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Abstract

This study is concerned with double-shear bolted connections in cold-reduced steel sheets that undergo the pure bearing failure mode of the inside sheet. Compared to the published test results of bolted connections failing in the net section fracture, those involving the bearing failure mode had very wide scatter in the ultimate test loads of specimens having seemingly similar configurations. This technical note presents the laboratory test results of 51 specimens composed of G2 and G450 steel sheets, which have very different ductility properties. One new and significant finding is that the absolute bearing capacity can be considerably higher in the rolling direction of the cold-reduced steel sheet than in the perpendicular direction, even though the tensile strength has the opposite trend. Another result is that material ductility has a much greater effect on the bearing capacity than on the net section tension capacity. It was also found that snug tightening had little effect on the bearing capacity of specimens thicker than 1.5 mm. For the inside sheet of a double-shear bolted connection, the current American Iron and Steel Institute provision for bearing capacity is reasonably accurate if the load is applied in the rolling direction of G2 steel sheet, but is overoptimistic in the perpendicular direction.

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Effect of Loading Direction on the Bearing Capacity of Cold-Reduced Sheet Steels

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Abstract:

This study is concerned with double-shear bolted connections in cold-reduced steel sheets that undergo the pure bearing failure mode of the inside sheet. Compared to the published test results of bolted connections failing in net section fracture, those involving the bearing failure mode had very wide scatters of the ultimate test loads of specimens having seemingly similar configurations. This paper presents the laboratory test results of 51 specimens composed of G2 and G450 sheet steels, which have very different ductility properties. One new and significant finding is that the absolute bearing capacity can be considerably higher in the rolling direction of the cold-reduced sheet steel than in the perpendicular direction, even though the tensile strength has the opposite trend. Another result is that material ductility has a much greater effect on the bearing capacity than on the net section tension capacity. It was also found that snug tightening had little effect on the bearing capacity of specimens thicker than 1.5 mm. For the inside sheet of a double-shear bolted connection, the current AISI provision for bearing capacity is reasonably accurate if the load is applied in the rolling direction of G2 sheet steel, but is over-optimistic in the perpendicular direction.

Subject headings: bolted connections, cold-formed steel, structural design, thin wall sections

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Introduction

The bearing capacity of a bolted connection in cold-formed steel sheet is specified in the North American Specification for the Design of Cold-formed Steel Structural Members (AISI 2012) and the European code EN-1993-1-3:2006 (ECS 2006). For the inside sheet of a double-shear bolted connection, the American code gives a much larger bearing capacity as the maximum effective bearing coefficient is 4.0, compared to 2.5 given in the Eurocode. It should be noted that the effective bearing coefficient only increased from 3.33 to 4.0 in the 2001 AISI specification (AISI 2001).

Irrespective of the significant difference in the effective bearing coefficient between the two major codes, the authors note that there have been very wide scatters of the ultimate test loads of specimens having seemingly similar configurations, and of the professional factors. This fact is evident from the test results published by Yu & Mosby (1981), Wallace et al. (2001), and Yan & Young (2013). Yu & Mosby (1981) believed the bearing capacity of a bolted connection to be significantly affected by the ratio of tensile strength to yield stress of the steel material. They also suggested that, for connections with a large ratio of bolt diameter to sheet thickness, the bearing capacity could be affected by the installation torque.

The present work originally set out to investigate the reliability of the current AISI bearing strength equation for the inside sheet of a double-shear bolted connection, and to explore and explain the effects of material ductility and bolt tightening. In the process, the very significant effect of loading direction on the bearing capacity came to the authors' attention. The present issue of loading direction is distinct from that of material ductility, as will be evident later.

For the purpose of the present work, two types of cold-reduced sheet steels are used. The first is named G2, and the second G450. During manufacturing, both sheet steels undergo reduction in thickness through a milling process, which causes the grain structure to elongate in the rolling direction leading to an increase in tensile strength but a decrease in ductility. However, G2 sheet steel is subsequently heat treated to return the grain structure almost to the original state, and is therefore much more ductile than G450 sheet steel. G2 is classified as a formability grade, while G450 is a structural grade (SA 2011).

The present data comprise the test results of 51 double-shear bolted connection specimens, of which the inside sheet failed in pure bearing. There are a total of 40 configurations in terms sheet thickness, bolt diameter, material ductility, bolt tightening and loading direction.

Bolt hole deformation at service load is not a concern in this technical note. The bearing capacity is defined as the ultimate test load achievable when the bearing failure mode governs the load-carrying capacity of the bolted connection.

Code equations for ultimate bearing capacity

The bearing capacity P_b of a bolt provided by the connected steel sheet is most commonly expressed as

$$P_b = C_b\, d\, t F_u \tag{1}$$

in which C_b is the effective bearing coefficient, d is the bolt diameter, t is the sheet thickness and F_u is the material tensile strength.

According to Section J3-6b of the AISC Specifications for Structural Steel Buildings (AISC 2010), C_b is invariably equal to 3.0 when bolt hole deformation at service load is not a concern, which is the case in the present work. However, for the inside sheet of a double-shear bolted connection, Section E3.3.1 of the North American Specification for the Design of Cold-formed Steel Structural Members 2012 (AISI 2012) specifies a modification factor m_f of 1.33, resulting in the following effective bearing coefficient

$$C_b = \min[4.0, 1.33(4 - 0.1d/t)]; \quad d/t \leq 22 \tag{2}$$

Equation (2) means that, for a double-shear connection in which the ratio d/t is less than or equal to 10, the effective bearing coefficient of the inside sheet is equal to 4.0.

Test materials

The G2 and G450 sheet steel materials used in the laboratory tests, which have trade names GALVABOND® and GALVASPAN®, respectively, were manufactured and supplied by Bluescope Steel Port Kembla Steelworks, Australia. The average yield stresses F_y, tensile strengths F_u and elongations at fracture over 15 mm, 25 mm and 50 mm gauge lengths ε_{15}, ε_{25} and ε_{50}, and uniform elongation outside the fracture ε_{uo} of the steel materials as obtained from 12.5 mm wide tension coupons are shown in Tables 1 and 2 for the G2 and G450 sheet steels, respectively. The suffix “R” in the nominal thickness designation denotes the loading to be in the rolling direction of the sheet steel, and the suffix “T” denotes loading in the direction perpendicular to the rolling direction.

Tables 1 and 2 show that G2 steel is considerably more ductile than G450 steel. The 1.9-mm and 2.4-mm G450 sheet steels just meet the requirements for being used without restriction according to Section A2.3.1 of the specification (AISI 2012), while the 1.5-mm and 3.0-mm ones marginally fail them. In design practice, steel materials not meeting the requirements shall have their yield stress and tensile strength reduced by 10%. However, in order to investigate the effect of material ductility, no such reduction is applied in the present work.

It should be noted that, for the statutory purpose of determining the material properties of the structural grade G450 sheet steel, tension coupons shall be cut parallel to the direction of rolling (SA 2011). For each thickness of either G2 or G450 sheet steel, the tensile response in the rolling direction is somewhat more ductile than that in the perpendicular direction.

Specimen configurations and test arrangements

All specimens were double-shear, single bolt connections, as shown in Figure 1. The concentrically loaded inner sheet, shown as the lower one in the figure, was the critical element since the two outer sheets had identical nominal properties. The geometry of each specimen was such that bearing was the governing failure mode, as illustrated in Figure 2.

Two bolt diameters were used, 12 and 16 mm, resulting in the ratios d/t ranging from 4 to 11. Equation (2) is therefore applicable to all specimens tested in the present work. Each bolt hole was drilled with a diameter that was 1 mm larger than the bolt diameter.

For each configuration, the specimens were alternately snug and finger tightened. Some repeat tests were conducted as denoted by the suffices “a” and “b” in the specimen labels. All specimens were tested at a stroke rate of 5 mm per minute.

Laboratory test results and discussions

Table 3 lists the dimensions, loading directions, bolt tightening conditions, effective bearing coefficients according to Equation (2), and test results of the G2 sheet steel specimens. An empty cell in the table indicates that the data in the above cell applies. The corresponding data for G450 sheet steel specimens are given in Table 4.

The tables show the ratios of ultimate test load P_t to bearing capacity P_b predicted by using Equations (1) and (2), called the professional factors. The ultimate test loads P_t are also given to facilitate the discussion on the effect of loading direction. A difference of 15% or more between comparable specimens is considered to be parametrically significant.

Effect of material ductility

Irrespective of the accuracy of Equation (2), and the effects of snug tightening and loading direction discussed in the next subsections, the results shown in Tables 3 and 4 indicate that material ductility has a significant effect on the bearing capacity of a bolted connection. For comparable geometries, the professional factors of the G2 sheet steel specimens are generally much higher than those of the G450 sheet steel specimens, ranging from -2% to 67%.

The effect of material ductility on the bearing capacity is significantly more pronounced than its effect on the net section tension capacities found by Rogers & Hancock (1999) and Teh & Gilbert (2012), which typically resulted in some 5% differences only. This phenomenon can be explained by comparing the conclusion of Clements & Teh (2013) regarding shear strain hardening capability of low ductility steel sheets against that of Teh & Yazici (2013a) for ductile steel plates. Bolted connections composed of low ductility steel sheets are far from being able to achieve complete shear stress redistribution along the shear failure paths. On the other hand, those composed of ductile steel plates are able to achieve full strain hardening along the shear failure paths. The less able the shear stress is to be redistributed away from the bolt hole, the earlier bearing fracture will take place.

The present finding is consistent with that of Yu & Mosby (1981), who viewed the results in terms of the ratio of tensile strength to yield stress of the sheet steel material. Although the authors believe the elongation at fracture to be the more important parameter for ductility, there is a correlation between the elongation at fracture and the ratio of tensile strength to yield stress, as evident from Tables 1 and 2. The finding is also consistent with that of Rogers & Hancock (1999) for single-shear specimens composed of G300 and G550 sheet steels.

Effect of snug tightening

Snug-tightened specimens are indicated by the letter “S” in the “Tightening” column, while finger-tightened ones by the letter F. It can be seen from Tables 3 and 4 that snug tightening resulted in 10% to 25% higher bearing capacities for the 1.5 mm G2 and G450 sheet steel specimens. However, the effects were much less pronounced if at all for the thicker specimens. This finding is consistent with the suggestion of Yu & Mosby (1981) that the bearing capacity of connections with a large ratio of bolt diameter to sheet thickness, i.e. thin sheets, could be affected by the installation torque.

In practice, the ratio of bolt diameter to sheet thickness rarely exceeds 8 for structural members. It can be surmised that tightening performed by different persons would not have a significant effect on the variability of bearing capacities of steel sheets thicker than 1.5 mm. This contention is also consistent with the finding of Yu & Mosby (1981) that the use of low torques did not degrade the bearing capacities of high-strength structural bolt connections.

The fact that snug tightening had no effect on the bearing capacities of specimens thicker than 1.5 mm was likely due to the significant bulging of the material downstream of the bolt, as shown in Figure 2. This bulging loosened the contact between the two outer sheets and the inside sheet in the region immediately upstream, resulting in no friction resisting the applied load. The mechanism of bolt tightening (friction) contributing to the tension capacity of a bolted connection has been explained in Fig. 3 of Teh & Yazici (2013b). The friction between the outer sheets and the bulging material, which is located downstream from the bolt, does not contribute to the connection capacity.

Effect of loading direction

The letters “R” and “T” in the “Direction” column have the same meaning as the suffices in Tables 1 and 2, explained in the “Test materials” section. The professional factors P_t/P_b and the ultimate test loads P_t shown in Table 3 for the G2 sheet steel specimens, which can be used without restriction according to Section A2.3.1 of the design specification (AISI 2012), indicate that the effective bearing coefficients given by Equation (2) are only accurate for the specimens loaded in the rolling direction of the sheet steel. It should be noted that the use of one nominal tensile strength for both directions in practice does not affect this conclusion.

The ultimate test loads of specimens IB7 and IB8 shown in Table 3, which were loaded in the rolling direction, are 37% higher than those of specimens IB5 and IB6, which had the same geometry but were loaded in the perpendicular direction. This outcome is despite the fact that the tensile strength of the 1.5-mm G2 sheet steel is 7% lower in the rolling direction.

A similar observation can be made for specimens IB13 through IB16, and for specimens IB39a through IB40 listed in Table 4, which were composed of 3.0-mm G450 sheet steel. Some effects can also be seen for other specimens in Tables 3 and 4, especially with regard to the professional factors. The exceptions are specimens IB9 through IB12 (2.4-mm G2 specimens), and IB21 through IB24 (1.9-mm G450 specimens).

The significantly lower bearing capacities of the specimens loaded in the perpendicular direction to rolling were due to at least two reasons. First, the material ductility was lower in this direction, meaning that stress redistribution prior to fracture was more limited. This indication is consistent with the results showing that the effect of loading direction is more pronounced for 16-mm bolt specimens than 12-mm ones. Second, the bearing fractures took place in planes more aligned with the tension fracture planes of coupons loaded in the rolling direction, which had lower tensile strengths. As shown in Figure 2, the propagation of bearing fractures was almost parallel to the loading direction.

The failed specimens IB8 and IB6, respectively loaded in the rolling and perpendicular directions, are shown in Figure 3. The authors do not detect a visual explanation other than the two likely reasons mentioned in the preceding paragraph. More research is required to investigate the significant effect of loading direction on the bearing capacity of double-shear bolted connections in cold-reduced steel sheets, including its fracture mechanism.

In any case, it is evident from the results plotted in Figure 4 that the bearing strength provision for the inside sheet of a double-shear bolted connection given in Section E3.3.1 of the AISI specification (AISI 2012) is reasonably accurate when the load is applied in the rolling direction of the G2 sheet steel, but is over-optimistic in the perpendicular direction to rolling. For repeat specimens, only the average professional factor is plotted in Figure 4.

Conclusions

Laboratory test results of 51 double-shear bolted connections composed of G2 and G450 sheet steels have been presented in this technical note. The inside sheet of each specimen failed in bearing. In total there were 40 configurations in terms sheet thickness, bolt diameter, material ductility, bolt tightening and loading direction.

Material ductility was found to have a significant effect on the bearing capacity, more pronounced than its effect on the net section tension capacity. It is concluded that different levels of snug tightening would not cause significant variations in the bearing capacity of most structural bolted connections. The most important finding is that the absolute bearing capacity can be considerably lower in the direction perpendicular to the rolling direction of the sheet steel, even though the tensile strength is correspondingly higher. The bearing strength provision in the current AISI specification is over-optimistic for connections loaded in this direction.

Plausible reasons for the three effects mentioned above have been offered in this technical note. However, more research is required to establish the effect of loading direction.

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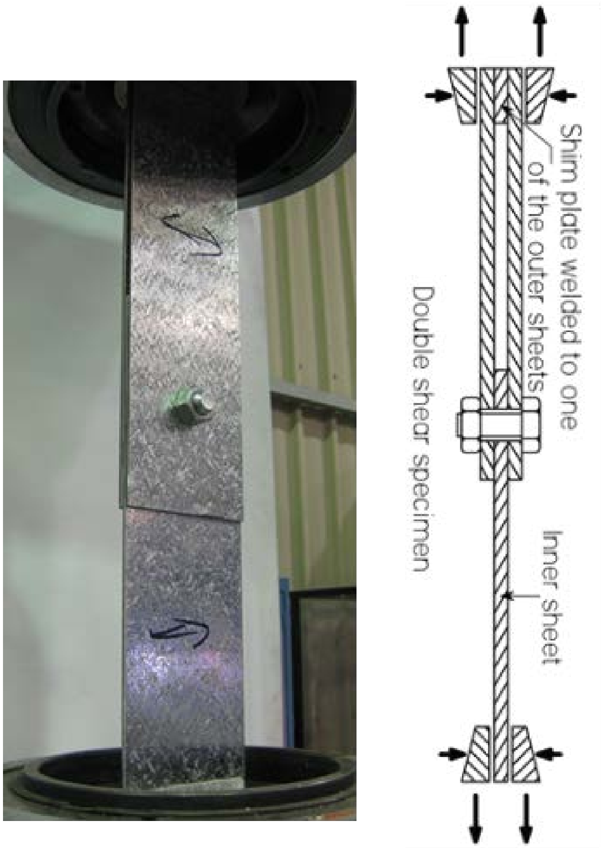

Figure 1 Configuration of test specimens

Figure 2 Bearing failure

Figure 3 Failed specimens IB6 and IB8

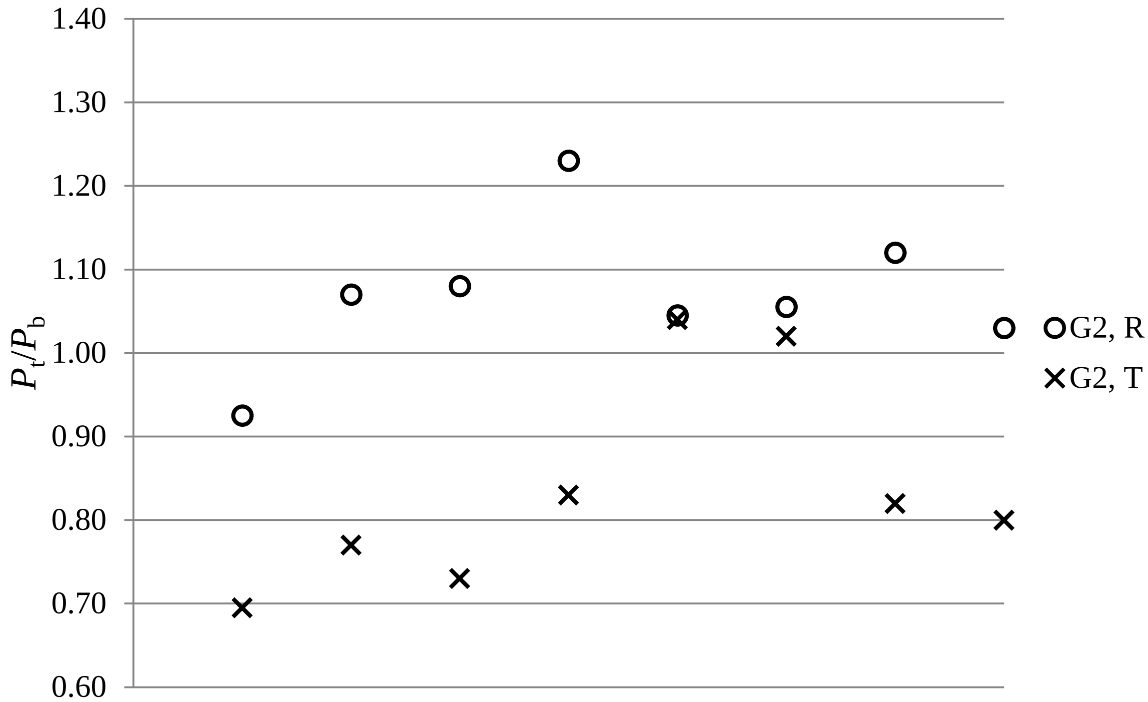

Figure 4 Professional factors of G2 specimens loaded in the rolling (R) and perpendicular (T) directions

Table 1 Average material properties for G2 sheet steels

Designation	F_y (MPa)	F_u (MPa)	F_u / F_y	ε_{15} (%)	ε_{25} (%)	ε_{50} (%)	ε_{uo} (%)
1.5 mm T	390	430	1.10	58.1	47.8	32.2	17.3
1.5 mm R	320	400	1.25	55.2	45.9	37.7	24.5
2.4 mm T	345	395	1.14	68.5	53.8	40.4	24.1
2.4 mm R	310	390	1.26	62.4	51.5	40.1	26.8

Table 2 Average material properties for G450 sheet steels

Designation	F_y (MPa)	F_u (MPa)	F_u / F_y	ε_{15} (%)	ε_{25} (%)	ε_{50} (%)	ε_{uo} (%)
1.5 mm R	555	590	1.06	21.5	16.3	12.0	6.9
1.9 mm T	600	630	1.05	22.6	17.2	9.9	5.0
1.9 mm R	540	585	1.08	26.3	22.3	12.1	8.4
2.4 mm T	580	620	1.07	25.3	17.2	10.7	5.8
2.4 mm R	535	580	1.08	31.0	23.8	16.3	8.9
3.0 mm T	570	610	1.07	27.5	18.0	10.9	6.3
3.0 mm R	520	555	1.07	30.5	21.4	14.8	8.2

Table 3 Test results for G2 sheet steel specimens

Spec	t (mm)	d (mm)	Direction	Tightening	C_b	P_t (kN)	P_t/ P_b
IB1a	1.5	12	T	F	4.0	21.6	0.72
IB1b						20.0	0.67
IB2a				S		22.0	0.74
IB2b						23.9	0.80
IB3a			R	F		24.7	0.89
IB3b						26.7	0.96
IB4				S		29.6	1.07
IB5		16	T	F	3.9	28.1	0.73
IB6				S		31.9	0.83
IB7			R	F		38.6	1.08
IB8				S		43.8	1.23
IB9	2.4	12	T	F	4.0	46.1	1.04
IB10a				S		42.1	0.95
IB10b						48.3	1.09
IB11a			R	F		46.0	1.05
IB11b						45.7	1.04
IB12a				S		45.2	1.03
IB12b						47.5	1.08
IB13		16	T	F		48.4	0.82
IB14				S		47.2	0.80
IB15			R	F		65.3	1.12
IB16				S		60.0	1.03

Table 4 Test results for G450 sheet steel specimens

Spec	t (mm)	d (mm)	Direction	Tightening	C_b	P_t (kN)	P_t/P_b
IB17	1.5	12	R	F	4.0	29.7	0.71
IB18				S		37.1	0.89
IB19a		16		F	3.9	34.1	0.63
IB19b						36.1	0.67
IB20a				S		41.4	0.76
IB20b						46.1	0.85
IB21	1.9	12	T	F	4.0	44.3	0.81
IB22				S		44.3	0.81
IB23			R	F		40.5	0.79
IB24				S		42.9	0.84
IB25		16	T			53.8	0.73
IB26			R	F		55.9	0.82
IB27				S		57.3	0.84
IB28	2.4	12	T	F		49.5	0.71
IB29				S		58.5	0.84
IB30			R	F		54.2	0.83
IB31				S		61.2	0.93
IB32		16	T			75.6	0.81
IB33			R	F		78.0	0.89
IB34				S		74.2	0.85
IB35a	3.0	12	T	F		65.5	0.76
IB35b						65.8	0.76
IB36				S		75.9	0.88
IB37			R			74.6	0.95
IB38a		16	T	F		81.3	0.71
IB38b						87.7	0.76
IB39a				S		79.5	0.69
IB39b						77.9	0.68
IB40			R			97.8	0.94