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Short communication

Unconventional block shear failures of bolted connections in cold-reduced steel sheets

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ABSTRACT

This paper examines the block shear design equation proposed by the first author based on laboratory tests of bolted connection specimens failing in the conventional block shear failure mode. It shows that the explanation regarding the feasible mechanism of block shear failures previously provided by the first author does not necessarily apply to staggered bolted connections, in which the downstream bolts do not have the same edge distance. For staggered bolted connections, a block shear failure may occur through the shear rupture and tensile yielding mechanism for particular configurations, as demonstrated for the first time in this paper. The present laboratory tests included specimens failing in the split block shear failure mode. This paper presents the equations for determining staggered and split block shear capacities. It also cautions against potential misidentifications for the simultaneous shear and tensile ruptures mechanism.

1. Introduction

In a recent paper, Teh and Clements [1] pointed out that, for an unstaggered bolted connection, there is no aspect ratio at which the shear rupture and tensile yielding mechanism governs the conventional block shear failure mode. The aspect ratio is the ratio between the length of the shear resistance plane and the length of the tensile resistance plane in a "block". Connections with low aspect ratios fail by individual (and simultaneous) shear-out of the bolts, while those with higher aspect ratios fail in block shear by the shear yielding and tensile rupture mechanism. Published experimental tests have found that block shear failures invariably occurred by the shear yielding and tensile rupture mechanism [1–4].

However, the expositions of Teh and Clements [1] have been based on unstaggered bolting patterns. In a staggered bolted connection, the bolts have different edge distances from the downstream end, so it is not possible for simultaneous shear-out failures to occur under concentric loading. The shear stresses downstream from the leading bolt are greater than those downstream from the other bolt(s), and for certain configurations shear rupture at the leading bolt may occur in conjunction with tensile yielding along the inclined net section to form a block shear failure. A laboratory test supporting this assertion will be presented.

In this paper, the equation presented by Teh and Clements [1], used for determining the block shear capacity of an unstaggered bolted connection, will be combined with that presented by Teh and Clements [5], used for determining the net section tension capacity of a staggered bolted connection, to form one for determining the block shear capacity of a staggered bolted connection in cold-reduced steel sheets having low material ductility and minimal strain hardening capability. The derived equation will then be verified against laboratory test results.

This paper includes the laboratory test results of bolted connection specimens failing by the split block shear failure, in which there are two critical tensile resistance planes. Such a failure mode is particularly relevant to channel braces bolted at both flanges, which is a common arrangement for the frame braces of a cold-formed steel storage rack. The equation presented by Teh and Clements [1] will be modified to suit a split block shear failure.

This paper also cautions against possible misidentifications for block shear failures by the simultaneous shear and tensile ruptures mechanism. It points out two phenomena that can lead to such misidentifications. It may be noted that possible misidentification of a block shear failure by the shear yielding and tensile rupture mechanism for a net section fracture has been discussed previously by the authors [6]. There is also continuing research in the area of block shear failures of steel bolted connections as represented by a very recent paper [7]. Block shear failures of welded connections [8,9] are distinct from those of bolted connections, and are outside the scope of this paper.

2. Relevant equations

Teh and Clements [1] proposed the following equation for determining the conventional block shear capacity P_c of the

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unstaggered bolted connection in cold-reduced steel sheet shown in Fig. 1

$$P_c = 0.6F_yA_{av} + F_uA_{nt}(0.9 + 0.1d/g) \tag{1}$$

in which F_u is the material tensile strength, F_y is the yield stress, A_{nt} is the net tensile area and A_{av} is the active shear area determined from the length of the active shear planes [10], as indicated in the figure. The variable d in Eq. (1) denotes the bolt diameter, and g is the connection gage as defined in Fig. 1. In the figure, d_h is the bolt hole diameter.

For a staggered bolted connection in cold-reduced steel sheet shown in Fig. 2, Teh and Clements [5] proposed the following equation for determining the net section tension capacity

$$P_{ns} = F_ut\left[W - \max\left(d_h, 2d_h - \frac{s^2}{4g + 2d_h}\right)\right](0.9 + 0.1d/W) \tag{2a}$$

which, for a connection with tension failure along the staggered path, becomes

$$P_{ns} = F_ut\left[W - 2d_h + \frac{s^2}{4g + 2d_h}\right](0.9 + 0.1d/W) \tag{2b}$$

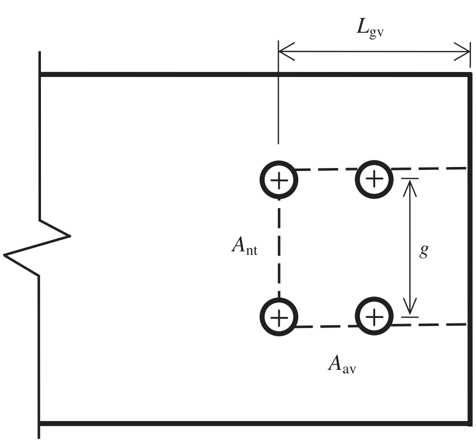
The in-plane shear lag terms shown inside the last brackets of Eqs. (1) and (2) have been derived by Teh and Gilbert [11]. The variable t in Eq. (2) denotes the sheet thickness, and s is the bolt pitch defined in Fig. 2.

For the staggered bolted connection shown in Fig. 2, Eqs. (1) and (2b) can be combined to determine the staggered block shear capacity

$$P_{st} = 0.6F_yA_{av} + F_ut\left[g - d_h + \frac{s^2}{4g + 2d_h}\right](0.9 + 0.1d/g) \tag{3}$$

For certain rectangular connection configurations where the sum of the outer tensile areas is less than the inner tensile area, the "split" block shear failure may occur, as illustrated in Fig. 3. Eq. (1) becomes

$$P_{sp} = 0.6F_yA_{av} + F_uA_{nt}(0.9 + 0.05d/e_2) \tag{4}$$



$$L_{av} = L_{gv} - \left(\frac{n_r - 1}{2} + \frac{1}{4}\right)d_h$$

$$\approx L_{gv} - n_rd_h/2$$

$$A_{av} = 2L_{av}t$$

Fig. 1. Conventional block shear failure diagram [10].

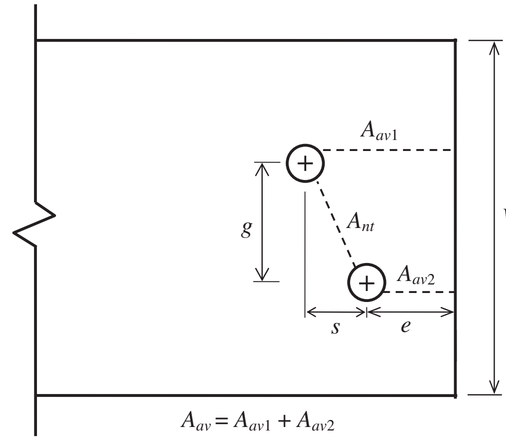


Fig. 2. Staggered block shear failure diagram.

3. Test materials

The G450 sheet steel materials used in the laboratory tests, which have a trade name GALVASPAN®, were manufactured and supplied by Bluescope Steel Port Kembla Steelworks, Australia. Two nominal thicknesses were used in the present work, being 1.5 mm and 3.0 mm. The average base metal thicknesses t_{base}, 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 fracture ε_{uo} of the steel materials as obtained from six 12.5 mm wide tension coupons are shown in Table 1 [11]. Tensile loadings of all coupons and bolted connection specimens are in the direction perpendicular to the rolling direction of the G450 sheet steel.

The tensile strengths in the direction perpendicular to the rolling direction of 1.5 mm and 3.0 mm G450 sheet steels obtained for the present work, rounded to the nearest 5 MPa, are 6% and 10% higher than those obtained by Teh and Hancock [12] in the rolling direction. While Teh and Hancock [12] did not provide the elongations at fracture, it is believed that the rolling direction is associated with higher ductility. In any case, it can be seen from Table 1 that the present materials have low ductility and relatively insignificant strain hardening capability.

4. Laboratory tests and discussions

All specimens were subjected to concentric loading as depicted by Teh and Clements [1].

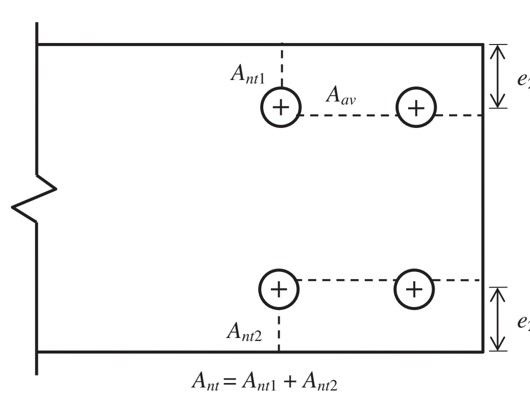


Fig. 3. Split block shear failure diagram.