Structural Behaviour of Cold Formed Stainless Steel Bolted Connections

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Abstract

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

Keywords

Bolted connection, experimental investigation, failure mode, material properties, stainless steel, ultimate strength.

1   Introduction

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

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

2   Experimental Investigation

2.1   Test specimens

Three types of cold-formed stainless steel were investigated in this study, including austenitic stainless steels EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti having small amount of titanium) as well as lean duplex stainless steel EN1.4162 (AISI S32101). The austenitic stainless steels have a lower strength than the lean duplex material. The lean duplex stainless steel is considered as high strength material and the austenitic stainless steels as normal strength materials. For simplicity, these three types of stainless steels, EN1.4301 (AISI 304), EN1.4571 (AISI 316Ti) and EN1.4162 (AISI S32101) are labelled as types A, T and L, respectively, in the context of this paper.

The coupon test specimens and connection test specimens were both cut from the same batch of stainless steel rectangular hollow sections. The stainless steel hollow sections were supplied from STALA Tube Finland in uncut lengths of 3000 mm and nominal section size of 20×50×1.5 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 two-bolted test specimens of the assembled connected parts are illustrated in Fig. 1. The single shear connection specimen is bolted with two plates together having one shear plane, while the double shear connection specimen is bolted with three plates having two shear planes. It should be noted that the connection specimens were designed with lips as shown in Figs 1 and 2. Previous researchers found that standard flat specimens curled out of plane and affected the mode of failure [11] and may not accurately represent the true behaviour of profiled structural members, for example channel sections. Therefore, lips of nominal 10 mm height were used in the connection specimens to prevent the out-of-plane curling at the overlapped connection region in this study. The 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 372-405 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.
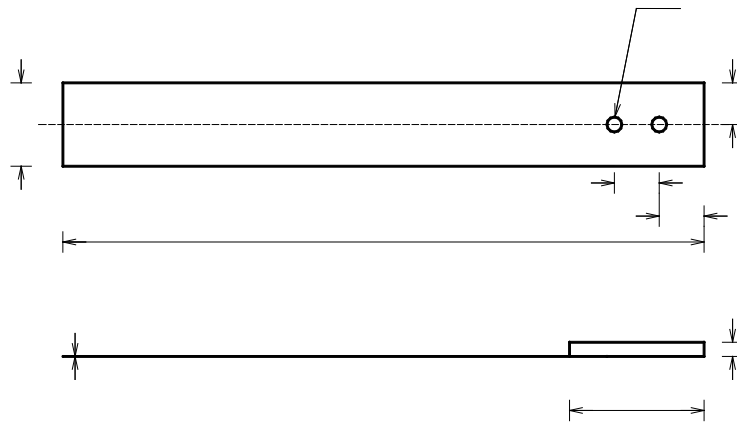

(a) Single shear   (b) Double shear
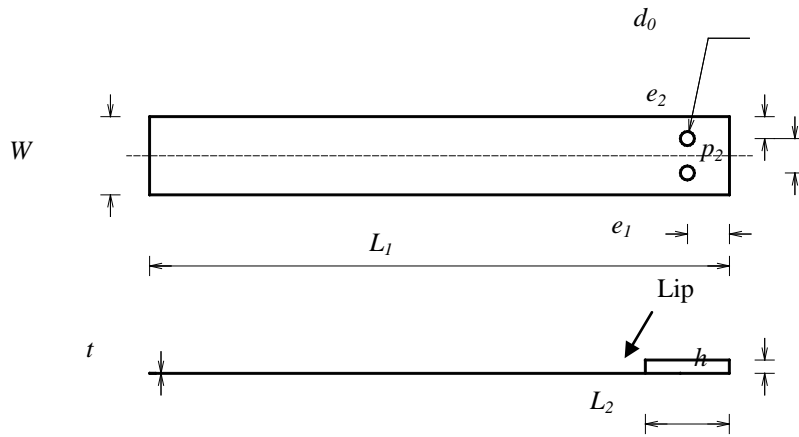
Fig. 1   Test specimens of two-perpendicular bolted connections
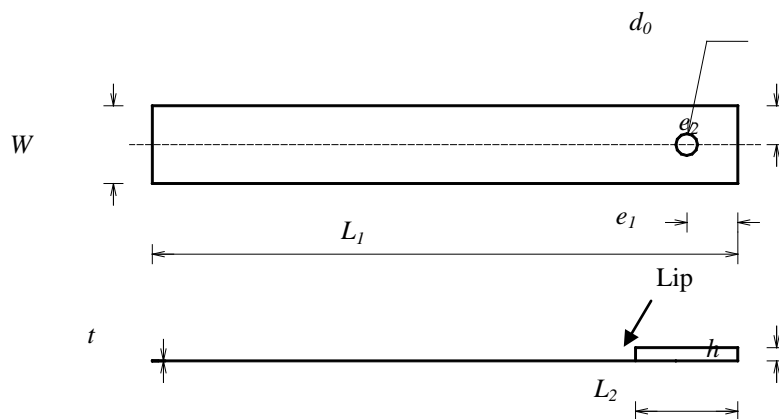
(a) One-bolted connection
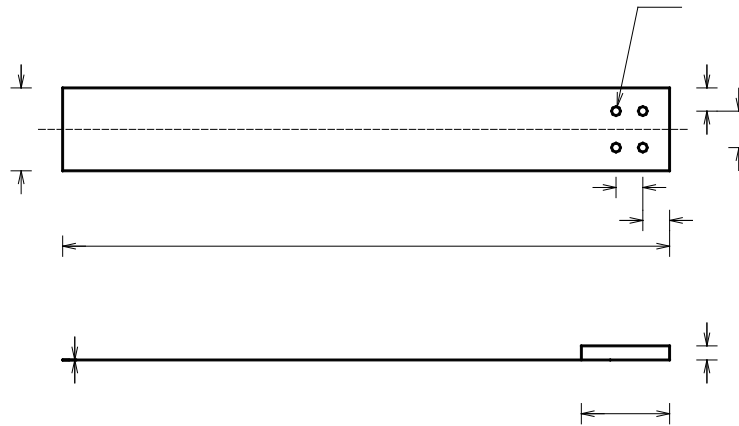
(b) Two-parallel bolted connection

d_0

e_2

p_2

W

L_1

e_1

Lip

t

h

L_2

(c) Two-perpendicular bolted connection

d_0

e_2

p_2

W

p_1

L_1

e_1

Lip

t

h

L_2
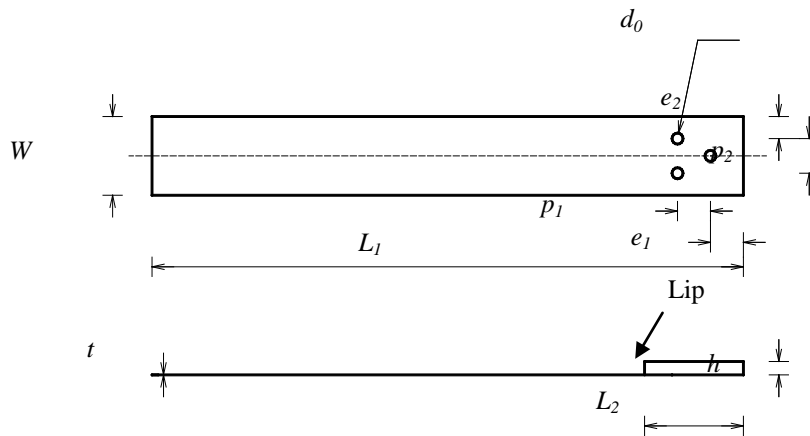
(d) Three-bolted connection

(e)   Four-bolted connection

Fig. 2.   **Configuration of connection specimens**

Each type of connection specimen has five different configurations of bolt number and bolt arrangement as shown in Fig. 2. The bolts assembled in the specimens were all hand-tightened to a torque of approximately 10 Nm, which allowed slip in the bolt holes of the connection at a small load level. Four different sizes of A4 stainless steel bolts [15] of grade 8.8 were used, namely M6, M8, M10 and M12 bolts. Standard size of bolt holes (d_o) were adopted in accordance with the ASCE [4] and AS/NZS standards [5], 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. The spacing requirements in the connection as specified in the specifications [4, 5 and 14] as well as the nominal spacing of the single shear and double shear bolted connection test specimens are presented in Tables 1-3, respectively. Generally, the spacing in the connected parts satisfies the minimum requirements of the specifications, except for the case when there are two bolt holes perpendicular to the direction of loading as shown in Fig. 2(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 [14], but 2 mm less than the minimum requirements of 24 mm in the ASCE Specification [4] and AS/NZS Standard [5].

Table 1   Spacing requirements in different specification

Specification	End distance e_1	Edge distance e_2	Longitudinal spacing p_1	Transverse spacing p_2
EC3-1.8	$\geq 1.2d_0$	$\geq 1.2d_0$	$\geq 2.2d_0$	$\geq 2.4d_0$
ASCE	$\geq 1.5d$	$\geq 1.5d$	$\geq 3.0d$	$\geq 3.0d$
AS/NZS	$\geq 1.5d$	$\geq 1.5d$	$\geq 3.0d$	$\geq 3.0d$

Table 2   Nominal and measured dimensions of the single shear bolted connection specimens

Specimen	Nominal (mm)							Measured (mm)
	h	L_2	e_1	e_2	p_1	p_2	L_1	t_m
A-S-1-10	10	66	33	25	---	---	381	1.44
A-S-1-12	10	72	36	25	---	---	381	1.48
T-S-1-12	10	72	36	25	---	---	381	1.47
L-S-1-10	10	66	33	25	---	---	381	1.48

Specimen								
L-S-1-12	10	72	36	25	---	---	381	1.50
A-S-2Pa-8	10	81	27	25	27	---	386	1.44
A-S-2Pa-8-R	10	81	27	25	27	---	386	1.45
T-S-2Pa-8	10	81	27	25	27	---	386	1.45
L-S-2Pa-8	10	81	27	25	27	---	386	1.47
L-S-2Pa-8-R	10	81	27	25	27	---	386	1.44
A-S-2Pe-8	10	54	27	14	---	22	372	1.47
A-S-2Pe-8-R	10	54	27	14	---	22	372	1.44
T-S-2Pe-8	10	54	27	14	---	22	372	1.44
L-S-2Pe-8	10	54	27	14	---	22	372	1.46
L-S-2Pe-8-R	10	54	27	14	---	22	372	1.45
A-S-3-6	10	63	21	14	21	22	377	1.46
A-S-3-8	10	81	27	14	27	22	386	1.48
A-S-3-8-R	10	81	27	14	27	22	386	1.45
T-S-3-8	10	81	27	14	27	22	386	1.45
L-S-3-8	10	81	27	14	27	22	386	1.46
L-S-3-8-R	10	81	27	14	27	22	386	1.44
A-S-4-6	10	63	21	14	21	22	377	1.45
A-S-4-6-R	10	63	21	14	21	22	377	1.44
T-S-4-6	10	63	21	14	21	22	377	1.47
T-S-4-6-R	10	63	21	14	21	22	377	1.47
L-S-4-6	10	63	21	14	21	22	377	1.46
L-S-4-8	10	81	27	14	27	22	386	1.46

Table 3   Nominal and measured dimensions of the middle plates for double shear bolted connection specimens

Specimen	Nominal (mm)				Measured (mm)	
	e_1	e_2	p_1	p_2	L_1	t_m
A-D-1-12	55	25	---	---	405	1.45
T-D-1-12	55	25	---	---	405	1.46
T-D-1-12-R	55	25	---	---	405	1.47
L-D-1-12	55	25	---	---	405	1.47
L-D-1-12-R	55	25	---	---	405	1.46
A-D-2Pa-8	45	25	27	---	404	1.45
A-D-2Pa-8-R	45	25	27	---	404	1.45
T-D-2Pa-8	45	25	27	---	404	1.45
L-D-2Pa-8	45	25	27	---	404	1.45
L-D-2Pa-8-R	45	25	27	---	404	1.45
A-D-2Pe-8	45	14	---	22	390	1.46
T-D-2Pe-8	45	14	---	22	390	1.48

L-D-2Pe-8	45	14	---	22	390	1.47
L-D-2Pe-8-R	45	14	---	22	390	1.49
A-D-3-8	45	14	27	22	404	1.47
T-D-3-8	45	14	27	22	404	1.47
L-D-3-8	45	14	27	22	404	1.46
L-D-3-8-R	45	14	27	22	404	1.48
A-D-4-6	35	14	21	22	391	1.45
A-D-4-6-R	35	14	21	22	391	1.46
T-D-4-6	35	14	21	22	391	1.48
L-D-4-8	45	14	27	22	404	1.45

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 as shown in Tables 2 and 3, respectively. Each group of connection contains five different configurations based on the number of bolt and bolt arrangement. Each specimen is generally labelled by four segments in order to identify the type of stainless steel, the connection type, the number of bolt and bolt arrangement as well as the bolt size. For example, the labels "A-S-4-6-R" and "T-D-2Pa-8" define the following specimens:

- The first letter indicates the type of stainless steel, where A = EN1.4301 (AISI 304) and T = EN1.4571 (AISI 316Ti).
- The second letter represents 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, where "4" means that there are four bolts used in the specimen. If the specimen is assembled by two bolts, then the letters "Pa" mean the bolts arranged parallel to the loading direction, while "Pe" mean the bolts arranged perpendicular to the loading direction, as shown in Figs 2(b) and 2(c), respectively. 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 "6" represents the bolt diameter of 6 mm, while "8" stands for 8 mm.
- If a test was repeated, then the last letter "R" indicates the repeated test.

2.3 Material properties

Longitudinal tensile coupon tests were conducted to determine the material properties of each type of stainless steel. The coupon test specimens were extracted from the untested specimens in the longitudinal direction belonging to the same batch of stainless steel connection specimens. The coupons were taken from the centre of the web face at 90° angle from the weld. The coupons were designed in accordance with the Australian Standard AS-1391 [16]. The dimension of the coupon specimens had 6 mm width and 25 mm gauge length. The coupons were tested in an MTS 810 Universal testing machine using friction grips. A calibrated extensometer of 25 mm gauge length was used to measure the longitudinal strain of the coupon specimens.

A constant tensile loading rate of 0.5 mm/min was used and the strain rate obtained from the extensometer was approximately 0.0002/s in the non-linear range of the stress-strain curves, which is smaller than the range from 0.00025 to 0.0025/s as specified by the Australian Standard AS-1391 [16]. The static load was obtained by pausing the applied strain for 1.5 minutes near the 0.2% tensile proof stress ($f_{0.2}$) and the ultimate tensile strength (f_u). This allows the stress relaxation associated with plastic straining to take place. Therefore, the static $f_{0.2}$ and f_u were obtained from the stress-strain curves. The dynamic $f_{0.2}$ and f_u were also obtained, where the term dynamic is used in the context of this paper to refer the $f_{0.2}$ and f_u obtained from the stress-strain curves under constant loading rate without considering the stress relaxation take place. A data acquisition system was used to record the specimen strain and applied load at regular intervals during the test. The material properties obtained from the tensile coupon tests are presented in Table 4. The material properties include the initial elastic Young's modulus E, static and dynamic 0.2% proof stress ($f_{0.2}$), static and dynamic tensile strength (f_u), maximum strain after fracture (ε) based on the measured gauge length and the parameter n. The Ramberg-Osgood parameter n is used to describe the initial non-linear part of the stress-strain curve, and was obtained from the measured $0.01\% (f_{0.01})$ and $0.2\% (f_{0.2})$ proof stresses using the equation $n = ln(0.01/0.2) / ln(f_{0.01}/f_{0.2})$.

Table 4   Material properties obtained from tensile coupon tests

Test series	Type	E	Static			Dynamic			ε
		GPa	$f_{0.2}$ MPa	f_u MPa	n	$f_{0.2}$ MPa	f_u MPa	n	%
A	EN1.4301 (AISI 304)	199	438	720	5	474	759	5	52.6
T	EN1.4571 (AISI 316Ti)	199	444	648	8	463	677	7	46.8
L	EN1.4162 (AISI S32101)	200	675	813	4	724	862	7	36.8

The 0.2% proof stress was used as the corresponding yield stress in calculating the nominal strength of the bolted connections in this study. The measured static material properties were also compared with the values obtained from the Eurocode 3 Part 1-4 (EC3-1.4) [6] and STALA Tube mill certificates as shown in Table 5. It is found that the $f_{0.2}$ and f_u obtained from the coupon tests are higher than the values obtained from the EC3-1.4 and mill certificates for all three types of stainless steel.

Table 5   Comparison of static material properties with data obtained from Eurocode and STALA

Test series	Euro Code 3-1.4		Test/EC3-1.4		STALA		Test/STALA	
	$f_{0.2,EC}$ (MPa)	$f_{u,EC}$ (MPa)	$\dfrac{f_{0.2}}{f_{0.2,EC}}$	$\dfrac{f_u}{f_{u,EC}}$	$f_{0.2,mill}$ (MPa)	$f_{u,mill}$ (MPa)	$\dfrac{f_{0.2}}{f_{0.2,mill}}$	$\dfrac{f_u}{f_{u,mill}}$
A	230	540	1.90	1.33	268	623	1.63	1.16
T	240	540	1.85	1.20	300	606	1.48	1.07
L	---	---	---	---	603	804	1.12	1.01

2.4   Shear resistance of stainless steel bolts

The shear resistances of stainless steel bolts were tested. The A4 stainless steel bolts of grade 8.8 [15] were used in this study. The quality of stainless steel bolts is quite important as the bolted connection specimens were designed to avoid bolt shear failure. The stainless steel bolts had the threads extended up to the bolt heads. The measured dimensions of the stainless steel bolts and the corresponding washers are shown in Table 6. The shear resistance of the bolts was determined by one-bolted single shear connection tests. Thick steel plates were used in the tests to avoid bearing failure of the steel plates. The bolts were assembled with washers on both sides of the bolted connections. Each type of bolt (M6, M8 and M10) was tested twice and the test results are shown in Table 7.

Table 6   Measured dimensions of stainless steel bolts and washers

Type	Grade 8.8 stainless steel bolt	Stainless steel washer		
	diameter (mm)	Inner diameter (mm)	Outside diameter (mm)	Thickness (mm)
M6	5.8	6.4	12.7	1.5
M8	7.9	8.6	17.7	1.5
M10	9.8	10.4	21.8	1.5
M12	11.8	12.6	25.7	1.9

Table 7   Shear resistance of stainless steel bolts under one-bolted single shear connection tests

Type	First test	Second test	Average load
	P_s (kN)	P_s (kN)	P_{s-ave} (kN)
M6	12.5	12.8	12.7
M8	22.7	23.9	23.3
M10	32.6	33.0	32.8

2.5   Test rig and operation

Stainless steel single shear and double shear bolted connections were tested in the same MTS Universal testing machine as those of the coupon tests. A typical double shear bolted connection test set-up is shown in Fig. 3. The schematic views of single shear and double shear bolted connection tests are shown in Fig. 4 and Fig. 5, respectively. Two displacement transducers 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 connected to the grips of the MTS machine.
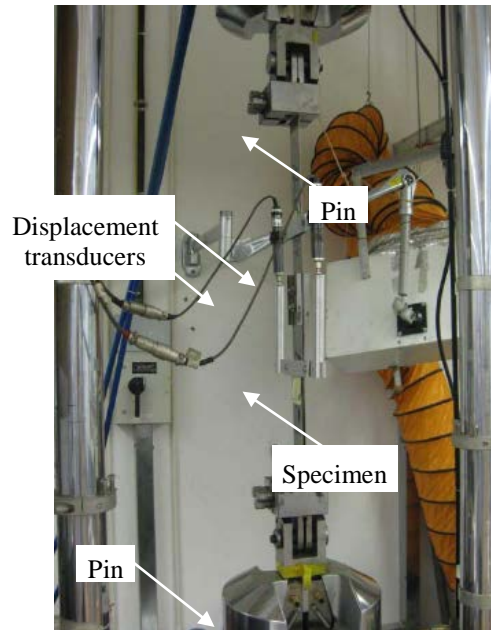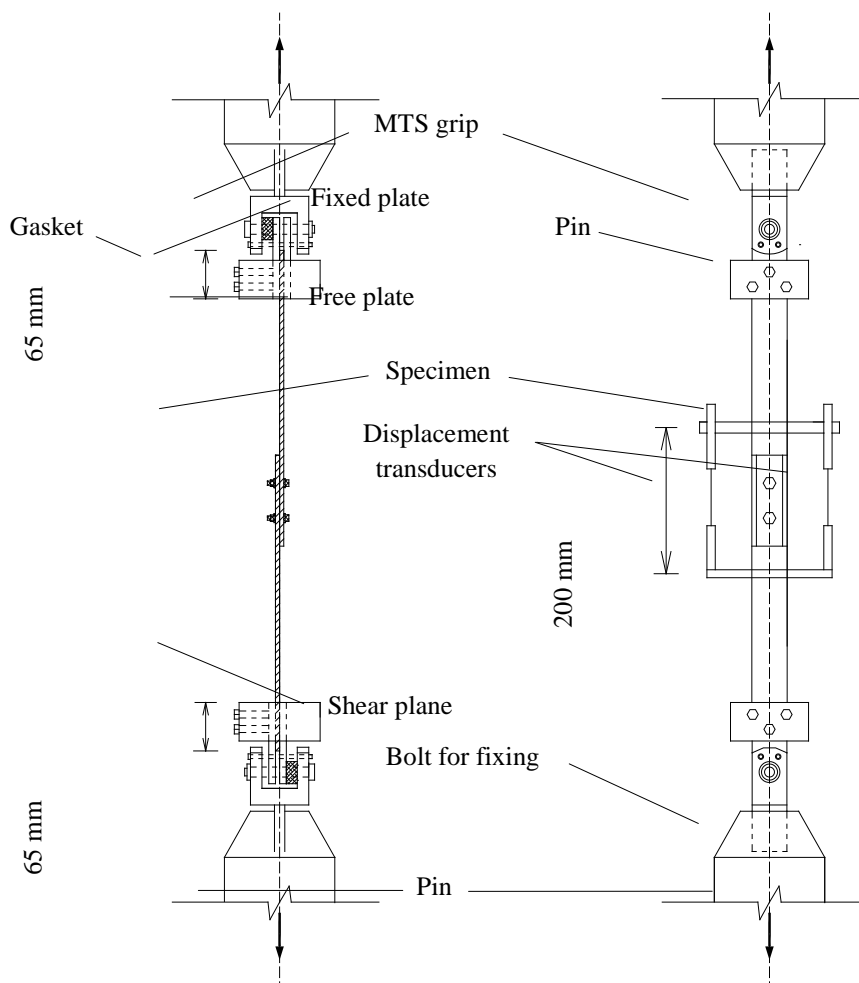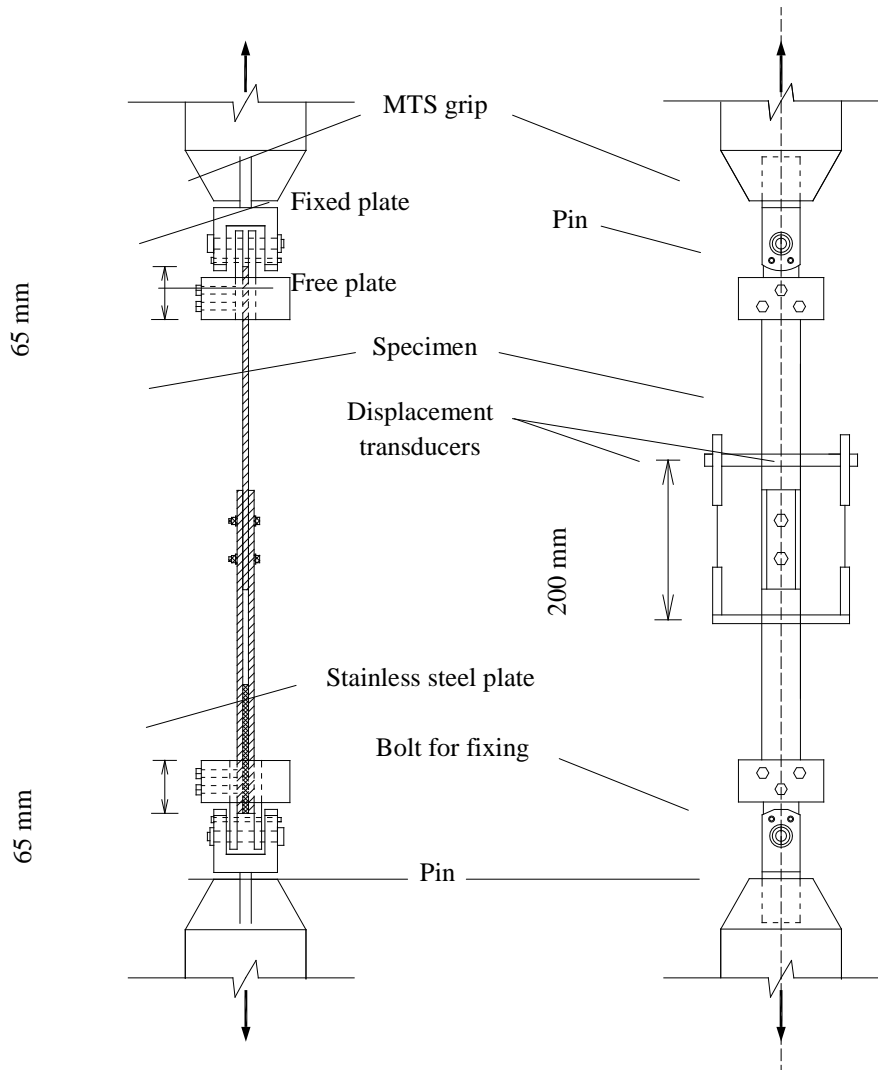

**Fig. 3. Test set-up of cold-formed stainless steel double shear bolted connection**

Fig. 4   **Schematic views of cold-formed stainless steel single shear bolted connection test**

The gripping apparatus mainly comprises of two pieces of steel plates with rough surfaces. One piece of the plate is fixed while another piece is free to move before setting up of the connection specimen. This allows the loading applied through the shear plane in the single shear connection specimens, and loading through the centre line of the double shear connection specimens. One gasket was used in each end of the single shear bolted connection specimens, so that the load can be applied through the shear plane. The gasket is not required in the double shear bolted connection specimens, where the steel plates were adjusted to a specified position according to the thickness of the specimens. In addition, stainless steel plate of nominal thickness 1.5 mm, which having the same thickness as the middle plate of the double shear bolted connection specimens, with 150 mm length was used. Hence, the double shear bolted connection specimens were loaded concentrically during the tests as illustrated in Fig. 5.


Fig. 5   **Schematic views of cold-formed stainless steel double shear bolted connection test**

All specimens were gripped with a constant length of 65 mm in the gripping apparatus and the three specified bolts were tightened by a torque of approximately 80 Nm, which can eliminate the slippage of the test specimens. The bolted connection 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.
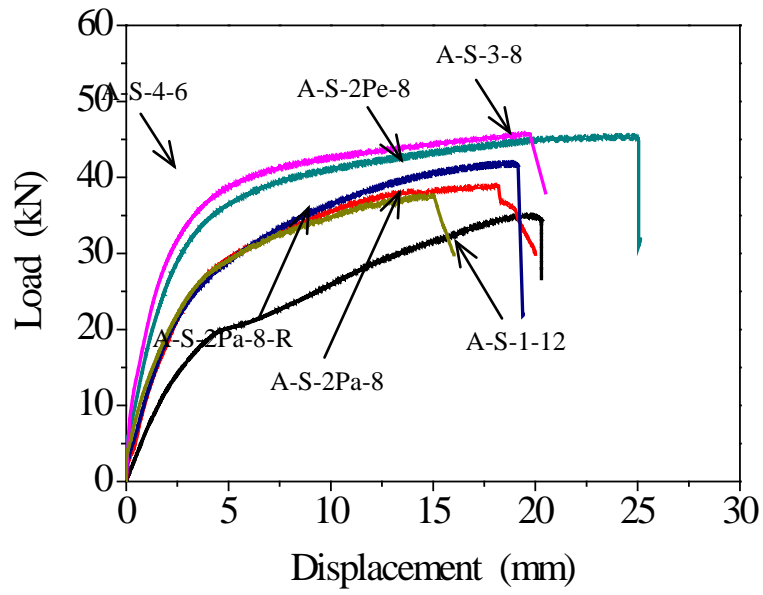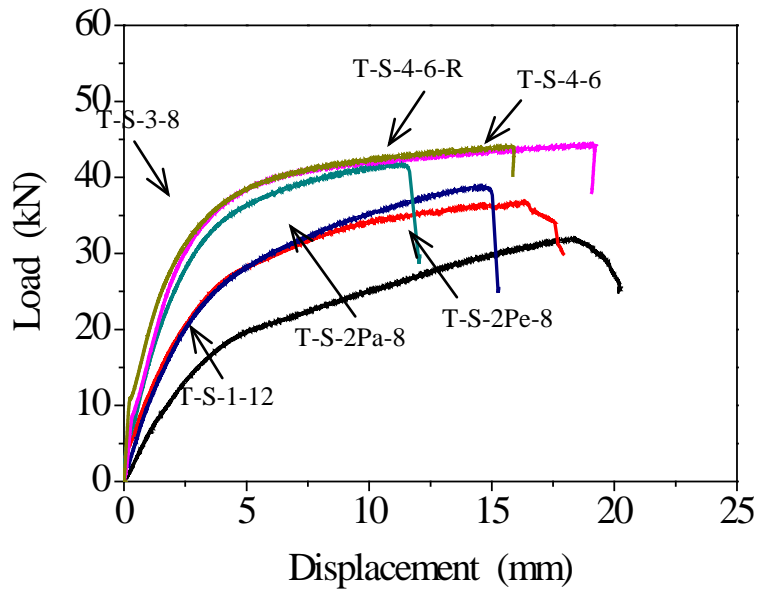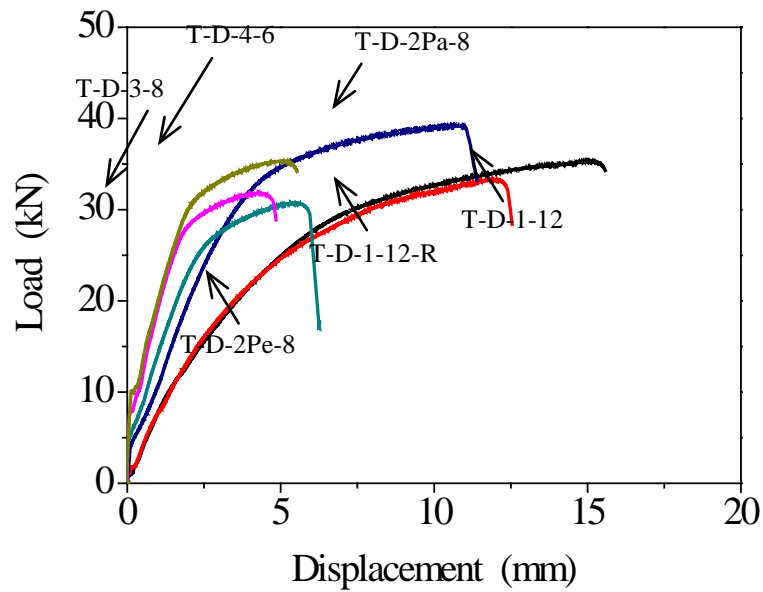
(a) Single shear
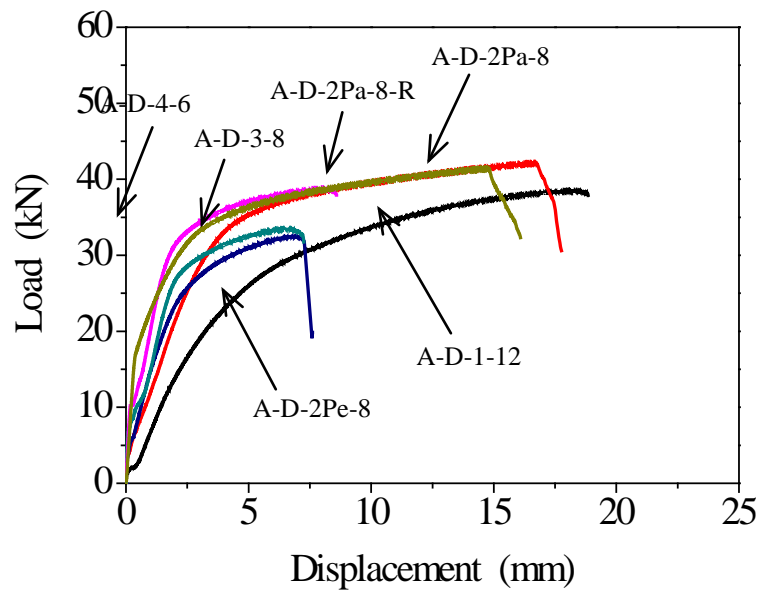
(b) Double shear

Fig.6 **Test curves of austenitic stainless steel EN1.4301 (AISI 304) bolted connections**
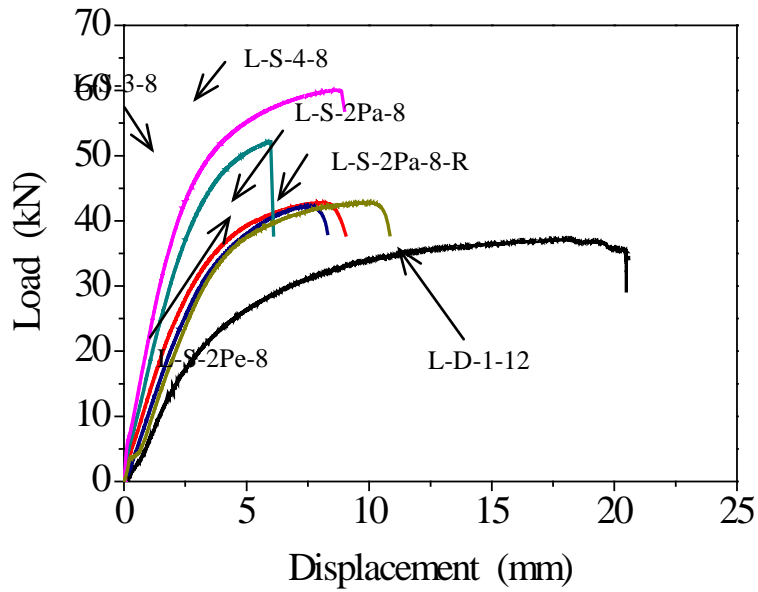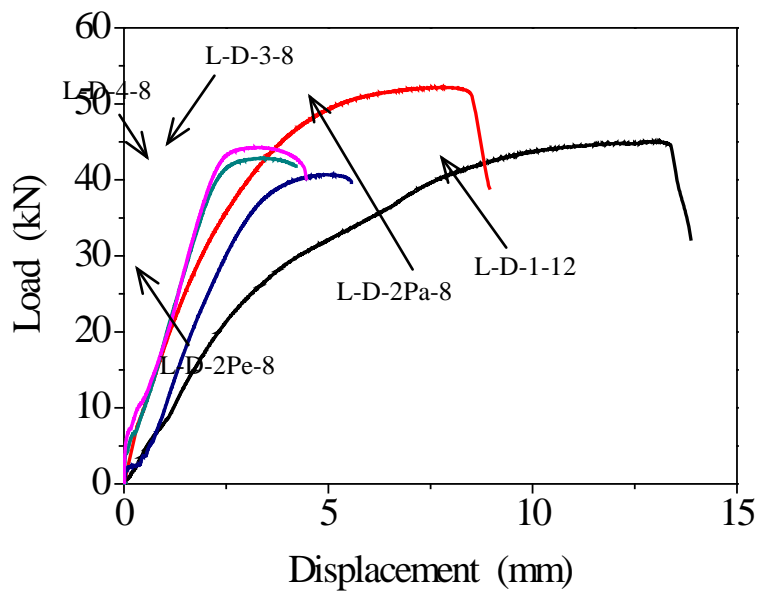
(a) Single shear

a.

(b) Double shear

Fig.7 **Test curves of austenitic stainless steel EN1.4571 (AISI 316Ti) bolted connections**

(a) Single shear

(b) Double shear

Fig.8   **Test curves of lean duplex stainless steel EN1.4162 (AISI S32101) bolted connections**

2.6   Connection test results

The ultimate loads (P_{Exp}) and failure modes of the single shear and double shear bolted connection specimens are shown in Tables 8 and 9, respectively. A total of forty-nine tests including fifteen repeated 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 6.6%. A relatively small difference between the first and repeated test values demonstrated the reliability of the tests. The load-displacement test curves for austenitic stainless steel EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti) as well as lean duplex stainless steel EN1.4162 (AISI S32101) are shown in Figs 6, 7 and 8, respectively. 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.

Table 8   Comparison of test strengths with nominal strengths for single shear bolted connections

| Specimen | Test | | Comparison | | | | Predicted failure mode | |
| | | | Using static material properties | | Using dynamic material properties | | | |
	P_{Exp} (kN)	Failure mode	P_{Exp}/P_{ASCE} and $P_{Exp}/P_{AS/NZS}$	P_{Exp}/P_{EC}	P_{Exp}/P_{ASCE} and $P_{Exp}/P_{AS/NZS}$	P_{Exp}/P_{EC}	ASCE and AS/NZS	EC
A-S-1-10	29.5	B	1.46	2.09	1.38	1.97	NS	B
A-S-1-12	34.9	B	1.52	2.02	1.44	1.90	NS	B
T-S-1-12	31.8	B	1.54	1.96	1.48	1.88	NS	B
L-S-1-10	29.9	B+BS	1.27	1.66	1.20	1.57	NS	B
L-S-1-12	37.1	B	1.41	1.69	1.33	1.59	NS	B
A-S-2Pa-8	38.9	B	1.50	1.23	1.39	1.14	NS	NS
A-S-2Pa-8-R	37.5	B	1.44	1.18	1.33	1.09	NS	NS
T-S-2Pa-8	36.7	B	1.39	1.18	1.33	1.13	NS	B
L-S-2Pa-8	42.8	B+BS	1.25	1.06	1.18	1.00	NS	NS
L-S-2Pa-8-R	42.8	B+BS	1.27	1.09	1.20	1.03	NS	NS
A-S-2Pe-8	41.8	B	2.03	1.82	1.87	1.71	NS	B
A-S-2Pe-8-R	41.6	B	2.06	1.85	1.91	1.74	NS	B
T-S-2Pe-8	38.7	B	1.89	1.83	1.82	1.76	NS	B
L-S-2Pe-8	42.2	B+BS	1.34	1.48	1.25	1.40	NS	B
L-S-2Pe-8-R	43.4	B+BS	1.39	1.53	1.29	1.45	NS	B
A-S-3-6	35.7	B+BS	1.55	1.12	1.43	1.03	NS	NS
A-S-3-8	45.4	B+NS	2.19	1.40	2.03	1.29	NS	NS
A-S-3-8-R	42.4	B+NS	2.09	1.33	1.93	1.23	NS	NS
T-S-3-8	41.7	B+NS	2.02	1.39	1.94	1.33	NS	NS
L-S-3-8	52.2	B+NS	1.66	1.37	1.54	1.30	NS	NS
L-S-3-8-R	51.5	B+NS	1.66	1.37	1.54	1.30	NS	NS
A-S-4-6	45.4	B+BS	1.98	1.43	1.84	1.32	NS	NS
A-S-4-6-R	45.7	B+BS	2.01	1.45	1.86	1.34	NS	NS
T-S-4-6	44.2	B	1.88	1.36	1.80	1.30	NS	NS
T-S-4-6-R	44.0	B	1.87	1.35	1.80	1.29	NS	NS
L-S-4-6	47.8	B+BS	1.35	1.12	1.25	1.06	NS	NS
L-S-4-8	60.1	B+NS	1.91	1.58	1.78	1.49	NS	NS
Mean			1.66	1.48	1.56	1.39		
COV			0.181	0.200	0.180	0.204		

Note: B=Bearing failure; NS=Net section tension failure; BS=Bolt shear failure

The failure mode at ultimate load of the bolted connection tests involved bearing (B), net section tension (NS) and bolt shear (BS) as shown in Tables 8 and 9. The failure modes were determined by observation of the deformed test specimens at ultimate load. Tear out (end pull out) failure mode was not observed, as the specimens were designed to avoid such failure. For single shear bolted connections, all specimens were failed in bearing and bolt shear was also found in some of the specimens near ultimate load. The net section tension failure was also observed in most of the three-bolted connection specimens, and the four-bolted connection specimen L-S-4-8. The combined bearing and net

section tension failure modes (B+NS) of specimen A-S-3-8 is shown in Fig. 9(a). It should be noted that tilting of bolts was observed in all single shear connection specimens.

Table 9   **Comparison of test strengths with nominal strengths for double shear bolted connections**

Specimen	Test		Comparison				Predicted failure mode	
			Using static material properties		Using dynamic material properties			
	P_{Exp} (kN)	Failure mode	P_{Exp}/P_{ASCE} and $P_{Exp}/P_{AS/NZS}$	P_{Exp}/P_{EC}	P_{Exp}/P_{ASCE} and $P_{Exp}/P_{AS/NZS}$	P_{Exp}/P_{EC}	ASCE and AS/NZS	EC
A-D-1-12	38.5	B	1.68	1.36	1.56	1.28	NS	B
T-D-1-12	35.3	B	1.51	1.32	1.45	1.26	NS	B
T-D-1-12-R	33.3	B	1.42	1.24	1.36	1.18	NS	B
L-D-1-12	45.0	B	1.26	1.29	1.17	1.30	NS	B
L-D-1-12-R	47.1	B	1.33	1.36	1.24	1.37	NS	B
A-D-2Pa-8	42.1	B	1.62	1.33	1.49	1.23	NS	NS
A-D-2Pa-8-R	41.4	B	1.59	1.30	1.47	1.20	NS	NS
T-D-2Pa-8	39.2	B	1.49	1.26	1.42	1.21	NS	B
L-D-2Pa-8	52.2	B	1.37	1.32	1.29	1.24	NS	NS
L-D-2Pa-8-R	51.3	B	1.34	1.29	1.27	1.22	NS	NS
A-D-2Pe-8	32.5	B+NS	1.59	1.02	1.47	0.94	NS	NS
T-D-2Pe-8	30.7	B+NS	1.46	1.00	1.40	0.96	NS	NS
L-D-2Pe-8	40.7	B+NS	1.28	1.06	1.20	1.00	NS	NS
L-D-2Pe-8-R	40.9	B+NS	1.27	1.06	1.18	1.00	NS	NS
A-D-3-8	33.4	B+NS	1.62	1.04	1.50	0.96	NS	NS
T-D-3-8	31.8	B+NS	1.52	1.04	1.46	1.00	NS	NS
L-D-3-8	42.8	B+NS	1.36	1.13	1.27	1.06	NS	NS
L-D-3-8-R	42.6	B+NS	1.33	1.11	1.24	1.04	NS	NS
A-D-4-6	38.7	B+NS	1.69	1.22	1.56	1.13	NS	NS
A-D-4-6-R	39.5	B+NS	1.72	1.24	1.59	1.14	NS	NS
T-D-4-6	35.3	B+NS	1.49	1.07	1.43	1.03	NS	NS
L-D-4-8	44.3	B+NS	1.41	1.17	1.32	1.11	NS	NS
Mean			1.47	1.19	1.38	1.13		
COV			0.098	0.104	0.095	0.112		

For double shear bolted connections, similar to the single shear bolted connections where bearing failure mode was found in all tests. The bearing failure mode of specimen T-D-1-12 is shown in Fig. 9(b). In addition to the bearing failure, the net section tension failure mode was also observed in the two-perpendicular bolted, three-bolted and four-bolted connection specimens. The bolt shear failure was not observed in double shear bolted connections tests. The characteristics of different failure modes for single shear bolted connections of thin sheet carbon steels are illustrated in Yan and Young [17].

(a) Bearing and net section tension failure (A-S-3-8)   (b) Bearing failure (T-D-1-12)

Fig. 9   **Failure modes of cold-formed stainless steel bolted connection specimens**

3   Design Rules

The design rules for stainless steel bolted connections in this study are based on the following specifications, including the American Society of Civil Engineers Specification (ASCE) [4] for the design of cold-formed stainless steel members, the Australian/New Zealand Standard (AS/NZS) [5] for cold-formed stainless steel structures, the Eurocode 3 - Design of steel structures - Part 1-4: General Rules - Supplementary rules for stainless steels (EC3-1.4) [6] and Eurocode 3: Design of steel structures - Part 1-8: Design of joints (EC3-1.8) [14]. The design equations for bolted connection members in the ASCE Specification [4] are identical to those in the AS/NZS Standard [5]. Different failure modes for cold-formed stainless steel bolted connections are specified in the current design specifications. These failure modes include the bolt in shear, bearing, net section tension, bolt in tension and bolt subject to combined shear and tension.

The design equations for determining the bearing strength are given in clause 5.3.3 of the ASCE Specification [4] and in clause 5.3.6 of the AS/NZS Standard [5]. Different nominal bearing stresses (F_p) for bolts with washers under both bolt head and nut are used, where $F_p = 2.00f_u$ for single shear bolted connections, and $F_p = 2.75f_u$ for double shear bolted connections. The net section tensile strength is specified in clause 5.3.2 of the ASCE Specification [4] and in clause 5.3.5 of the AS/NZS Standard [5]. Different nominal tension stresses (F_t) for single shear and double shear connections are used. The shear strength of stainless steel bolted connection is specified in clause 5.3.4 of the ASCE Specification [4], and in clauses 5.3.7 and 5.3.8 of the AS/NZS Standard [5].

The design equation of bearing strength ($F_{b,Rd}$) for stainless steel bolted connections is specified in Table 3.4 of the EC3-1.8 [14], where the ultimate tensile strength (f_u) is replaced by the reduced ultimate strength ($f_{u,red}$) in calculating the bearing strength of stainless steel bolted connection as recommended by the EC3-1.4 [4] in equation 6.1. The spacing in the connections related to the bolt holes, such as e_1/d_0, e_2/d_0, p_1/d_0 and p_2/d_0, are considered in the design equation as shown in Table 3.4 of the EC3-1.8 [14]. For single shear one-bolted and two-perpendicular bolted connections, the bearing strengths were calculated from equation 3.2 under clause 3.6.1 of the EC3-1.8 [14] for single lap joints with one row of bolts. The design equations of net section tensile strength are shown in clause 5.3.1 of the EC3-1.4 [6]. The plastic resistance of the gross cross-section $N_{pl,Rd}$ and the ultimate resistance of the net cross-section $N_{u,Rd}$ are given in equation 5.4 and equation 5.5 of the EC3-1.4 [6], respectively. It should be noted that in the calculation of the plastic resistance, the gross cross-section area of the connection part is used, while the ASCE Specification [4] and AS/NZS Standard [5] considered the net cross-section area only. The shear strength of stainless steel bolted connection is specified in equation 6.2 of the EC3-1.4 [6].

4   Comparison of Test Strengths with Nominal Strengths

The cold-formed stainless steel bolted connection test strengths (P_{Exp}) are compared with the nominal (unfactored) strengths predicted by the ASCE Specification [4], AS/NZS Standard [5] and European Codes [6, 14], as shown in Tables 8 and 9. The measured specimen thickness and material properties were used to calculate the nominal strengths. The nominal strength of bolted connection is determined by the minimum strength considered different failure modes. However, the shear resistances of the stainless steel bolts as shown in Table 7 were used directly instead of calculating from the specifications. The design rules for bolted connections in the ASCE Specification [4] are identical to those in the AS/NZS Standard [5]. Therefore, the predicted values obtained from these two specifications are identical.

It is shown that the nominal strengths predicted by the ASCE Specification [4], AS/NZS Standard [5] and Eurocodes [6, 14] are generally conservative for cold-formed stainless steel single shear and double shear bolted connections, as shown in Tables 8 and 9. For single shear and double shear bolted connections, when the static values of material properties were used, the mean values of the load ratio P_{Exp}/P_{ASCE} ($P_{Exp}/P_{AS/NZS}$) are 1.66 and 1.47, with the corresponding coefficient of variation (COV) of 0.181 and 0.098, respectively; while the mean values of the load ratio P_{Exp}/P_{EC} are 1.48 and 1.19, with the corresponding COV of 0.200 and 0.104, respectively. When the dynamic values of material properties were used, the mean values of the load ratio P_{Exp}/P_{ASCE} ($P_{Exp}/P_{AS/NZS}$) are 1.56 and 1.38, with the

corresponding COV of 0.180 and 0.095, respectively; while the mean values of the load ratio P_{Exp}/P_{EC} are 1.39 and 1.13, with the corresponding COV of 0.204 and 0.112, respectively. It is found that the nominal strengths predicted by the three specifications are generally more conservative for single shear bolted connections than those for double shear bolted connections as shown in Tables 8 and 9. Generally, the nominal strengths predicted by the American and Australian/New Zealand specifications are more conservative than the strengths predicted by the European specifications for both single shear and double shear bolted connections, as shown in Tables 8 and 9.

5   Comparison of Failure Modes

The failure modes observed from the tests are compared with the failure modes predicted using the ASCE Specification [4], AS/NZS Standard [5] and Eurocodes [6, 14] for stainless steel bolted connections, as shown in Tables 8 and 9. The predicted failure mode is determined from the corresponding minimum nominal strength for each specimen. For single shear bolted connections, the failure mode predicted by the ASCE Specification [4] and AS/NZS Standard [5] is net section tension failure for all specimens. However, the tests were failed either in bearing only or combined bearing and bolt shear. Generally, the three-bolted connections failed in combined bearing and net section tension. Therefore, the ASCE Specification [4] and AS/NZS Standard [5] are not able to predict the failure mode correctly. The Eurocodes [6, 14] generally predicted the bearing failure for the one-bolted and two-perpendicular bolted connections, but net section tension failure for the rest of the specimens. Therefore, the Eurocodes [6, 14] are capable to predict the failure mode for some of the tested specimens.

For double shear bolted connections, net section tension failure mode was predicted by the ASCE Specification [4], AS/NZS Standard [5] and Eurocodes [6, 14], except that Eurocodes [6, 14] predicted bearing failure for the one-bolted connection specimens and specimen T-D-2Pa-8, as shown in Table 9. The bearing failure mode was observed in the tests of one-bolted and two-parallel bolted connections, while combined bearing and net section tension failure was observed for the two-perpendicular bolted, three-bolted and four-bolted connections. It is shown that the failure mode predicted by the ASCE Specification [4] and AS/NZS Standard [5] is less accurate than the Eurocodes predictions.

6   Conclusions

An experimental investigation of cold-formed stainless steel bolted connections has been presented. The connection specimens were fabricated from three different types of stainless steel, including austenitic stainless steel EN1.4301 (AISI 304) and EN1.4571 (AISI 316Ti having small amount of titanium) as well as lean duplex stainless steel EN1.4162 (AISI S32101). The tests were carried out under both single shear and double shear bolted connections. The test specimens were designed by varying the size of bolt, the number of bolt and the bolt arrangement.

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 nominal strengths predicted by the three specifications are generally conservative for both single shear and double shear bolted connections. However, the single shear bolted connections are generally more conservative than the double shear bolted connections predicted by the three specifications. Generally, the nominal strengths predicted by the American and Australian/New Zealand specifications are more conservative than those predicted by the European specifications.

The bearing failure and the combined of bearing and net section tension failure were mainly observed from the stainless steel bolted connection tests. The failure modes observed from the tests were also compared with the failure modes predicted by the specifications. It is shown that the failure modes predicted by the European codes are generally agreed with the failure modes observed from the tests. The failure modes predicted by the American and Australian/New Zealand specifications are less accurate than the European codes predictions.

Notation

The following symbols are used in this paper:

W	nominal width of connection specimen;
t	nominal thickness of stainless steel tube;
t_m	measured thickness of stainless steel plate;
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 centers 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;
E	the initial elastic Young's modulus;
$f_{0.2}$	longitudinal 0.2% proof stress;
$f_{0.2,mill}$	longitudinal 0.2% proof stress stated in mill certificate;
$f_{0.2,EC}$	longitudinal 0.2% proof stress from EC3-1.4;
f_u	longitudinal tensile strength;
$f_{u,mill}$	longitudinal 0.2% proof stress stated in mill certificate;
$f_{u,EC}$	longitudinal tensile strength from EC3-1.4;
ε	elongation (longitudinal tensile strain) after fracture;
n	exponent in the Ramberg-Osgood expression;
$f_{u,red}$	reduced value of bearing strength;
P_s	test shear resistance of stainless steel bolt;
$P_{s\text{-}ave}$	average shear resistance of tested stainless steel bolts;
P_{exp}	experimental ultimate load of connection (test strength);
F_p	nominal bearing stress;
F_t	nominal tension stress;
$F_{b,Rd}$	the design bearing resistance of the connection part;
$N_{pl,Rd}$	the plastic resistance of the cross-section in connection;
$N_{u,Rd}$	the ultimate resistance of the cross-section in connection;
P_{ASCE}	nominal strength of bolted connection predicted using ASCE Specification;
$P_{AS/NZS}$	nominal strength of bolted connection predicted using AS/NZS Standard;
P_{EC}	nominal strength of bolted connection predicted using European Codes.

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