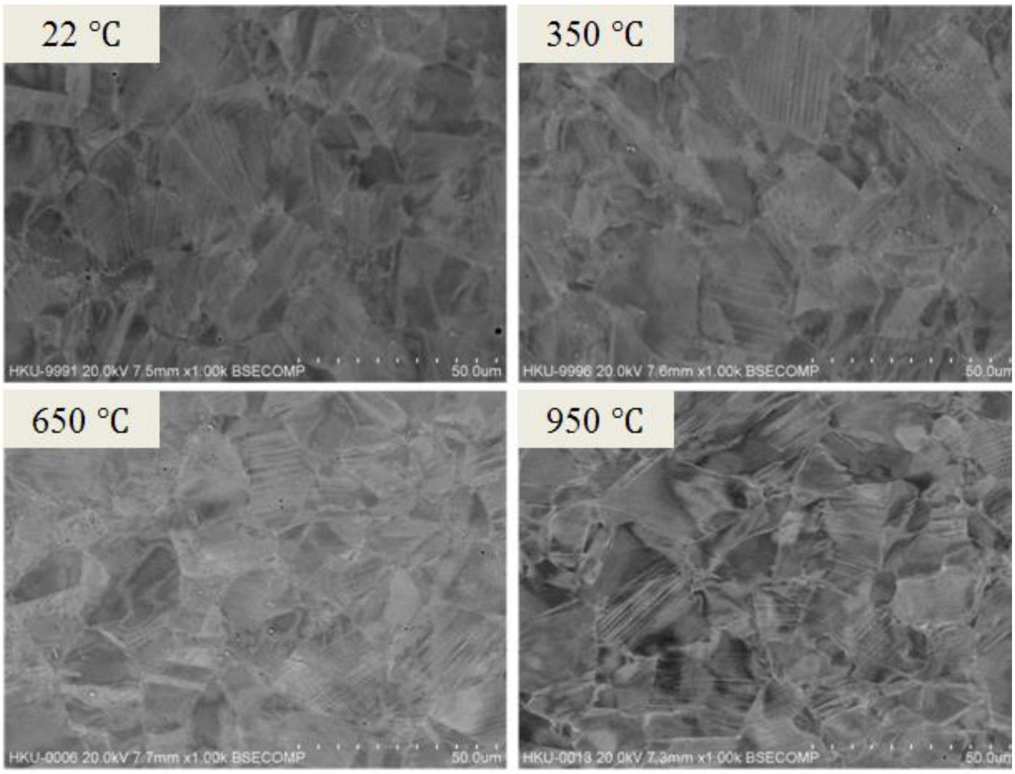
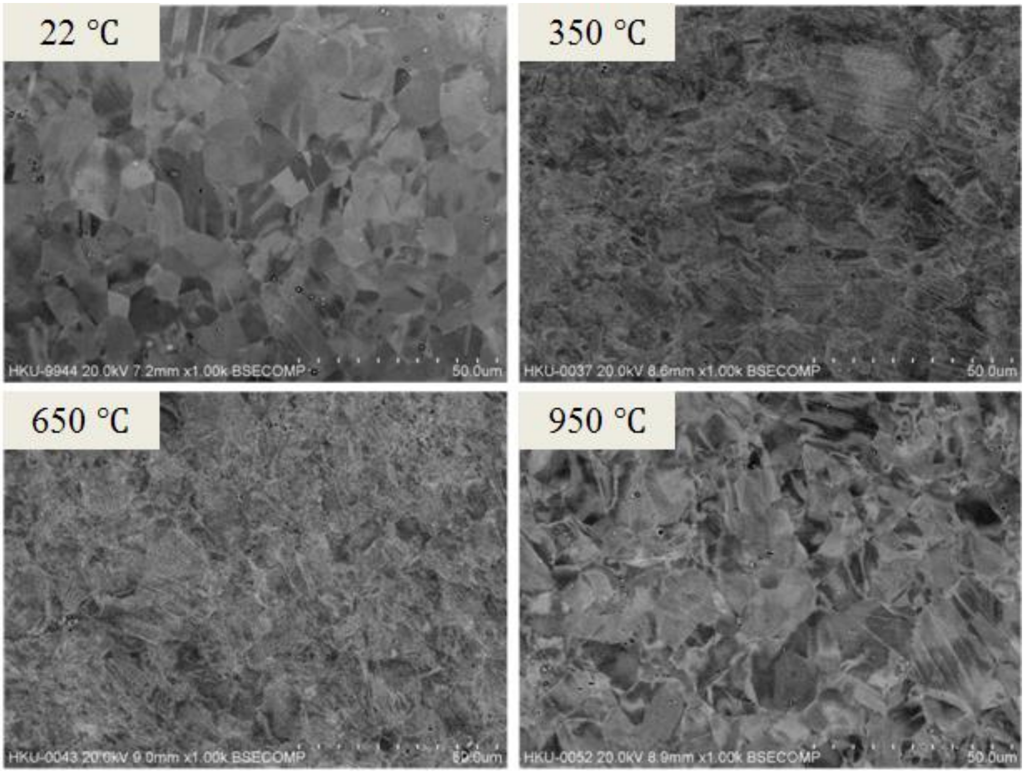


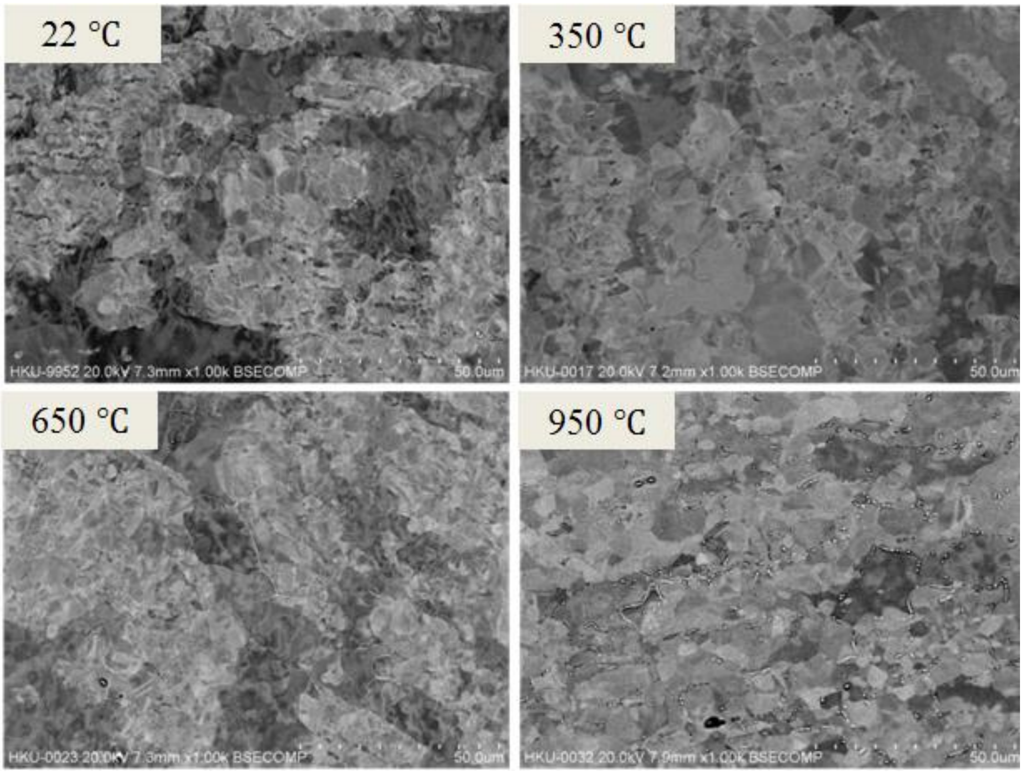
Fig. 9 The polished samples for scanning electron microscope (SEM) study



(a) Type A (EN 1.4301)



(b) Type T (EN 1.4571)



(c) Type L (EN 1.4162)

Fig. 10 SEM images of samples from different grades of cold-formed stainless steel with and without post-fire conditions

9 Tables

Table 1 Nominal dimensions of the plates for cold-formed stainless steel bolted connection specimens [11]

Specimen	Nominal (mm)						
	h	L_2	e_1	e_2	p_1	p_2	L_1
A-S-1-12	10	72	36	25	---	---	381
T-S-1-12	10	72	36	25	---	---	381
L-S-1-12	10	72	36	25	---	---	381
A-S-2Pa-8	10	81	27	25	27	---	386
T-S-2Pa-8	10	81	27	25	27	---	386
L-S-2Pa-8	10	81	27	25	27	---	386
A-S-3-8	10	81	27	14	27	22	386
T-S-3-8	10	81	27	14	27	22	386
L-S-3-8	10	81	27	14	27	22	386
A-D-1-12	---	---	55	25	---	---	405
T-D-1-12	---	---	55	25	---	---	405
L-D-1-12	---	---	55	25	---	---	405
A-D-2Pa-8	---	---	45	25	27	---	404
T-D-2Pa-8	---	---	45	25	27	---	404
L-D-2Pa-8	---	---	45	25	27	---	404
A-D-3-8	---	---	45	14	27	22	404
T-D-3-8	---	---	45	14	27	22	404
L-D-3-8	---	---	45	14	27	22	404

Table 2 Post-fire test results of cold-formed stainless steel single shear bolted connections

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}/ P_{u,N}$	Failure Mode
A-S-1-12	22	34.9*	1.01	B
	22	34.0	0.99	B
	352	38.0	1.10	B
	653	38.9	1.13	B
	954	34.4	1.00	B
A-S-2Pa-8	22	38.9*	1.02	B
	22	37.5*	0.98	B
	357	40.1	1.05	B
	354	40.3	1.05	B
	653	40.0	1.05	B
	653	40.6	1.06	B
	652	39.9	1.04	B
	954	35.5	0.93	B
	950	33.5	0.88	B
A-S-3-8	22	45.4*	1.03	B+NS
	22	42.4*	0.97	B+NS
	356	46.9	1.07	B+NS
	652	47.5	1.08	B+NS
	653	47.2	1.08	B+NS
	954	40.1	0.91	B+NS

Note: * reported in Cai and Young [11]

(a) Type A (EN 1.4301)

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}$/ $P_{u,N}$	Failure Mode
T-S-1-12	22	31.8*	0.97	B
	22	33.9	1.03	B
	353	36.4	1.11	B
	355	36.1	1.10	B
	654	39.1	1.19	B
	653	38.6	1.18	B
	954	35.0	1.07	B
	952	35.3	1.07	B
T-S-2Pa-8	22	36.7*	1.00	B
	355	38.5	1.05	B
	653	38.1	1.04	B
	652	39.3	1.07	B
	654	37.4	1.02	B
	954	33.2	0.90	B
	952	32.8	0.89	B
T-S-3-8	22	41.7*	1.00	B+NS
	359	44.2	1.06	B+NS
	653	44.3	1.06	B+NS
	652	44.3	1.06	B+NS
	951	39.7	0.95	B+NS

Note: * reported in Cai and Young [11]

(b) Type T (EN 1.4571)

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}$/ $P_{u,N}$	Failure Mode
	22	37.1*	1.01	B
	22	36.6	0.99	B
L-S-1-12	350	51.0	1.38	B
	653	52.0	1.41	B
	953	45.2	1.23	B
	22	42.8*	1.00	B+BS
	22	42.8*	1.00	B+BS
	357	46.4	1.08	B+BS
L-S-2Pa-8	353	45.4	1.06	B+BS
	656	47.2	1.10	B+BS
	956	36.3	0.85	B+BS
	951	36.4	0.85	B+BS
	22	52.2*	1.01	B+NS
	22	51.5*	0.99	B+NS
	358	59.4	1.15	B+NS
L-S-3-8	655	60.5	1.17	B+NS
	653	60.2	1.16	B+NS
	953	52.5	1.01	B+NS
	951	51.8	1.00	B+NS

Note: * reported in Cai and Young [11]

(c) Type L (EN 1.4162)

Table 3 Post-fire test results of cold-formed stainless steel double shear bolted connections

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}$/ $P_{u,N}$	Failure Mode
A-D-1-12	22	38.5*	1.01	B
	22	37.8	0.99	B
	352	37.9	0.99	B
	657	38.0	1.00	B
	954	32.8	0.86	B
A-D-2Pa-8	22	42.2*	1.01	B
	22	41.4*	0.99	B
	355	41.7	1.00	B
	652	41.7	1.00	B
	657	40.4	0.97	B
	952	37.1	0.89	B
A-D-3-8	22	33.4*	1.00	B+NS
	352	34.8	1.04	B+NS
	652	34.5	1.03	B+NS
	652	34.7	1.04	B+NS
	952	30.8	0.92	B+NS

Note: * reported in Cai and Young [11]

(a) Type A (EN 1.4301)

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}$/ $P_{u,N}$	Failure Mode
T-D-1-12	22	35.3*	1.03	B
	22	33.3*	0.97	B
	356	36.1	1.05	B
	655	35.5	1.03	B
	657	36.3	1.06	B
	955	31.9	0.93	B
T-D-2Pa-8	22	39.2*	1.00	B
	350	40.5	1.03	B
	650	40.8	1.04	B
	652	40.5	1.03	B
	950	35.8	0.91	B
T-D-3-8	22	31.8*	1.00	B+NS
	354	34.9	1.10	B+NS
	354	33.5	1.05	B+NS
	653	35.1	1.10	B+NS
	954	29.5	0.93	B+NS

Note: * reported in Cai and Young [11]

(b) Type T (EN 1.4571)

Specimen series	Temperature (℃)	$P_{u,N}$ or $P_{u,P}$ (kN)	$P_{u,P}/ P_{u,N}$	Failure Mode
L-D-1-12	22	47.1*	1.02	B
	22	45.0*	0.98	B
	353	47.0	1.02	B
	654	49.2	1.07	B
	650	48.1	1.04	B
	950	40.2	0.87	B
L-D-2Pa-8	22	52.2*	1.01	B
	22	51.3*	0.99	B
	354	56.0	1.08	B
	652	54.8	1.06	B
	651	54.2	1.05	B
	951	49.5	0.96	B
L-D-3-8	22	42.8*	1.00	B+NS
	22	42.6*	1.00	B+NS
	352	44.8	1.05	B+NS
	653	46.8	1.10	B+NS
	952	40.8	0.96	B+NS
	950	40.3	0.94	B+NS

Note: * reported in Cai and Young [11]

(c) Type L (EN 1.4162)

Table 4 Chemical composition of different grades of cold-formed stainless steel

Cold-formed stainless Steel	From mill certificates					From SEM EDX spectrum				
	Element (%)					Element (%)				
	Si	Cr	Mn	Ni	Ti	Si	Cr	Mn	Ni	Ti
A (EN 1.4301)	0.40	18.2	1.6	8.1	---	0.32	18.7	1.8	7.9	---
T (EN 1.4571Ti)	0.39	16.9	1.3	10.7	0.34	0.39	17.1	1.3	10.7	0.26
L (EN 1.4162)	0.76	21.3	5.0	1.5	---	0.77	21.7	5.2	1.4	---