Mechanical Properties of Single Shear Plane of Bolted Steel Connection

A F Kamarudin, M K Musa, S N Mokhatar, T N Tuan Chik, S S Mohd Zuki, A Abu Bakar, J Hadipramana and H H Ahmad Johari

1 Jamilus Research Centre, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Pt. Raja, Bt. Pahat, Johor, MALAYSIA
2 Faculty of Technology Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Pt. Raja, Bt. Pahat, Johor, MALAYSIA
3 Program Studi Teknik Sipil, Universitas Muhammadiyah Sumatera Utara Jl. Muctar Basri, Medan 20238, INDONESIA
Corresponding author: fahmy@uthm.edu.my and hanisjoe.hj@gmail.com

Abstract. A 5-storey portable steel tower based on prefabricated frame concept has been built in Jamilus Research Centre, UTHM. It is now undergoing laboratory testing for static and dynamic performance. In this study, the mechanical properties of the connections were investigated via their connection condition between elements (beam and column) and connectors. The frame elements were designed based on S275 steel grade of 77 mm x 77 mm hollow section with 3 mm thickness, and 8 mm thickness of connectors’ plate. The connection was subjected to single shear plane action which fastened by bolts. Mild steel (grade 4.6) and high tension (grade 8.8) bolts with 10 mm diameter size were used. Shear, bearing and tensile strengths of the bolts and steel plates were determined via tension testing using 50 tonnes of Universal Testing Machine (UTM). From the results, all bolts and steel plates have satisfied the design strengths requirement of 640 N/mm² (high tension bolt), 240 N/mm² (mild steel bolt) and 275 N/mm² as required by EN 1993-1-8. Meanwhile the ultimate shear force of bolts was found within ranges of 25% (high tension) and 12.5% (mild steel) from their respective ultimate tensile force. Bearing failure was occurred at bolt hole of 3 mm thickness of steel plate but only when it was fastened to high tension bolt. No bearing failure occurred when mild steel bolt was used. It has proven that all bolt spacing and edges distances were sufficient, without tearing failure observed in all testing. Finally, the permissible bearing resistance were checked based on the ratio of experiment against the EN 1993-1-8 relationships, when it has shown to satisfaction if the value is less than 1 as recommended by previous researcher.

1. Introduction
Connections between beams and columns or column to foundation are fragile segments that need to be emphasized in steel frame constructions. The functions of connections are to distribute axial force and moments to columns. Bolted connections are the most preferable in steel constructions because it able to reduce the construction cost since less experience and skilled workers are needed during handling of construction activities.

Geometrical factors of the connections components such as bolt sizes, angle of sections, edge and spacing have given a big impact during preference of materials. Bearing occurs when it has a contact surface area between the shanks of the bolt and the bolt hole. Meanwhile, a bolt is also subjected to a shear and tension resistances that need to be given a great attention in steel constructions. According to
Prinz et al. [1], a bolted beam to column connection is often expected to be fully rigid or fully pinned. However, to be truth, the rigidity of connections is clarified as semi-rigid connection [1]. Besides, the deliberations made for connections rigidity can be used to determine the limits of strength forces for beams and columns in a building system [2].

Bolt is mainly used in connection to resist shear on the surface of plates, and tensile force along the axis of bolts. In a bolt connection, the forces can be transferred into bearing, shear and tension conditions. John and Stephen [3] stated, the force that comes from vertical components, V, act to break off the bolts out of the column, while horizontal component in the case of moment loading, M, acts as to fracture the bolts in tension. There are several types of malfunction in bolt connection which are, plate tearing failure, bearing failure on the plate material, tension failure on the surface area, bolt shearing and any combinations malfunction [3].

Mehran et al. [4] describes most failures in connections are due to plate tearing (refer to figure 1). It occurs when the bolt is at a critical distance or space alongside bolts align with pressure is low [4]. The failure such as plate shear/tear-out and tension failure on the net section mostly fail on plate, and this can be described as catastrophic failure which is sudden failure.

Shearing failure of a bolt shear can be occurred when modulus material of bolt is much lower than the plate which also depending on grade of a bolt. The grade of a bolt is determined when it has greater strength to resist the shearing force more than the capacity of plate load, and its positioning of connection as a whole. In spite of that, there are some factors that influence the shear behaviour. To name a few, sheet thickness, grades of bolts, diameter of bolt, mechanical properties of steel, resistance coefficient and torque applied on bolt [5].

In contrast to bolt bearing, when the failure can be occurred if the modulus material of bolt is much higher than the material of plate. Consequently, the bolt will tilt due to lowest strength of its grade. Meanwhile, the tension failure on the net section can occurs due to the existence of holes that will increase the concentrated of stresses areas on plates [6]. This kind of failure commonly occurs at the joints due to lower net section area of the sheet and thus it can contribute as the fragile section of the plate. These failures have been controlled by the number of bolts and spacing arrangement. Thus, to prevent this failure a proper design with minimum satisfied edge distance and bolt spacing need to be considered [7].

According to American Iron and Steel Institute (AISI) [9], shear and tension testing are used to determine the hardness and rigidity of the specimens. Standard shear tests can be conducted when two specimens is jointed and placed in tensile testing machine [8]. This tension testing will be loaded till failure. Table 1 shows a guideline to a standard shear test dimension of a specimen with specific width, edge distance, spacing and length. The length of extensometer gauge length, L_e must be short enough to reduce the stretch impact in specimens on the extensometer readings.

This paper is a part of static testing report which involved in portable steel tower investigation built in Jamalus Research Centre, UTHM. In this study, a single shear plane jointed plates (lapping) samples with 3 mm and 8 mm of S275 steel thicknesses is fastened by 10 mm of bolt (high tension and mild steel) with specific edge distance and bolt spacing. The samples were tested under tension testing by using 50 tonnes of UTM machine in order to determine the mechanical properties of the materials and the connections (bolt and connecting plates). Some other discussion was also made on the end distance. Tensile strength, shear strength, bearing resistance and failure modes of the material as well as the connection were reported as the major part in mechanical properties investigations in this study. Allowable strength and acceptable design considerations as provided by previous code of practices and researches in [9][11-13] were also studied and discussed.

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![Figure 1. Types of steel connection failures [6]](image-url)
Table 1. Recommended dimensions for standard shear test [9]

| Fastener diameter, \( d \) (mm) | Dimensions of specimen (mm) |   |   |   |
|-------------------------------|-----------------------------|---|---|---|
|                               | Width, \( w \)               | Strap length, \( L_s \) | End distance, \( e_1 \) | Spacing, \( p \) | Extensometer gage length, \( L_g \) |
| \( \leq 6.5 \)                | 60                          | 260                        | 30            | 60            | 150                      |
| \( > 6.5 \)                  | 10d                         | 200+10d                    | 5d            | 10d           | 30.20d                   |
| Tolerance                    | \( \pm 2 \)                 | \( \pm 5 \)                | \( \pm 1 \)   | \( \pm 1 \)   | \( \pm 5 \)               |

2. Materials and Methodology
All element and connector plates were designed and manufactured from S275 steel grade. 77 mm \( \times \) 77 mm cross section of square hollow elements section with 3 mm thickness has been cut out into coupon shape (refer to figure 2) for tension testing. 5 mm/min speed was used in tension testing. Similar procedure was carried out on the plate’s connector of 8 mm plate thickness for tensile testing. The preparation and testing procedure of tensile specimens was done in accordance to the code of practice of BS EN ISO 6892-1:2016 [11] for tensile strength determination (see figure 3). The specimen preparation of shear and bearing strength on plates and bolts was prepared as given in figure 4. Figure 5 shows the mild steel bolts (Grade 4.6) and high tension bolts (Grade 8.8) with diameter 10 mm which also involved in the tension testing.

The design requirements of the bolts have been referred to MS 146-2006 [12]. The nominal yield strength of the high tension bolt, mild steel bolts and plate must be satisfied to the minimum design requirement of 640 N/mm\(^2\), 240 N/mm\(^2\), and 275 N/mm\(^2\) as required by EN 1993-1-8 [10]. The commentary of the shear test can be referred to American Iron and Steel Institute (AISI) guidelines [9].

A total of eight specimens in single shear plane connection were prepared. The variation of specimen parameters can be differentiated against the bolt types, plate thickness, number of bolts, edge distance and spacing. All steel plates were provided by the strain gauges at the edge distance region, in order to investigate tensile or compression action against the elongation or contractions behaviour. Observation on specific type of failures (refer to figure 1) was also carried out in this study. The recorded yield strength and ultimate strength of bolt and plate from tension testing were tabulated in table 2, whereas figure 6 and 7 show the bolts and coupon failures which taken after testing. Details specification of the each specimen is provided in the Appendix.

Figure 2. Plate coupon
Figure 3. Experimental setup for tensile test on coupon
Figure 4. Experimental setup for shear/bearing strengths
3. Results and Discussions

3.1 Ultimate shearing force and failure modes of specimens

The ultimate shearing force with respective observed failures has been summarized in table 3. From a sample of testing result on load versus stroke curve of specimen A (see figure 8), the curve has been shown in linear appearance of elastic behaviour which acted by the shearing and bearing resistance of the bolt and plates. According to Mehran et al. [4] taken from an instance of truss connection, the load-stroke curves will implicate the connections of members and bolts as a whole. However, when the bolt is started to tear and unsecure tightly fixed in place, the non-linearity curve is developed then ended by failures.

| Specimen | Thickness | Ultimate shearing force (kN) | Failure description |
|----------|-----------|------------------------------|---------------------|
| TP       | BP        | Mild steel bolt | High tension bolt |
| A (two bolts) | 3 mm | 20.02 | 65.90 | • Bolt shearing failure |
| B (one bolt) | 3 mm | 14.00 | 30.04 | • Plate bearing failure only occurred at 3 mm plate thickness which fastened by high tension bolts |
| C (one bolt) | 8 mm | 14.01 | 34.02 | • Free damage at 8 mm thickness of steel plate |
| D (one bolt) |  | 16.00 | 31.03 | |

Table 3. Ultimate shearing force on bolt and type of failures

TP: Top plate, / BP: Bottom plate
3.2 Strain gauge

Figure 9 shows the strain curves from one of samples marked as specimen C. The strain gauges were attached at the edge distance region of both plates which closer to the bolt hole. The elongation of the plate is occurred along the longitudinal direction of the plates, which inline to the direction of tensile forces. At the first 60 seconds, both steel plates behave in elastic behaviour based on the linear strain curves pattern obtained. At this stage, the plates were able to withstand the external axial load applied which subjected to compression behaviour. After 60 seconds, 3 mm thickness plate is started to deform which then ended by bolt shearing failure after 162 secs. For this specimen, the maximum shear force has archived up to 14.01 kN (refer to mild steel bolt case in table 3). All bolts were failed in shearing. However, in case of high tension bolt, the 3 mm thickness of steel plate was failed in bearing and none of failure observed for 8 mm thickness of steel plate. The strain curve pattern of the rest specimens are attached in the Appendix.

3.3 Analytical result on bearing resistances

The resistance of a bolted connection is also depended on its plate bearing resistance. In EN 1993-1-8 [10], a design considerations for bearing resistance is given by equation 1, whereby $\gamma_{n2} = 1.25$ has been taken as partial safety factor as recommended.

$$F_{b,Rd} = \frac{k_1 \alpha_b f_u dt}{\gamma_{n2}}$$  \hspace{1cm} (1)

where:

- $F_{b,Rd}$ : bearing resistance,
- $d$ : bolt diameter with $d_{hole} = d + 1$mm
- $t$ : thickness of plate
- $f_u$ : ultimate tensile force = 410 N/mm$^2$ for S275 $t \geq 3$mm
- $\gamma_{n2}$ : safety factor = 1.25
- $\alpha_v$ : $\alpha_b = \frac{e}{3 d_{hole}}$ or $\alpha_d = \frac{f_{ub} = 800 N/mm^2}{f_u}$ (the lesser)
- $e$ is the edge distance at 3 mm thickness (all dimensions refer to the Appendix) and,
- $s$ is the bolt spacing.
The limitations between design resistances of bolts can be calculated according to the ratio of bearing resistance of specimens obtained from laboratory outcomes \((F_{b,Ed})\) to the bearing resistance relationship as expressed in equation (1). The computed results from this ratio have been summarized in table 4 and 5. For permissible criteria, \(F_{b,Ed} \leq F_{b,Rd}\) it must be less than 1 [13], and all tested samples in this study have fulfilled to the acceptable limit.

### Table 4. Acceptable limit to bearing resistance of high tension bolt connection

| Types of bolt       | Load due to bearing, \(F_{b,Ed}\) (kN) (Experimental results) | Maximum bearing resistance, \(F_{b,Rd}\) (kN) (Manual calculation) | Description \((F_{b,Ed}/F_{b,Rd}) [13]\) |
|---------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------|
| High tension bolt   | 65.90                                                           | 95.94                                                                | \(\frac{65.90}{95.94} = 0.69 \leq 1\), Acceptable                  |
|                     | 30.04                                                           |                                                                     | \(\frac{30.04}{47.97} = 0.63 \leq 1\), Acceptable                  |
|                     | 34.02                                                           | 47.97                                                                | \(\frac{34.02}{47.97} = 0.71 \leq 1\), Acceptable                  |
|                     | 31.03                                                           |                                                                     | \(\frac{31.03}{47.97} = 0.65 \leq 1\), Acceptable                  |

### Table 5. Acceptable limit to bearing resistance of mild steel bolt connection

| Types of bolt       | Load due to bearing, \(F_{b,Ed}\) (kN) (Experimental results) | Maximum bearing resistance, \(F_{b,Rd}\) (kN) (Manual calculation) | Description \((F_{b,Ed}/F_{b,Rd}) [13]\) |
|---------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------|
| Mild steel bolt     | 20.02                                                           | 47.97                                                                | \(\frac{20.02}{47.97} = 0.42 \leq 1\), Acceptable                  |
|                     | 14.00                                                           |                                                                     | \(\frac{14.00}{24.00} = 0.58 \leq 1\), Acceptable                  |
|                     | 14.01                                                           | 24.00                                                                | \(\frac{14.01}{24.00} = 0.58 \leq 1\), Acceptable                  |
|                     | 16.00                                                           |                                                                     | \(\frac{16.00}{24.00} = 0.67 \leq 1\), Acceptable                  |

3.4 Failure modes of steel plate

According to Zadanfarrokh et al. [8], a ratio between the edge/end distance and bolt diameter can be used to predict the failures types \((e/d)\) of the plate which expressed in equation 2 and 3. But, the influence of bearing failure on a plate is mostly occurred to the thin plate compared to the thick plate [14].

\[
\text{Sheet tearing} : \text{for } e/d \leq 1.5 \quad (2)
\]
\[
\text{Sheet bearing} : \text{for } e/d \geq 2.25 \quad (3)
\]

where:

- \(e\) : edge/end distance
- \(d\) : diameter of bolt.

Based on the calculated \(e/d\) ratio of specimens A, B, C and D (refer to table 6), the sheet bearing failure has shown to a great potential when it has exceeded to 2.25. The sheet bearing failure significantly occurred on 3 mm thickness of steel plate when it fastened to the high tension bolt. However, none of a plate failure was observed on specimens with mild steel bolts connection, due to lower resistance of shearing force which makes the bolt to break first before the bearing failure of the steel plate.
Table 6. e/d ratio of specimens A, B, C and D for mild steel and high tension bolts connection

| Specimen (3 mm plate thickness) | Minimum end distance and e/d ratio | Single bolt connection | e/d | Double bolts connection | e/d |
|---------------------------------|-----------------------------------|------------------------|-----|-------------------------|-----|
| A                               |                                   |                        |     |                        |     |
| B                               | 80/10                             | 40/10                  | 4.0 |                        |     |
| C                               | 80/10                             | 40/10                  | 4.0 |                        |     |
| D                               | 79/10                             | 40/10                  | 4.0 |                        |     |

4. Conclusions
Following are some conclusions made based on the outcomes from laboratory testing and analytical analysis carried out in this study:

i. The tensile strengths of the mild steel bolt, high tension bolt and steel plate have satisfied the minimum yield strength requirement of 240 N/mm², 640 N/mm² and 275 N/mm² as required by BS EN 1993-1-8. Besides, it has found that the tensile strength of high tension bolt (grade 8.8) has indicated two times higher compared to the mild steel bolt (grade 4.6).

ii. The specimens had experienced compression behaviour at the edge/end distance of the steel plate from the result of strain gauge shown in this region.

iii. The shearing failure of 10 mm diameter of mild steel bolt in single shear plane connection testing is higher if compared to potential of bearing failure of 3 mm thickness of steel plate.

iv. The design consideration on bearing resistance based on the calculations made against the ratio from experimental results to the bearing resistance equation of EN 1993-1-8 have shown to acceptable limit when the values are less than 1.

v. The ultimate shearing forces of both bolt types are found to archive 12.5% (mild steel bolt) and 25% (high tension bolt) from respective ultimate tensile force.

vi. Bearing failure has occurred on the 3 mm thickness of steel plate when 10 mm of high tension bolt was used. This failure has also agreed to e/d ratio as recommended by Zadanfarrokh et al. [8]. However, lower shear resistance of mild steel bolt has caused to shearing failure to be occurred first, which slightly different against high tension bolt scenario.

5.0 References

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**Appendix:** Dimension of specimen A, B, C & D, and strain gauge curves (all dimension in mm).