Experimental study of the screw connection of cold-formed steel applied in the same and opposite directions

S Haris¹, J Sunaryati¹ and A D Masdar¹

¹Civil Engineering Department, Andalas University, Indonesia

Corresponding author: sabil.haris@eng.unand.ac.id

Abstract. Cold-formed steel has been used widely on buildings, especially for the roof truss-structures. This material and its typical section are beneficial in weight and strength. Despite the minimum total weight, the structure can fulfil the strength requirement. For the truss installations, screws are commonly used to join the truss members due to time consideration and convenience process. However, there is a potential failure using the screw because it does not have a nut to prevent it from detaching. In this research, experimental tests of the screw connection of the cold-formed steel were conducted. The specimens consist of two groups: 8 specimens using screws were applied in the same direction and the other 8 specimens in the opposite direction. A different application of screws was aimed to observe the effect of the screw’s head, which may play a role as a nut to prevent detaching. Typical conditions of tilted screw and indented hole on the joined channel section were found during the test. The experimental results showed that the ultimate load for two different directions of screw were slightly different within the range of 0.4 – 10.0 %. The effect of the screw’s head position was minor to the resistance of the connection.

1. Introduction
Cold-formed steel has been used in numerous residential buildings, particularly for the roof structures. This material is suitable for light to medium-weight structures and short to medium span of structures. Cold-formed steel is characterized by a lightweight section with high strength and stiffness [1]. Most of the cold-formed steel section is the open section formed at room temperature by rolling, folding, and press braking of a thin sheet of steel. The open channel section is commonly used as the truss member’s main section for the roof truss-structures. Screws are preferred to assemble the members because a thin section can be drilled directly using the screw itself, and the section can be joined and tightened utilizing the thread of the screw. This simple one-step process is very satisfactory due to the time and method of installation.

Unlike bolts, the screw does not have a nut at its end of the threads. This absence may initiate failure of the connection because the screw can be detached from the specimen. For the shear connection type, tilting of the screw is a common failure mode. When tension load continued, this screw tilting may be followed by an indentation on the hole and separation of the joined channel sections.

Experimental studies of bolt and screw connection have been reported by several researchers [2–5]. Kulkarni and Vaghe [2] presented experimental results of 12 mm diameter bolt connections using an additional packing plate. They found that failure occurred on the cold-formed section and the packing plate. No damage was observed on the bolts. Haris et al. [3] conducted experimental tests for bolt
connection using smaller bolt size, and shear failure occurred on the bolt as well as an indentation on the hole. Meanwhile, rotation of the screw and separation of the connection due to increasing of the hole size using screw connection was reported in [4–5]. The screws were applied in the same direction.

The use of screws to assemble cold-formed steel and different material infill wall panel has been investigated by Fiorino et al. [6]. They observed failure mechanisms during the test and classified them into tilting of screws, screws pull-out, bearing in the sheathing, and breaking of sheathing edge. Based on the previous research of screw connection, the tilting of the screw was always found on the specimens because the screw does not have a nut that can prevent movement of the screw.

In this paper, an experimental study of the screw connection applied in the opposite direction was conducted. This idea is to confirm the effect of the screw head placed on the contrary position which is presumed to contribute resistance as a nut for another adjacent screw. The specimens will consist of screw connections applied in the same dan opposite directions. All specimens were subjected to a constant speed axial load until failure occurred. The types of ultimate conditions of the connection were observed. Predicted resistance using analytical formulae from the standard were used as a comparison to the experimental results.

2. Experimental works

2.1. Description of test specimens and setup

Sixteen specimens were tested in this study. All the specimens were built up from two identical cold-formed steel sections which section size was 75 mm in height, 35 mm in width, and 0.75 mm in thickness (Figure 1). Two groups of specimens, namely Group-1 and Group-2, were observed. For 8 specimens of Group-1, two-channel sections were joined by screws applied in the same direction. For 8 other specimens of Group-2, the screws merged the channel sections through the opposite direction of application. Furthermore, the different numbers of screws and layout were designed to figure out the effect of direction of screws application. There were 8 specimens joined by two screws, and the eight others were clamped using three screws. All screws were 5 mm in diameter.

At both ends of the specimen, jigs were used to connect the specimen to the grip part of the Universal Testing Machine. The jig and the end of the specimen were joined by eight bolts sized 8 mm in diameter, ensuring failures did not occur on this connecting area. Detail of the specimens was illustrated and summarized in Table 1 and Figure 2.

The specimen was subjected to a tension load, which increased monotonically with a speed of 2 mm per minute. Applied load and displacement during loading was tracked through a visual monitor connected to the Universal Testing Machine. The loading process was stopped when the ultimate load passed.
### Table 1. Description of the specimens

| Group          | Screw’s layout | Specimen id | Screw spacing (s) |
|----------------|----------------|-------------|-------------------|
| Group-1        |                |             |                   |
| Screws applied in the same direction (SD) | | | |
|                |                | 2SD-20      | 20 mm             |
|                |                | 2SD-30      | 30 mm             |
|                |                | 2SD-40      | 40 mm             |
|                |                | 2SD-50      | 50 mm             |
|                |                | 3SD-20      | 20 mm             |
|                |                | 3SD-25      | 25 mm             |
|                |                | 3SD-30      | 30 mm             |
|                |                | 3SD-35      | 35 mm             |
| Group-2        |                |             |                   |
| Screws applied in the opposite direction (OD) | | | |
|                |                | 2OD-20      | 20 mm             |
|                |                | 2OD-30      | 30 mm             |
|                |                | 2OD-40      | 40 mm             |
|                |                | 2OD-50      | 50 mm             |
|                |                | 3OD-20      | 20 mm             |
|                |                | 3OD-25      | 25 mm             |
|                |                | 3OD-30      | 30 mm             |
|                |                | 3OD-35      | 35 mm             |

**Figure 2.** Detail of the specimen using two screws: (a) Model of the specimen with two screws, (b) Application of the screws in the same direction, (c) Application of the screws in the opposite direction, (d) Photo of the two-screws’ specimen.
2.2. Material properties of test specimens

A typical material of cold-formed steel applied commonly for residential construction in Indonesia was used in this study. A tensile test was conducted to obtain material properties. Specimen for the tensile test was cropped from the web of the channel section to form a profile of the specimen. The observed tensile zone was 50 mm in length and 12.5 mm in width, as defined in the ASTM Standards for Metals Test 1991 [7]. Both ends of the specimen were prolonged and widened to provide a space merging the coupon test and the grip of the Universal Testing Machine through a connecting jig. Four bolts were used to clamp the connecting jig and the end of the tensile specimen firmly. Detail of the tensile specimen is shown in figure 3.

![Tensile specimen](image)

**Figure 3.** Tensile specimen no. 5 placed on the UTM before applying tension load (left), specimen after testing showing oblique failure plan, and the observed zone was elongated (right).

It was observed a common ultimate condition on all tensile specimens. The oblique fracture occurred at the observed tensile zone. After the onset of yielding, the specimen could receive a small load increment before it failed suddenly. The maximum strain was in the range of 5 – 8 %. For six tensile specimens, the ultimate stress ($f_u$) was 1.6 % higher than the yield stress ($f_y$) on average. The yield and the ultimate stresses for all tensile specimens are listed in table 2.

| Material specimen | Connection specimen | $f_y$ (MPa) | $f_u$ (MPa) | Elongation (mm) |
|-------------------|---------------------|-------------|-------------|-----------------|
| 1                 | 2SD-20, 2OD-20      | 468.8       | 475.2       | 3.0             |
|                   | 3SD-20, 3OD-20      |             |             |                 |
| 2                 | 2SD-50, 3SD-30      | 501.3       | 516.3       | 2.5             |
|                   | 2OD-30, 3OD-25      |             |             |                 |
| 3                 | 2SD-30, 3SD-25      | 521.6       | 532.3       | 4.0             |
| 4                 | 2SD-40, 3SD-35      | 549.3       | 558.8       | 2.5             |
| 5                 | 2OD-50, 3OD-30      | 565.3       | 569.6       | 3.0             |
| 6                 | 2OD-40, 3OD-35      | 559.0       | 561.1       | 3.5             |
3. Experimental results and discussion

3.1. The behaviour of the connection during the tension test

3.1.1. Group-1: Screws applied in the same direction. Connections in which the screws applied in the same direction showed similar behaviour for all 8 specimens. The behaviour of the connection during the tension test is described referring to the load-displacement curve, as shown in figure 4 (represented by specimen 2SD-20). At the beginning of the test, the relation between load and displacement was almost linear until the load of 5.75 kN (point A). There was no significant change on the specimen. The screws displaced slightly, but the axis of the screw was still perpendicular to the load direction. There was no damage observed in the area around the joint at this linear-elastic region. After point A, the screws started to rotate parallel to the tension load direction. This rotation generated the screws tilted, and damage started on the specimen around the hole. The load-displacement curve became non-linear and attained the maximum load of 6.96 kN at 5.20 mm displacement (point B). At this maximum load, the screws had been rotated about 20°. Afterward, contact between the screw and the channel moved from the first thread of the screw to the second thread, and during this moving, the load dropped to 4.38 kN (point C). The specimen regained its capacity to sustain load because the channel was already restrained at the second thread of the screw until another load peak of 6.42 kN. This second load peak (point D) was lower than the maximum load of 6.96 kN. At point E, which displacement and load were 13.30 mm and 5.80 kN, respectively, hole bearing failure was initiated. The hole on the channel section was enlarged as the screw was rotated further to 40° – 45° of inclination. One side of the screw’s head started to push surface contact, and the other part of the screw’s head was uplifted. The load was decreased to 4.09 kN (point F) since contact between the screw and the channel moved from the second thread of the screw to the next thread. The specimen capacity bounced up to 4.89 kN because the channel was yet restrained again. After this point, the load decreased, and there was a gap between two-channel sections. The screw was detached from the section, which had no contact with the screw’s head. The loading test was stopped at this declination stage.

![Figure 4](image.png)

**Figure 4.** The load-displacement curve for the same direction specimen of 2SD-20 (left), condition of the specimen at the end of the test (right).

3.1.2. Group-2: Screws applied in the opposite direction. In general, the specimens which the screws applied in the opposite direction had a similar response to subjected tension load with the specimens of Group-1. Specimen of 2OD-20 was picked up as the representation to be described (Figure 5). At the initial state, the load increased linearly without any substantial change on the channel section and the screw’s position. Later, tilting of the screws was started, and the first peak load at 6.62 kN (point A)
was attained just a moment before contact between the specimen, and one of the screws moved from the first thread of the screw to the second thread. Meanwhile, the other screw was still unshifted yet. The specimen’s resistance to subjected load declined slightly to 6.23 kN (point B), and it rebounded until the second peak load at 6.93 kN (point C), which was greater than the first peak one. At this point, both screws had rotated more than 10°. Again, the resistance to load decreased to 6.13 kN (point D) denoted by denting of contact area around the hole due to oppression of the tilted screw’s head and shifting of the screws to the next thread. The load resistance slightly raised before it declined deeply to 3.78 kN (point E). The loading process was continued, and up-and-down resistances were observed during this stage. Tilting of the screws has continuously occurred as well as the growth of the hole’s diameter. At the end of the loading test, screws were rotated about 70°.

Figure 5. The load-displacement curve for the opposite direction specimen of 2OD-20 (left), condition of the specimen at the end of the test (right).

3.2. Ultimate load
For each specimen, the ultimate loads during the loading test are listed in table 3 and table 4. Most of the ultimate load attained at the beginning of the loading test, right after the elastic response of the specimen passed. For 2-screws specimens, the differences of the ultimate load between specimens joined by screws applied in the same and opposite directions were in the range of 0.4 – 6.2 %. Meanwhile, for the 3-screws specimen, the differences were in the range of 0.2 – 10.0 %.

Table 3. Ultimate load for 2-screws specimens

| Screw spacing (mm) | Ultimate load (kN) | Difference |
|--------------------|-------------------|------------|
|                    | Same direction    | Opposite   | (kN) | %   |
| 20                 | 6.96              | 6.93       | 0.03 | 0.4% |
| 30                 | 7.44              | 6.98       | 0.46 | 6.2% |
| 40                 | 7.45              | 7.36       | 0.09 | 1.2% |
| 50                 | 6.88              | 7.00       | 0.12 | 1.7% |
Table 4. Ultimate load for 3-screws specimens

| Screw spacing (mm) | Ultimate load (kN) | Difference (kN) | % |
|-------------------|---------------------|-----------------|---|
|                   | Same direction | Opposite |                  |     |
| 20                | 11.04            | 11.02 | 0.02 | 0.2% |
| 25                | 10.85            | 9.91  | 0.94 | 8.7% |
| 30                | 10.74            | 10.92 | 0.18 | 1.7% |
| 35                | 10.35            | 9.31  | 1.04 | 10.0% |

3.3. Comparison of experimental results to the analytical calculation

According to Australian/New Zealand Standard for Cold-formed Steel Structures AS/NZS 4600:2005 [8] and Indonesian Standard Design for Cold-Formed Steel SNI 7971:2013 [9], the resistance of connection using screws ($V_b$) was determined as the minimum value between two following formulas:

$$V_b = 4.2 \sqrt{t^3 d_f} f_u n$$

$$V_b = C \ t \ d_f \ f_u n$$

where $t$ is the thickness of the section, $d_f$ is the diameter of the screw, $f_u$ is the ultimate stress of the channel section, $n$ is number of screws, and $C$ is bearing factor as a function of the diameter of the screw and section thickness.

The resistance of connection was calculated for the same section thickness and screw diameter but different ultimate stress that corresponded to the appropriate material section. The resistance formula for connection using screws applied in the same direction is therefore equal to the connection applied in the opposite direction. Furthermore, equation (1) provides a smaller resistance than equation (2). In Table 5, the calculation results are presented, and comparisons between experimental results and analytical calculation are shown in Figure 6.

Table 5. The analytical calculation for connection resistance

| Material specimen | $f_u$ (MPa) | Connection specimen | n | $V_b$ (kN) |
|------------------|-------------|---------------------|---|------------|
| 1                | 475.2       | 2SD-20, 2OD-20      | 2 | 5.80       |
|                  |             | 3SD-20, 3OD-20      | 3 | 8.70       |
| 2                | 516.3       | 2SD-50, 2OD-30      | 2 | 6.30       |
|                  | 516.3       | 3SD-30, 3OD-25      | 3 | 9.45       |
| 3                | 532.3       | 2SD-30              | 2 | 6.49       |
|                  | 532.3       | 3SD-25              | 3 | 9.74       |
| 4                | 558.8       | 2SD-40              | 2 | 6.82       |
|                  | 558.8       | 3SD-35              | 3 | 10.23      |
| 5                | 569.6       | 2OD-50              | 2 | 6.95       |
|                  | 569.6       | 3OD-30              | 3 | 10.42      |
| 6                | 561.1       | 2OD-40              | 2 | 6.85       |
|                  | 561.1       | 3OD-35              | 3 | 10.27      |
3.4. Discussion

Typical failure modes were observed for both groups of specimens. When the specimen was subjected to tension load, the screws bore the load proportionally and responded to it individually. Each screw rotated independently despite the different direction of screw application on the specimen. It means there was no effect of the screw head’s position on the surface of the specimen. Since the screw did not have a nut at its end, rotation of the screw could increase during the tension test; the screws could be detached from the specimen. A significant indentation was found around the hole on the specimen because the tilted screws dented it. The hole becomes bigger as the increment of displacement. The number and spacing of the screws did not affect the resistance of the connection.

The response of the specimen to the subjected load beyond the ultimate load was determined by the contact zone between screws and the channel section. When the contact zone displaced from one thread of the screw to the next one, the load dropped suddenly. Afterward, the specimen’s capacity to sustain load could increase since the channel section was restrained at the successive thread of the screw. At the end of the loading test, there was a gap between two joined channel sections due to the tilting of the screws and growing of the hole on the section.

Regarding the capacity of the connection, the difference between the connection joined by the screws in the same direction, and the connection combined by the screws at the opposite direction was insignificant. For eight pairs of specimens, the differences were within the range of 0.2 – 10.0 %, and the average was only 3.8 %. These slight variances were due to the capacity of the connection determined by a solely capacity of one screw, which was independent of spacing and configuration of the screws and direction of screw application.

Meanwhile, the calculated capacity based on the analytical formula showed a good agreement with the experimental results. In general, the analytical formula calculated the capacity of the connection lower than the experimental result.

4. Conclusions

The behaviour of screw connection of cold-formed steel which the screws applied in the same and opposite directions has been investigated experimentally. Typical ultimate conditions were observed, i.e., tilting of the screws, indentation on the hole, and separation of the two joined channel sections.
The ultimate load of the connection attained beyond the linear-elastic zone before it dropped suddenly due to shifting of screw thread. The connection resistance is proportional to the number of screws but independent of the direction of screw application on the specimen.

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