# THESIS APPROVAL

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**DEGREE**

Civil Engineering — **FIELD**

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**TITLE:** Investigation of Shear Lag Factors on Bolted Hot-rolled Steel Angles

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# THESIS

# INVESTIGATION OF SHEAR LAG FACTORS ON BOLTED HOT-ROLLED STEEL ANGLES

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master of Engineering (Civil Engineering)
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Tawan Khankruer 2013: Investigation of Shear Lag Factors on Bolted Hot-rolled Steel Angles. Master of Engineering (Civil Engineering), Major Field: Civil Engineering, Department of Civil Engineering. Thesis Advisor: Associate Professor Trakool Aramraks, Ph.D. 52 pages.

The objective of this experimental program is to investigate a shear lag factor "U" on tension members with net section fracture of bolted hot-rolled steel angle. The parameters considered in this experimental program were number of bolts, connection length (center of first hole to center of last hole), size/cross-section of angle member and ultimate tensile strength of steel angle.

The results showed that shear lag factor "U" were affected by number of bolts, connection length, size/cross section of steel angles and ultimate tensile strength of material. The shear lag factor obtained from the experiment were within the range between the values provided by AISC 2010, case 2 to case 8 depended on the values of ultimate tensile strength ($F_u$). Choosing the smallest value of $F_u$ was always safe and recommended for designer. Further study should be focused on how to choose $F_u$ for economical design.

_________________________ Student's signature    _________________________ Thesis Advisor's signature    ___ / ___ / ___

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I would like to show my grateful thanks and am deeply indebted to Associate Professor Trakool Aramraks, Ph.D. my thesis advisor for advice, encouragement and valuable suggestions since the beginning of my chosen topic, possibility study to start the test, recommendation of solving the problem during the period of test and the complete writing of this thesis.

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Tawan Khankruer

May 2013

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# LIST OF ABBREVIATIONS

Notation and definitions of the terms are

$A_e$ = effective net area

$A_g$ = gross area

$A_n$ = net area

$F_u$ = ultimate tensile strength

$F_y$ = ultimate yield strength

$K_1$ = an attempt to account for the ductility of material

$K_2$ = the fabrication factor

$K_3$ = the geometry factor

$K_4$ = shear lag factor from base on research by Munse and Chesson (1963)

L = connection length

$P_n$ = nominal tensile strength

$P_{exp}$ = ultimate tensile strength

Q = percent reduction in the area at rupture of a standard tensile test coupon (51 mm.gage length)

U = shear lag factor

$\tilde{x}$ = distance from shear plane to the center of gravity of the material connection to the shear plane

# INVESTIGATION OF SHEAR LAG FACTORS ON BOLTED HOT-ROLLED STEEL ANGLES

## INTRODUCTION

Nowadays, Steel Structure is used for many types of structures such as bridges, building, etc. The advantages of steel structure compared to others are light weight, homogeneous material, fast and easy erection and installation, disassembly and recycling. In most steel constructions in Thailand, hot-rolled sections are the main steel members which are usually used and member shape such as angles are often used as tension members. Bolted or fastener connection is the usual way for steel members, but when axial load is transferred to cross-section, a non-uniformed stress is produced and distributed to the net section area (Figure 1).

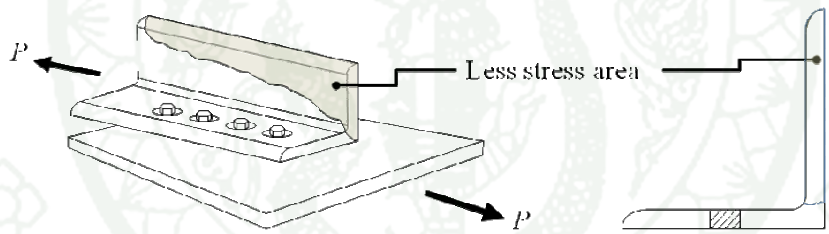



**Figure 1** Non-uniformed stress distribution on the net area section of angle member.

**Source:** Jiravacharadet (2005)

American Institute of Steel Construction (AISC, 2010) defined effective net area of tension member which shall be determined as follows;

$$A_e = A_n U \quad (1)$$

Notation and definitions of the terms are;

$A_e$ = effective net area, ($mm^2$)

$A_n$ = net area, ($mm^2$)

U = the shear lag factor.

Shear lag factor was suggested by AISC, 2010 as shown below.

$$U = 1 - \left( \frac{\tilde{x}}{L} \right) \tag{2}$$

Notation and definitions of the terms are;

$\tilde{x}$ = distance from shear plane to the center of gravity of the material connected to the shear plane, mm.

L = connection length, mm.

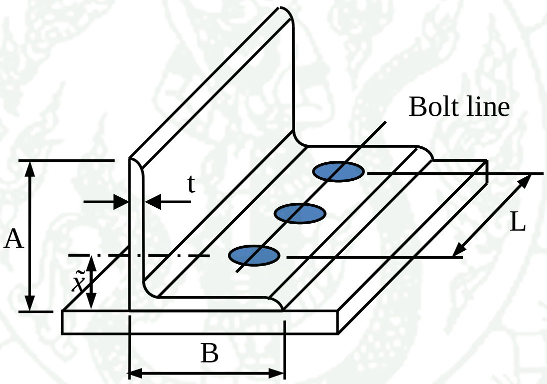



**Figure 2** Typical hot-rolled angle for a bolted connection.

**Source:** De Paula *et al*. (2008).

# OBJECTIVES

The objective of this experimental program is to investigate a shear lag factor "U" on tension members with net section fracture of bolted hot-rolled steel angle. Various parameters of the experimental program are considered such as, number of bolts, connection length (center of first hole to center of last hole), size/cross-section of angle member and ultimate tensile strength of steel angle.

The objective is summarized as follows;

1. To investigate behaviors of bolted hot-rolled steel angle under tension force.
2. To compare shear lag factor between test and design code.

## Scope of Study

1. Parameters to be studied are as follows:

    - Number of bolts
    - Connection length (center of first hole to center of last hole)
    - Size/Cross-section of angle member
    - Difference of ultimate tensile strength

2. 26 numbers of single angle specimens are tested.

3. The test considers net section failure mode only.

4. All single angle specimens follow the JIS G3101 standard Grade SS400 whose mechanical properties are;

- Yield strength of 245 MPa.
- Ultimate tensile strength of 400-510 MPa.

5. High-strength hex bolts ASTM A325M 8S, thread on shear plane

6. Types of Bolted Connections are bearing type connection,

# LITERATURE REVIEW

## 1. Previous Studies on shear Lag of Tension Members

There are three principal failure modes of members under tension forces;

(I) yielding of the gross section,
(II) net section failure, and
(III) failure of the end connection.

Shear lag is related to mode (II). Such failure describes behavior at an end connection of a tension member where some but not all of the cross-sectional elements are connected. In other words, the area that is effective in resisting tension may be less than the full calculated net area (Albert, 1996).

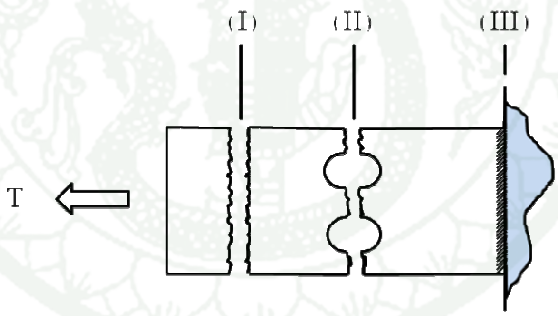



**Figure 3** Three principle failure modes of tension member. (Albert, 1996). .

Most steel structure design provisions, including American Institute of Steel Construction (AISC, 2010) are based on research by Munse and Chesson (1963). Munse and Chesson found that the value of section efficiency of tension members, bolted or riveted at end connections was a function of large number of factors. This equation was developed from the results of more than 1000 tests. They summarized the experiments and proposed an equation as shown below.

$$A_e = K_1 K_2 K_3 K_4 A_n \tag{3}$$

Notation and definitions of the terms are

$K_1$ = 0.82 + 0.0032Q < 1

$K_2$ = 0.85 for members with punched holes, 1.0 for members with drilled holes

$$K_3 = 1.6 - 0.7\left(\frac{A_n}{A_g}\right)$$

$$K_4 = 1 - \left(\frac{\tilde{x}}{L}\right)$$

$A_g$ = gross area of cross-section

Q = percent reduction in the area at rupture of a standard tensile test coupon (51 mm gauge length)

$\tilde{x}$ = distance from shear plane to the center of gravity of the material connected to the shear plane, mm.

L = connection length, mm.

The factor $K_1$ is an attempt to account for the ductility of material. The term Q applied in definition of $K_1$ is a reduction to the area of a standard tensile test coupon (51 mm gauge length). The fabrication factor $K_2$, is used to account for the reduction in efficiency due to the effect of punching the holes. To account for the effect of hole spacing on the connection, or the g/d ratio, a geometry factor, $K_3$, is included. Finally, $K_4$ is the shear lag factor, which takes into account both the eccentricity in the connected parts and the connection length.

In expression for $K_4$, $\tilde{x}$ refers to the distance from the face of gusset plate to the center of gravity of member and L is connection length, taken as the distance between extreme fasteners. Munse and Chesson note that Equation 3 predicted the net section efficiency within ± 10 percent range for most of test data.

For most practical case the ductility factor ($K_1$) and geometric factor ($K_3$) can be taken as unity (Wu and Kulak, 1993). The fabrication factor $K_2$ can be given the value 0.85 for punched holes and 1.0 for drilled holes (Munse and Chesson, 1963). According to these assumptions, the Equation 3 can be written as

$$A_e = \left(1 - \frac{\tilde{x}}{L}\right) A_n \qquad (4)$$

According to the Munse and Chesson (1963) formulation by substituted effective net section area from Equation 4 to Equation 3, the predicted tensile load of an angle will be

$$P_n = \left(1 - \frac{\tilde{x}}{L}\right) A_n F_u \qquad (5)$$

**2. Current Design Specifications**

American Institute of Steel Construction (AISC, 2010), Chapter D indicates that for the design tensile strength, $\phi_t P_n$, and the allowable tensile strength, $P_n/\Omega_t$, of tension members shall be the lower value obtained according to the limit states of tensile yielding in the gross section and tensile rupture in the net section.

a) For tensile yielding in the gross section

$$P_n = F_y A_g \qquad (6)$$

$\phi_t = 0.90$ (LRFD) and $\Omega_t = 1.67$ (ASD)

b) For tensile rupture in the net section

$$P_n = F_u A_e \qquad (7)$$

$\phi_t = 0.75$ (LRFD) and $\Omega_t = 2.00$ (ASD)

Notation and definitions of the terms are;

$P_n$ = nominal tensile strength, (N)

$A_e$ = effective net area, ($mm^2$)

$A_g$ = gross area of member, ($mm^2$)

$F_y$ = specified min. yield stress of the type of steel being used, (MPa)

Notation and definitions of the terms are;

$F_u$ = specified min. tensile strength of the type of steel being used, (MPa)

$\phi_t$ = resistance factor for tension.

$\Omega_t$ = Safety factor for tension.

To compute the net section strength of tension member in a way that includes the shear lag effect, an “effective” net area is used instead of the net area in order to take into account the reduction of efficiency as a result of this effect. The American Institute of Steel Construction (AISC, 2010), Section D3, defines effective net area of tension member shall be determined as follows:

$$A_e = A_n U \tag{8}$$

Notation and definitions of the terms are

$A_e$ = effective net area, ($mm^2$)

$A_n$ = net area, ($mm^2$)

U = the shear lag factor.

For all tension members where the tension load is transmitted directly to each of cross-sectional elements by fasteners or welds, the shear lag factor (U) equal to 1.0 is permitted to be used. And for all tension members, except plates and HSS, where the tension load is transmitted to some but not all of the cross sectional elements by fasteners or longitudinal welds, the shear lag factor shall be calculated by

$$U = 1 - \frac{\tilde{x}}{L} \tag{9}$$

However, AISC (2010) also defines an additional value of shear lag factor for single angle member, separated into two cases;

**Table 1** Shear lag factors for connections to tension members.

<table>
<tr><th>Case</th><th colspan="2">Description of Element</th><th>Shear Lag Factor, U</th></tr>
<tr><td>2</td><td colspan="2">All tension members, except plates and HSS, where the tension load is transmitted to some but not all of the cross sectional elements by fasteners or longitudinal welds or by longitudinal welds in combination with transverse welds. (Alternatively, for W, M, S and HP, Case 7 may be used. For angles, Case 8 may be used.)</td><td>$U = 1-\bar{x}/L$</td></tr>
<tr><td rowspan="2">8</td><td rowspan="2">Single angles (if U is calculated per Case 2, the large value is permitted to be used)</td><td>with 4 or more fasteners per line in direction of loading</td><td>$U = 0.80$</td></tr>
<tr><td>with 2 or 3 fasteners per line in direction of loading</td><td>$U=0.60$</td></tr>
</table>

**Source:** AISC (2010)

# MATERIALS AND METHODS

## 1. Hypothesis

1.1 Failure of steel angle under tensile force is related to assumed cross-section area.

1.2 Testing steel angles has the same properties ($F_y$ = 245MPa, $F_u$ = 400-510 MPa) for all the batch.

## 2. Materials and Equipment

2.1 Materials

2.1.1 Hot-rolled steel angles; JIS 3101 Grade SS400

2.1.1.1 Angle size 50x50x4, 500 mm long. (Figure 4)

2.1.1.2 Angle size 50x50x6, 500 mm long. (Figure 4)

2.1.1.3 Angle size 75x75x6, 500 mm long. (Figure 5)

2.1.2 Gusset plate 10 mm thickness (Figure 6)

2.1.3 ASTM A325M bolts, diameter 16.0 mm (Figure 7)

2.2 Equipment

2.2.1 Universal testing machine with monitor, capacity 2000 kN (Figure 9)

2.2.2 Data logger (Figure 10)

2.2.3 Dial gage

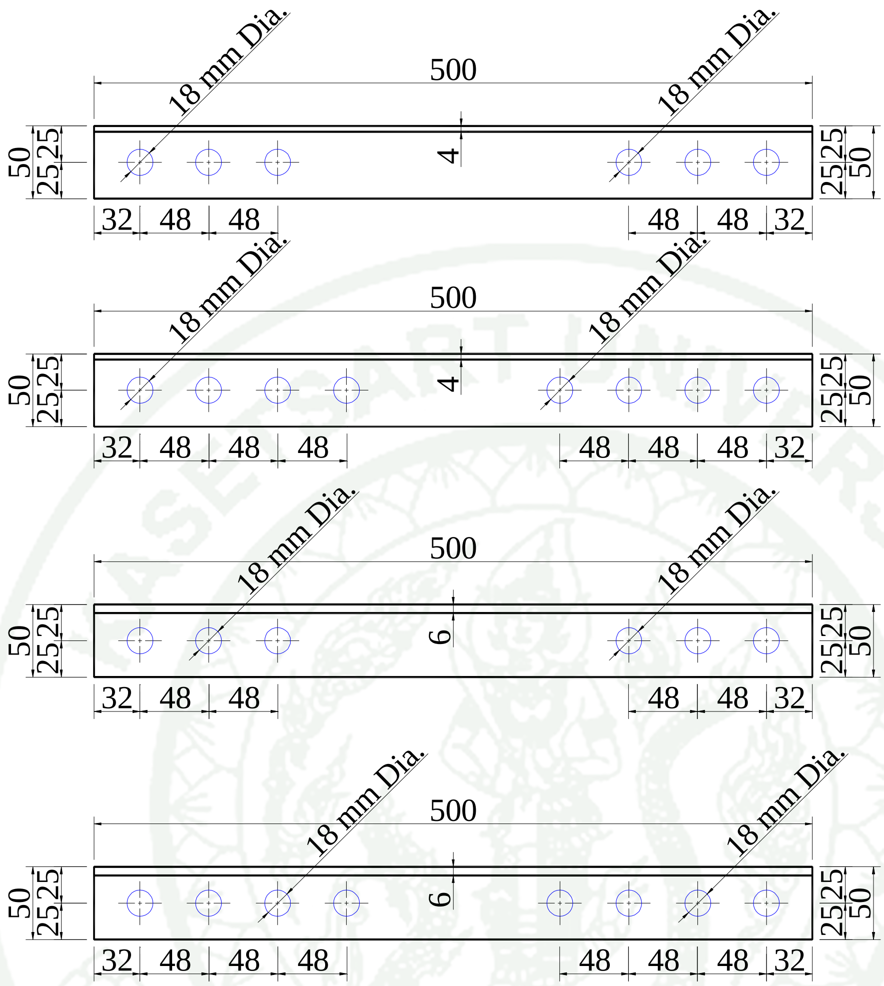



**Figure 4** 50x50x4 mm and 50x50x6 mm. hot-rolled steel angles

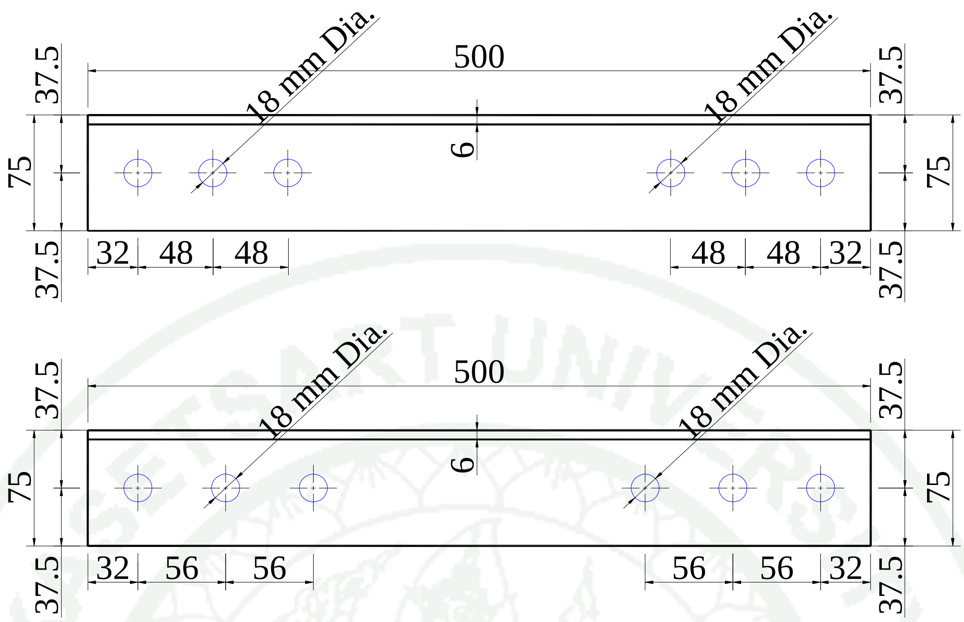



**Figure 5** 75x75x6 mm hot-rolled steel angles

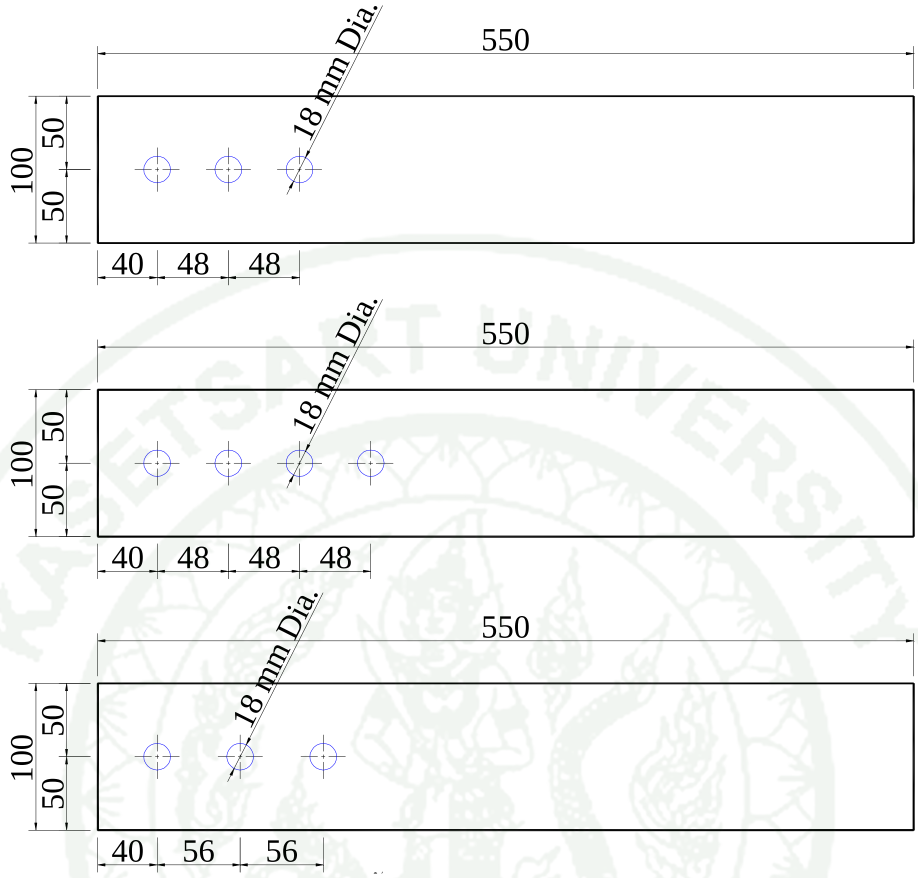



**Figure 6** 100x550x10 mm gusset plates.

**Figure 7** ASTM A325 bolts, diameter 16.0 mm

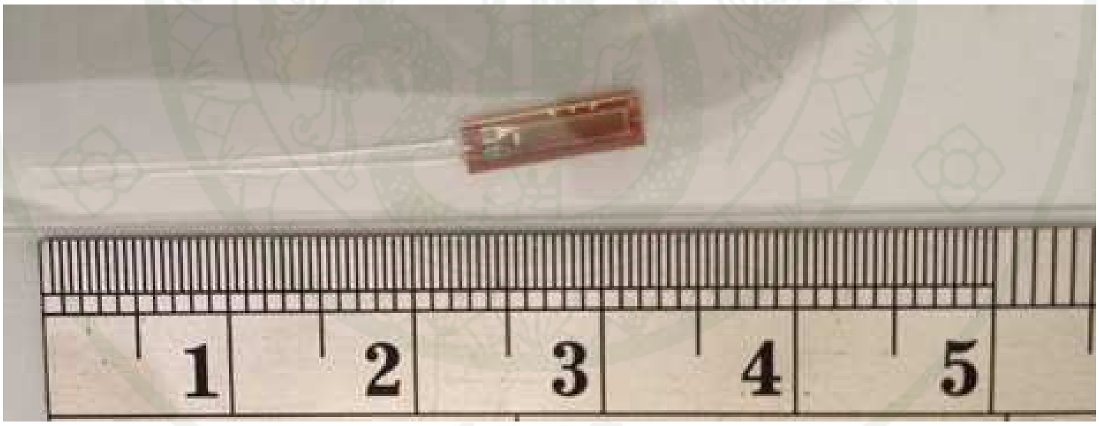


**Figure 8** Strain gages (gage length 5.0 mm)

**Figure 9** Universal Testing Machine (UTM) with monitor, Capacity 2000 kN.

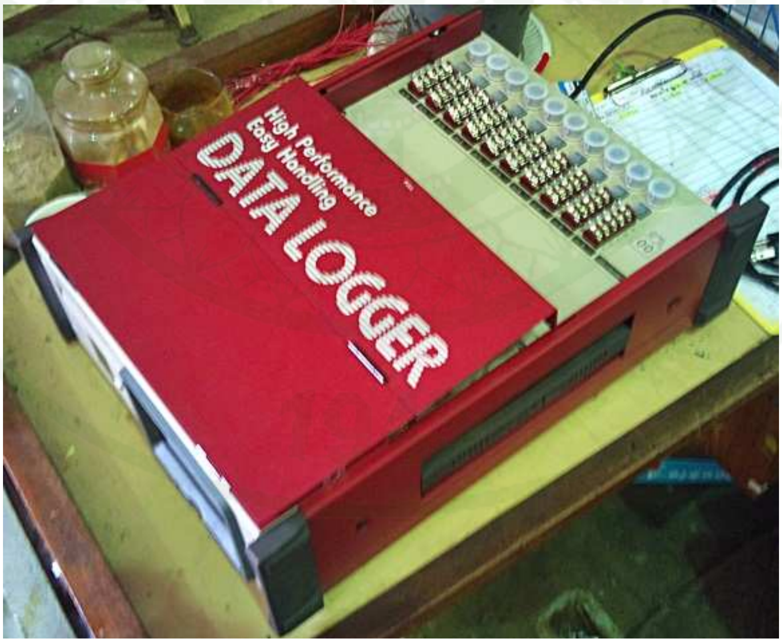



**Figure 10** Data logger.

## 3. Testing Procedure

### 3.1 General

To investigate the behavior of shear lag effect on hot-rolled single angle member, three different sizes of angles are produced. Twenty six specimens (Table 2) are tested in the laboratory. Results from the test are compared with the results calculated according to the AISC (2010). Various parameters of the experimental program are as follows:

- Number of bolts
- Connection length (center of first hole to center of last hole)
- Size/Cross-section of angle member
- Difference ultimate tensile strength

### 3.2 Specimens Description

The 26 specimens with the length of 500 mm. are prepared for the laboratory tests. JIS G 3101 grade SS400 is common class of steel member in Thailand whose mechanical properties are;

- Yield strength of 245 MPa
- Ultimate tensile strength of 400-510 MPa.

Angle members to be tested are varied in size and thickness. Each side of angle member has been drilled for bolted connections with 1 line pattern. Three and four bolts for a line are prepared and considered as factors of the test results. All holes are drilled to 18.0 mm diameter for ASTM A325 bolt diameter 16.0 mm. The description of the specimens and gusset plate geometry and dimensions are presented in Table 2.

**Table 2** Description of specimens

| Test | Group | Angle denomination | A (mm) | B (mm) | t (mm) | Number of bolt lines | No. of holes per bolt line |
|---|---|---|---|---|---|---|---|
| 1 | | 50-4-311 | 50 | 50 | 4 | 1 | 3 |
| 2 | | 50-4-312 | 50 | 50 | 4 | 1 | 3 |
| 3 | G1 | 50-4-313 | 50 | 50 | 4 | 1 | 3 |
| 4 | | 50-4-314 | 50 | 50 | 4 | 1 | 3 |
| 5 | | 50-4-315 | 50 | 50 | 4 | 1 | 3 |
| 6 | | 50-4-411 | 50 | 50 | 4 | 1 | 4 |
| 7 | | 50-4-412 | 50 | 50 | 4 | 1 | 4 |
| 8 | G2 | 50-4-413 | 50 | 50 | 4 | 1 | 4 |
| 9 | | 50-4-414 | 50 | 50 | 4 | 1 | 4 |
| 10 | | 50-4-415 | 50 | 50 | 4 | 1 | 4 |
| 11 | | 50-6-311 | 50 | 50 | 6 | 1 | 3 |
| 12 | | 50-6-312 | 50 | 50 | 6 | 1 | 3 |
| 13 | G3 | 50-6-313 | 50 | 50 | 6 | 1 | 3 |
| 14 | | 50-6-314 | 50 | 50 | 6 | 1 | 3 |
| 15 | | 50-6-315 | 50 | 50 | 6 | 1 | 3 |
| 16 | | 50-6-411 | 50 | 50 | 6 | 1 | 4 |
| 17 | | 50-6-412 | 50 | 50 | 6 | 1 | 4 |
| 18 | G4 | 50-6-413 | 50 | 50 | 6 | 1 | 4 |
| 19 | | 50-6-414 | 50 | 50 | 6 | 1 | 4 |
| 20 | | 50-6-415 | 50 | 50 | 6 | 1 | 4 |
| 21 | | 75-6-311 | 75 | 75 | 6 | 1 | 3 |
| 22 | G5 | 75-6-312 | 75 | 75 | 6 | 1 | 3 |
| 23 | | 75-6-313 | 75 | 75 | 6 | 1 | 3 |
| 24 | | 75-6-314 | 75 | 75 | 6 | 1 | 3 |
| 25 | G6 | 75-6-315 | 75 | 75 | 6 | 1 | 3 |
| 26 | | 75-6-316 | 75 | 75 | 6 | 1 | 3 |

**Table 2** (Continued)

| Test | Group | Angle denomination | d (mm) | x̃ (mm) | L (mm) | A mm2 | $A_n$ mm2 |
|---|---|---|---|---|---|---|---|
| 1 | | 50-4-311 | 18.0 | 13.7 | 96 | 389.2 | 317.2 |
| 2 | | 50-4-312 | 18.0 | 13.7 | 96 | 389.2 | 317.2 |
| 3 | G1 | 50-4-313 | 18.0 | 13.7 | 96 | 389.2 | 317.2 |
| 4 | | 50-4-314 | 18.0 | 13.7 | 96 | 389.2 | 317.2 |
| 5 | | 50-4-315 | 18.0 | 13.7 | 96 | 389.2 | 317.2 |
| 6 | | 50-4-411 | 18.0 | 13.7 | 144 | 389.2 | 317.2 |
| 7 | | 50-4-412 | 18.0 | 13.7 | 144 | 389.2 | 317.2 |
| 8 | G2 | 50-4-413 | 18.0 | 13.7 | 144 | 389.2 | 317.2 |
| 9 | | 50-4-414 | 18.0 | 13.7 | 144 | 389.2 | 317.2 |
| 10 | | 50-4-415 | 18.0 | 13.7 | 144 | 389.2 | 317.2 |
| 11 | | 50-6-311 | 18.0 | 14.4 | 96 | 564.4 | 456.4 |
| 12 | | 50-6-312 | 18.0 | 14.4 | 96 | 564.4 | 456.4 |
| 13 | G3 | 50-6-313 | 18.0 | 14.4 | 96 | 564.4 | 456.4 |
| 14 | | 50-6-314 | 18.0 | 14.4 | 96 | 564.4 | 456.4 |
| 15 | | 50-6-315 | 18.0 | 14.4 | 96 | 564.4 | 456.4 |
| 16 | | 50-6-411 | 18.0 | 14.4 | 144 | 564.4 | 456.4 |
| 17 | | 50-6-412 | 18.0 | 14.4 | 144 | 564.4 | 456.4 |
| 18 | G4 | 50-6-413 | 18.0 | 14.4 | 144 | 564.4 | 456.4 |
| 19 | | 50-6-414 | 18.0 | 14.4 | 144 | 564.4 | 456.4 |
| 20 | | 50-6-415 | 18.0 | 14.4 | 144 | 564.4 | 456.4 |
| 21 | | 75-6-311 | 18.0 | 20.6 | 96 | 872.7 | 764.7 |
| 22 | G5 | 75-6-312 | 18.0 | 20.6 | 96 | 872.7 | 764.7 |
| 23 | | 75-6-313 | 18.0 | 20.6 | 96 | 872.7 | 764.7 |
| 24 | | 75-6-314 | 18.0 | 20.6 | 112 | 872.7 | 764.7 |
| 25 | G6 | 75-6-315 | 18.0 | 20.6 | 112 | 872.7 | 764.7 |
| 26 | | 75-6-316 | 18.0 | 20.6 | 112 | 872.7 | 764.7 |

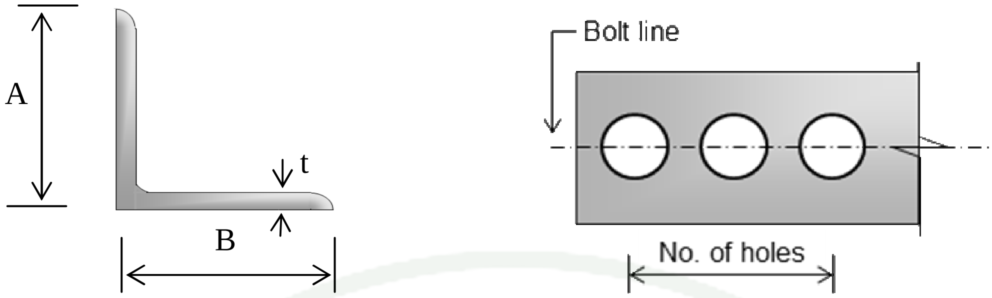



**Figure 11** Definition of bolt line, no. of holes and dimension A, B and t.

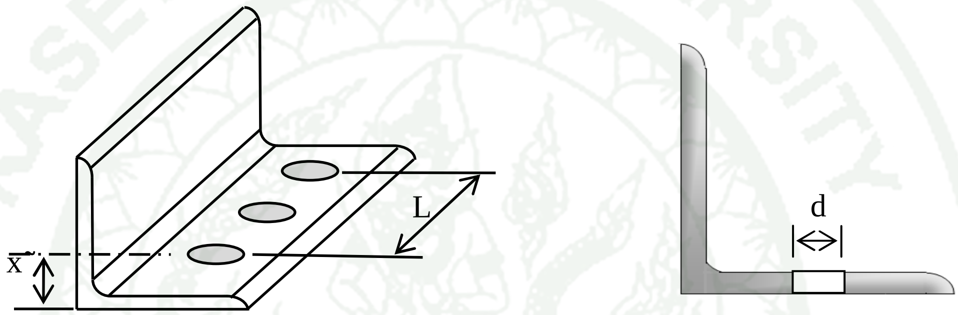



**Figure 12** Definition of x̃, L and d

The general form of angle denomination which is shown in Table 2 is defined by “A-T-HNS”. Each character at a certain position is explained as follows;

- First position (A), represents the width of angle legs in millimeters. 50 = 50x50, 75 = 75x75 and 100 = 100x100.
- Second position (T), represents the nominal thickness of angle legs in millimeters. 4 mm, 6 mm and 7 mm.
- Third position (H), represents the number of holes in 1 line.
- Fourth position (N), represents the number of lines.
- Fifth position (S), represents the number of specimens

**Table 3** Description of gusset plates

| No. | Gusset plates denomination | A (mm) | B (mm) | t (mm) | Number of bolt lines | No. of holes per line | d (mm) | L (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100-10-31B | 100 | 550 | 10 | 1 | 3 | 18 | 96 |
| 2 | 100-10-41B | 100 | 550 | 10 | 1 | 4 | 18 | 144 |
| 3 | 100-10-31C | 100 | 550 | 10 | 1 | 3 | 18 | 102 |

The general form of gusset plate denomination which is shown in Table 3 is defined by "A-T-HND". Each character at a certain position is explained as follows;

- First position (A), represents the length of gusset plate in millimeters. 100 = 100x550.
- Second position (T), represents the nominal thickness of gusset plate in millimeters.
- Third position (H), represents the number of holes in 1 line.
- Fourth position (N), represents the number of lines.
- Fifth position (D), represents the spacing between holes. B = 48.0 mm, C = 56.0 mm.

**Test set-up**

1. Prepare the test specimen as shown in Figure 13, 14, 15
   - Align an angle to the 2 gusset plates
   - Snug-tight (lightly tighten) the bolts to the prepared holes
   - Attach 2 strain gages to the specimen. Each is installed on the angle near the innermost hole of each end. Make sure that the washers do not touch the strain gages.

2. Set up the prepared specimen to the Universal Testing Machine (UTM). Make sure that the specimen is vertically aligned so that effects of bending will not occur (Figure 14).

3. Connect strain gages SG1 and SG2 electric wires to the Data Logger (Figure 13)

4. Apply 2 kN to the system so that the bolts have a full bearing face to the connected parts. This method can solve the problem of major slip at connection.

5. Set UTM tensile load to zero.

6. Apply force until some failure mode is shown. In this case, tearing at the holes is expected.

7. Collect data from Data Logger and plot graphs.

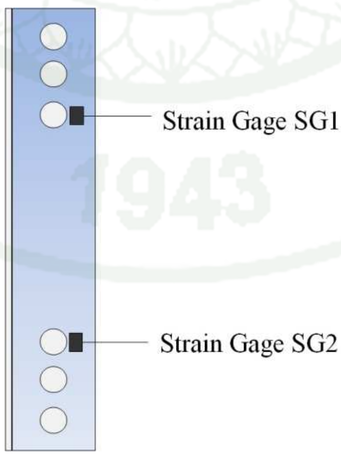



**Figure 13** Strain gage positions

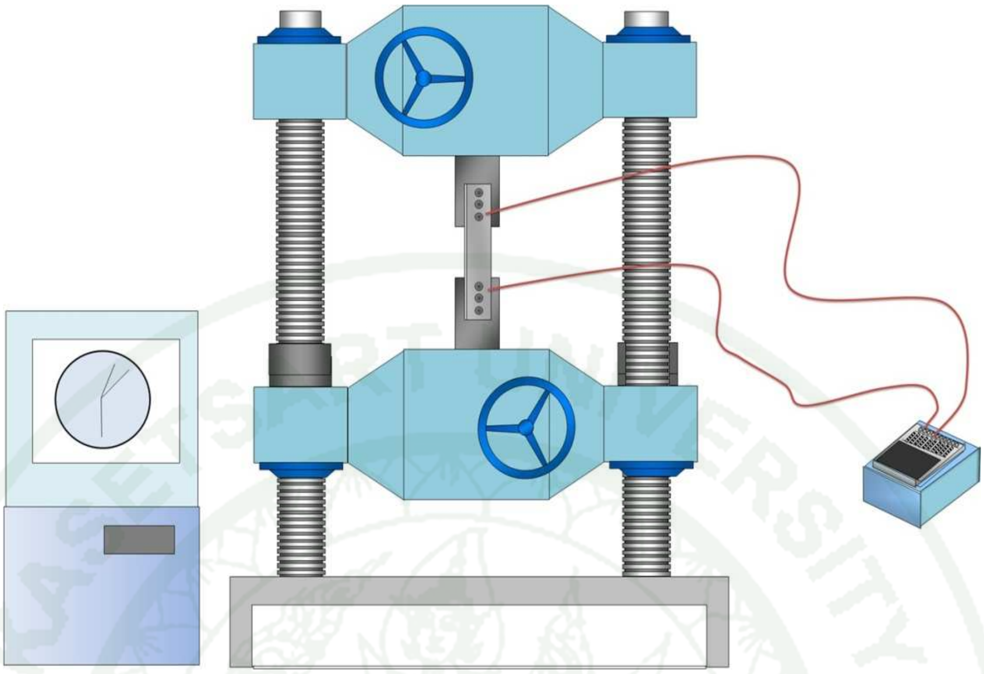


**Figure 14** Test setup

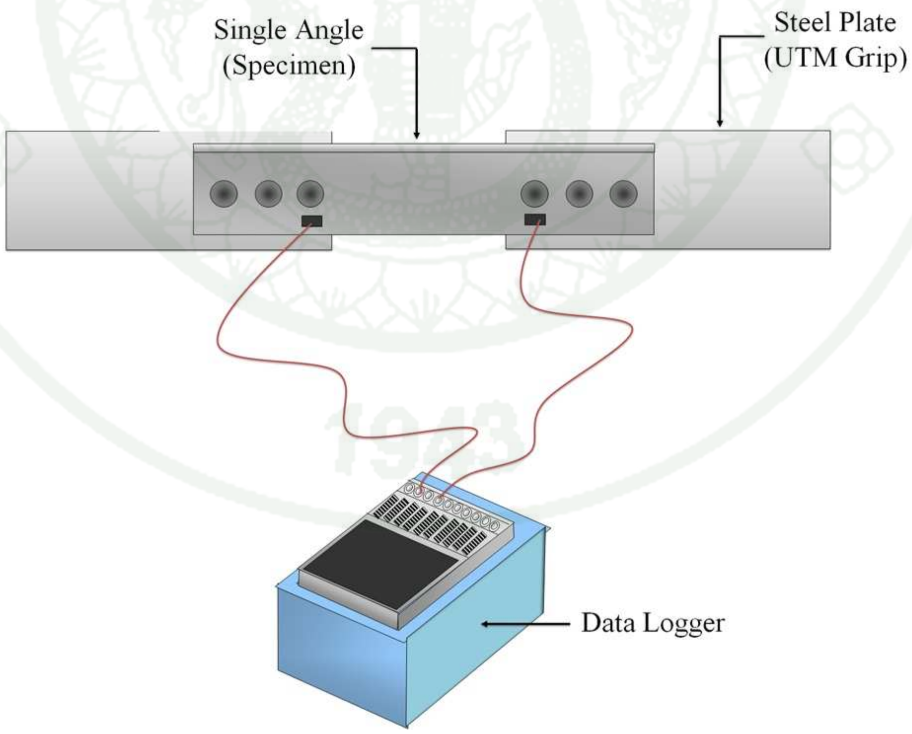



**Figure 15** Data logger setup

From AISC (2010), Chapter D Section D.2

$$P_n = F_u A_e$$

(10)

with $A_e = UA_n$

Notation and definitions of the terms are;

$A_e$ = effective net area, ($mm^2$)

$A_n$ = net area, ($mm^2$)

$F_u$ = specified minimum tensile strength of the type of steel being used, MPa

$U$ = the shear lag factor.

The Equation 10 can be rewritten as,

$$U = \frac{P_n}{F_u A_n}$$

(11)

And

$$U_{exp} = \frac{P_{exp}}{F_u A_n}$$

(12)

Notation and definitions of the terms are;

$U_{exp}$ = Shear lag factor from experimental test.

$P_{exp}$ = Ultimate tensile load from experimental test.


**Figure 16** Angle section 50x50x4THK., 500mm length


**Figure 17** Angle section 50x50x6THK., 500mm length**.**


**Figure 18** Angle section 75x75x6THK., 500mm length**.**


**Figure 19** Strain gages attachment

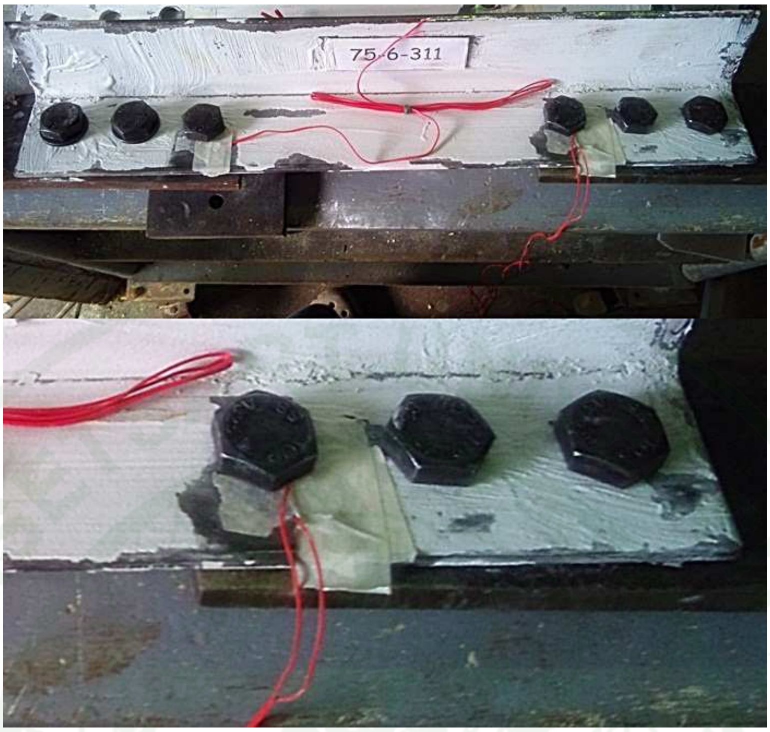



**Figure 20** Strain gage attached position

**Figure 21** Specimen installation

**Figure 22** Specimen installation

**Figure 23** Test process

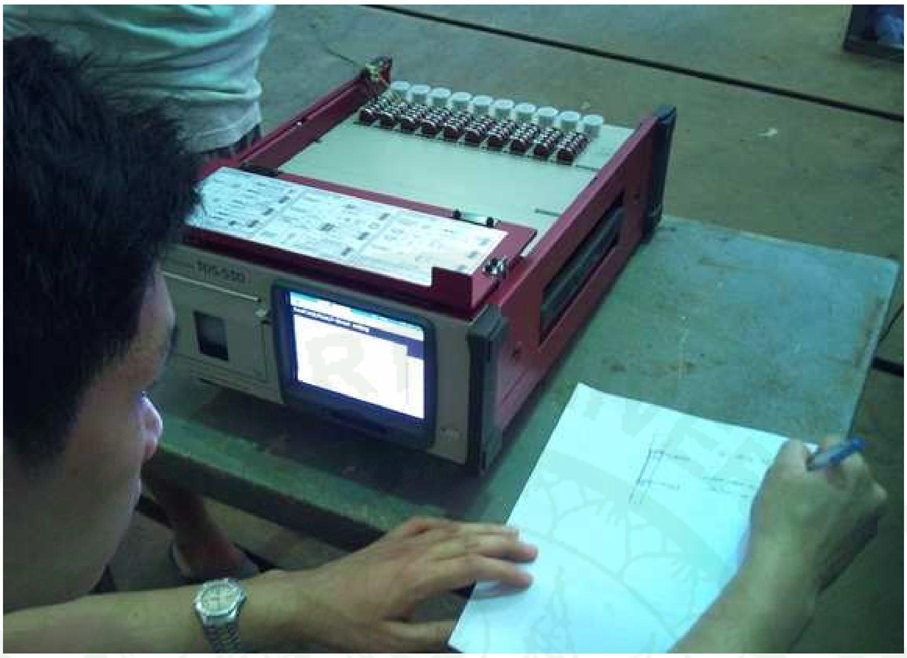


**Figure 24** Collecting data via Data Logger

# RESULT AND DISCUSSION

The shear lag test result of 26 specimens is recorded as shown in Table 4.

where,

$P_n$ = Nominal tensile strength, (kN)

$P_{exp}$ = Ultimate tensile load from experimental test, (kN)

$F_{u1}$ = minimum calculated tensile strength of the type of steel being used, (400MPa)

$F_{u2}$ = minimum calculated tensile strength of the type of steel being used, (455MPa)

$F_{u3}$ = minimum calculated tensile strength of the type of steel being used, (510MPa)

A = gross area of steel angles without bolt holes, ($mm^2$)

$A_n$ = net area of steel angles, ($mm^2$)

**Table 4** Comparison between $P_{exp}$ and.$P_n$ based on shear lag factor from AISC Case 2 and Case 8

| Test | Angle | $P_{exp}$ | Case2 | | | Case 8 | | |
|---|---|---|---|---|---|---|---|---|
| | | | $P_n$ [$F_{u1}$] | $P_n$ [$F_{u2}$] | $P_n$ [$F_{u3}$] | $P_n$ [$F_{u1}$] | $P_n$ [$F_{u2}$] | $P_n$ [$F_{u3}$] |
| | | (kN) | (kN) | (kN) | (kN) | (kN) | (kN) | (kN) |
| 1 | 50-4-311 | 104.5 | 108.8 | 123.7 | 138.7 | 76.1 | 86.6 | 97.1 |
| 2 | 50-4-312 | 100.3 | 108.8 | 123.7 | 138.7 | 76.1 | 86.6 | 97.1 |
| 3 | 50-4-313 | 97.0 | 108.8 | 123.7 | 138.7 | 76.1 | 86.6 | 97.1 |
| 4 | 50-4-314 | 93.6 | 108.8 | 123.7 | 138.7 | 76.1 | 86.6 | 97.1 |
| 5 | 50-4-315 | 102.3 | 108.8 | 123.7 | 138.7 | 76.1 | 86.6 | 97.1 |
| 6 | 50-4-411 | 123.8 | 114.8 | 130.6 | 146.4 | 101.5 | 115.5 | 129.4 |
| 7 | 50-4-412 | 121.8 | 114.8 | 130.6 | 146.4 | 101.5 | 115.5 | 129.4 |
| 8 | 50-4-413 | 121.6 | 114.8 | 130.6 | 146.4 | 101.5 | 115.5 | 129.4 |
| 9 | 50-4-414 | 120.8 | 114.8 | 130.6 | 146.4 | 101.5 | 115.5 | 129.4 |
| 10 | 50-4-415 | 125.6 | 114.8 | 130.6 | 146.4 | 101.5 | 115.5 | 129.4 |
| 11 | 50-6-311 | 157.5 | 155.2 | 176.5 | 197.8 | 109.5 | 124.6 | 139.7 |
| 12 | 50-6-312 | 153.0 | 155.2 | 176.5 | 197.8 | 109.5 | 124.6 | 139.7 |
| 13 | 50-6-313 | 147.1 | 155.2 | 176.5 | 197.8 | 109.5 | 124.6 | 139.7 |
| 14 | 50-6-314 | 150.1 | 155.2 | 176.5 | 197.8 | 109.5 | 124.6 | 139.7 |
| 15 | 50-6-315 | 146.4 | 155.2 | 176.5 | 197.8 | 109.5 | 124.6 | 139.7 |
| 16 | 50-6-411 | 167.8 | 164.3 | 186.9 | 209.5 | 146.0 | 166.1 | 186.2 |
| 17 | 50-6-412 | 167.0 | 164.3 | 186.9 | 209.5 | 146.0 | 166.1 | 186.2 |
| 18 | 50-6-413 | 180.3 | 164.3 | 186.9 | 209.5 | 146.0 | 166.1 | 186.2 |
| 19 | 50-6-414 | 160.1 | 164.3 | 186.9 | 209.5 | 146.0 | 166.1 | 186.2 |
| 20 | 50-6-415 | 164.7 | 164.3 | 186.9 | 209.5 | 146.0 | 166.1 | 186.2 |
| 21 | 75-6-311 | 235.4 | 240.2 | 273.3 | 306.3 | 183.5 | 208.8 | 234.0 |
| 22 | 75-6-312 | 274.7 | 240.2 | 273.3 | 306.3 | 183.5 | 208.8 | 234.0 |
| 23 | 75-6-313 | 269.8 | 240.2 | 273.3 | 306.3 | 183.5 | 208.8 | 234.0 |
| 24 | 75-6-314 | 240.3 | 249.6 | 283.9 | 318.3 | 183.5 | 208.8 | 234.0 |
| 25 | 75-6-315 | 238.4 | 249.6 | 283.9 | 318.3 | 183.5 | 208.8 | 234.0 |
| 26 | 75-6-316 | 288.4 | 249.6 | 283.9 | 318.3 | 183.5 | 208.8 | 234.0 |

**Table 5** Comparison between $P_{exp}$ and.0.75$P_n$ based on shear lag factor from AISC Case 2 and Case 8

| Test | Angle | $P_{exp}$ | Case 2 | | | Case 8 | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0.75$P_n$ [$F_{u1}$] | 0.75$P_n$ [$F_{u2}$] | 0.75$P_n$ [$F_{u3}$] | 0.75$P_n$ [$F_{u1}$] | 0.75$P_n$ [$F_{u2}$] | 0.75$P_n$ [$F_{u3}$] |
| | | (kN) | (kN) | (kN) | (kN) | (kN) | (kN) | (kN) |
| 1 | 50-4-311 | 104.5 | 81.6 | 92.8 | 104.0 | 57.1 | 64.9 | 72.8 |
| 2 | 50-4-312 | 100.3 | 81.6 | 92.8 | 104.0 | 57.1 | 64.9 | 72.8 |
| 3 | 50-4-313 | 97.0 | 81.6 | 92.8 | 104.0 | 57.1 | 64.9 | 72.8 |
| 4 | 50-4-314 | 93.6 | 81.6 | 92.8 | 104.0 | 57.1 | 64.9 | 72.8 |
| 5 | 50-4-315 | 102.3 | 81.6 | 92.8 | 104.0 | 57.1 | 64.9 | 72.8 |
| 6 | 50-4-411 | 123.8 | 86.1 | 97.9 | 109.8 | 76.1 | 86.6 | 97.1 |
| 7 | 50-4-412 | 121.8 | 86.1 | 97.9 | 109.8 | 76.1 | 86.6 | 97.1 |
| 8 | 50-4-413 | 121.6 | 86.1 | 97.9 | 109.8 | 76.1 | 86.6 | 97.1 |
| 9 | 50-4-414 | 120.8 | 86.1 | 97.9 | 109.8 | 76.1 | 86.6 | 97.1 |
| 10 | 50-4-415 | 125.6 | 86.1 | 97.9 | 109.8 | 76.1 | 86.6 | 97.1 |
| 11 | 50-6-311 | 157.5 | 116.4 | 132.4 | 148.4 | 82.2 | 93.4 | 104.7 |
| 12 | 50-6-312 | 153.0 | 116.4 | 132.4 | 148.4 | 82.2 | 93.4 | 104.7 |
| 13 | 50-6-313 | 147.1 | 116.4 | 132.4 | 148.4 | 82.2 | 93.4 | 104.7 |
| 14 | 50-6-314 | 150.1 | 116.4 | 132.4 | 148.4 | 82.2 | 93.4 | 104.7 |
| 15 | 50-6-315 | 146.4 | 116.4 | 132.4 | 148.4 | 82.2 | 93.4 | 104.7 |
| 16 | 50-6-411 | 167.8 | 123.2 | 140.2 | 157.1 | 109.5 | 124.6 | 139.7 |
| 17 | 50-6-412 | 167.0 | 123.2 | 140.2 | 157.1 | 109.5 | 124.6 | 139.7 |
| 18 | 50-6-413 | 180.3 | 123.2 | 140.2 | 157.1 | 109.5 | 124.6 | 139.7 |
| 19 | 50-6-414 | 160.1 | 123.2 | 140.2 | 157.1 | 109.5 | 124.6 | 139.7 |
| 20 | 50-6-415 | 164.7 | 123.2 | 140.2 | 157.1 | 109.5 | 124.6 | 139.7 |
| 21 | 75-6-311 | 235.4 | 180.2 | 205.0 | 229.7 | 137.6 | 156.6 | 175.5 |
| 22 | 75-6-312 | 274.7 | 180.2 | 205.0 | 229.7 | 137.6 | 156.6 | 175.5 |
| 23 | 75-6-313 | 269.8 | 180.2 | 205.0 | 229.7 | 137.6 | 156.6 | 175.5 |
| 24 | 75-6-314 | 240.3 | 187.2 | 213.0 | 238.7 | 137.6 | 156.6 | 175.5 |
| 25 | 75-6-315 | 238.4 | 187.2 | 213.0 | 238.7 | 137.6 | 156.6 | 175.5 |
| 26 | 75-6-316 | 288.4 | 187.2 | 213.0 | 238.7 | 137.6 | 156.6 | 175.5 |

**Table 6** Comparison of shear lag factor from AISC 2010 and experimental program

| Test | Angle | $U_{AISC}$ 2010 | $U_{AISC}$ 2010 | $U_{exp} = P_{exp}/ F_uA_n$ | | |
|---|---|---|---|---|---|---|
| | | | | $U_{exp}$ [$F_{u1}$] | $U_{exp}$ [$F_{u2}$] | $U_{exp}$ [$F_{u3}$] |
| | | Case 2, (1-x˜/L) | Case 8 | 400 MPa | 455 MPa | 510 MPa |
| 1 | 50-4-311 | 0.857 | 0.6 | 0.824 | 0.724 | 0.646 |
| 2 | 50-4-312 | 0.857 | 0.6 | 0.790 | 0.695 | 0.620 |
| 3 | 50-4-313 | 0.857 | 0.6 | 0.765 | 0.672 | 0.600 |
| 4 | 50-4-314 | 0.857 | 0.6 | 0.737 | 0.648 | 0.578 |
| 5 | 50-4-315 | 0.857 | 0.6 | 0.807 | 0.709 | 0.633 |
| 6 | 50-4-411 | 0.905 | 0.8 | 0.975 | 0.858 | 0.765 |
| 7 | 50-4-412 | 0.905 | 0.8 | 0.960 | 0.844 | 0.753 |
| 8 | 50-4-413 | 0.905 | 0.8 | 0.959 | 0.843 | 0.752 |
| 9 | 50-4-414 | 0.905 | 0.8 | 0.952 | 0.837 | 0.747 |
| 10 | 50-4-415 | 0.905 | 0.8 | 0.990 | 0.870 | 0.777 |
| 11 | 50-6-311 | 0.850 | 0.6 | 0.863 | 0.759 | 0.677 |
| 12 | 50-6-312 | 0.850 | 0.6 | 0.838 | 0.737 | 0.657 |
| 13 | 50-6-313 | 0.850 | 0.6 | 0.806 | 0.708 | 0.632 |
| 14 | 50-6-314 | 0.850 | 0.6 | 0.822 | 0.723 | 0.645 |
| 15 | 50-6-315 | 0.850 | 0.6 | 0.802 | 0.705 | 0.629 |
| 16 | 50-6-411 | 0.900 | 0.8 | 0.919 | 0.808 | 0.721 |
| 17 | 50-6-412 | 0.900 | 0.8 | 0.915 | 0.804 | 0.718 |
| 18 | 50-6-413 | 0.900 | 0.8 | 0.987 | 0.868 | 0.774 |
| 19 | 50-6-414 | 0.900 | 0.8 | 0.877 | 0.771 | 0.688 |
| 20 | 50-6-415 | 0.900 | 0.8 | 0.902 | 0.793 | 0.708 |
| 21 | 75-6-311 | 0.785 | 0.6 | 0.770 | 0.677 | 0.604 |
| 22 | 75-6-312 | 0.785 | 0.6 | 0.898 | 0.789 | 0.704 |
| 23 | 75-6-313 | 0.785 | 0.6 | 0.882 | 0.775 | 0.692 |
| 24 | 75-6-314 | 0.816 | 0.6 | 0.786 | 0.691 | 0.616 |
| 25 | 75-6-315 | 0.816 | 0.6 | 0.779 | 0.685 | 0.611 |
| 26 | 75-6-316 | 0.816 | 0.6 | 0.943 | 0.829 | 0.740 |

**Result discussion**

American Institute of Steel Construction (AISC, 2010) had proposed a shear lag factor of single angles as shown in Table 1:

AISC 2010 proposed two different approaches for shear lag effect calculation. AISC 2010 case 2 gave a formula as shown in Table 1, while there were two constant factors to be applied when considering the shear lag effects by Case 8. However, Case 8 also proposed additional option to use the greater value between both cases.

Shear lag factors calculated by Case 2 approach always give greater values than Case 8. For instance, single angle with 3 fasteners has shear lag factor around 0.8 according to AISC case 2, but it is 0.6 if considered by AISC case 8. 30% difference is unfavorable.

**Table 7** Comparison of shear lag factor between AISC 2010, Case 2 and Case 8

| Test | Angle | $U_{AISC}$ 2010 | $U_{AISC}$ 2010 | $(U_{AISC,Case8} - U_{AISC, Case2}) \times 100 / (U_{AISC, Case2})$ |
|---|---|---|---|---|
| | | Case 2, $(1-\tilde{x}/L)$ | Case 8 | (%) |
| 1 | 50-4-311 | 0.857 | 0.6 | -30.0 |
| 2 | 50-4-312 | 0.857 | 0.6 | -30.0 |
| 3 | 50-4-313 | 0.857 | 0.6 | -30.0 |
| 4 | 50-4-314 | 0.857 | 0.6 | -30.0 |
| 5 | 50-4-315 | 0.857 | 0.6 | -30.0 |
| 6 | 50-4-411 | 0.905 | 0.8 | -11.6 |
| 7 | 50-4-412 | 0.905 | 0.8 | -11.6 |
| 8 | 50-4-413 | 0.905 | 0.8 | -11.6 |
| 9 | 50-4-414 | 0.905 | 0.8 | -11.6 |
| 10 | 50-4-415 | 0.905 | 0.8 | -11.6 |
| 11 | 50-6-311 | 0.850 | 0.6 | -29.4 |
| 12 | 50-6-312 | 0.850 | 0.6 | -29.4 |
| 13 | 50-6-313 | 0.850 | 0.6 | -29.4 |
| 14 | 50-6-314 | 0.850 | 0.6 | -29.4 |
| 15 | 50-6-315 | 0.850 | 0.6 | -29.4 |
| 16 | 50-6-411 | 0.900 | 0.8 | -11.1 |
| 17 | 50-6-412 | 0.900 | 0.8 | -11.1 |
| 18 | 50-6-413 | 0.900 | 0.8 | -11.1 |
| 19 | 50-6-414 | 0.900 | 0.8 | -11.1 |
| 20 | 50-6-415 | 0.900 | 0.8 | -11.1 |
| 21 | 75-6-311 | 0.785 | 0.6 | -23.6 |
| 22 | 75-6-312 | 0.785 | 0.6 | -23.6 |
| 23 | 75-6-313 | 0.785 | 0.6 | -23.6 |
| 24 | 75-6-314 | 0.816 | 0.6 | -26.5 |
| 25 | 75-6-315 | 0.816 | 0.6 | -26.5 |
| 26 | 75-6-316 | 0.816 | 0.6 | -26.5 |

1. Effect of number of bolts

For the angle specimens with similar connection length, ultimate tensile strength and size/cross section, the angle specimens with 4 bolts give ~10% to ~19% higher shear lag factor when compared to the angle specimens with 3.

2. Effect of connection length

For the angle specimens with similar numbers of bolted connections, ultimate tensile strength and size/cross section, the angle specimens with more connection length give ~4% higher shear lag factor.

3. Effect of size/cross section

For the angle specimens with similar numbers of bolted connections, ultimate tensile strength and connection length, the angle specimens with smaller size/cross section give higher shear lag factor. By 31% increase of net section angle, the shear lag factor values reduce ~4% to ~5%.

4. Effect of ultimate tensile strength of material

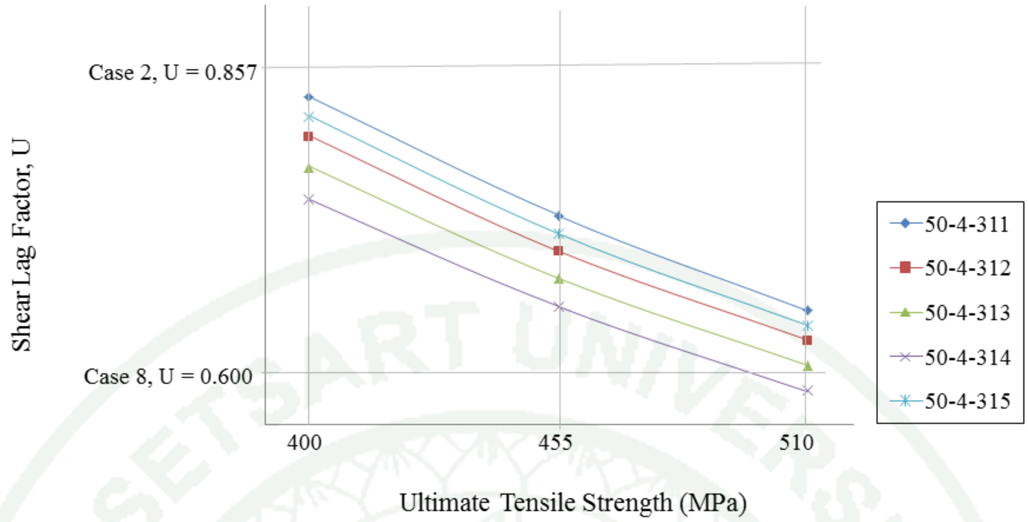
For the angle specimens with similar numbers of bolted connections, size/cross section and connection length, the angle specimens with lower ultimate tensile strength give higher shear lag factor.

From the test results (Table 5), the change of ultimate tensile strength 400 MPa, 455 MPa and 510 MPa is one of the major changes of shear lag factor. Table 8 shows the comparison of $U_{exp}$ between $U_{AISC,}$ Case 2 and $U_{AISC,}$ Case 8.

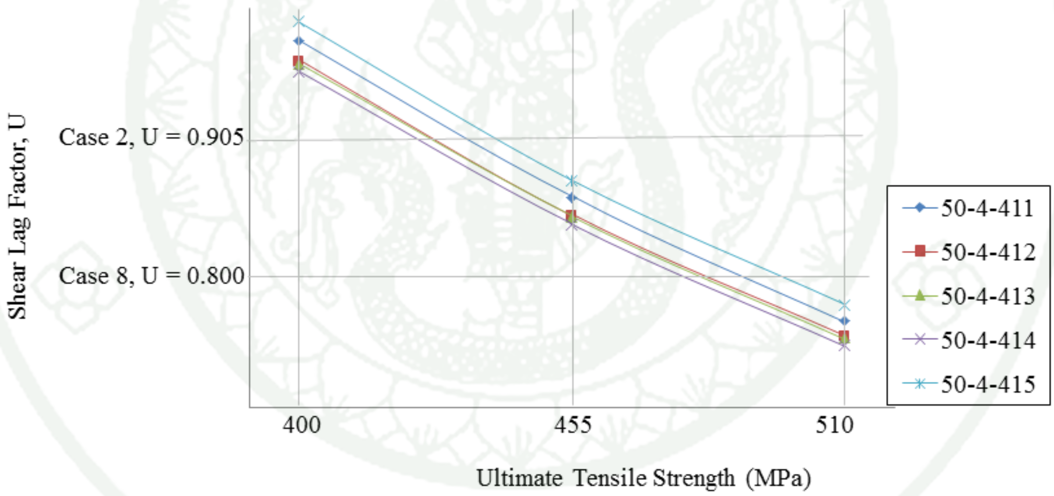
**Table 8** Comparison of $U_{exp}$ with $U_{AISC, 2010}$ Case 2 and $U_{AISC,2010}$ Case 8

| Test | Angle denomination | Compare with $U_{AISC, 2010}$ Case 2 | | | Compare with $U_{AISC, 2010}$ Case 8 | | |
|---|---|---|---|---|---|---|---|
| | | $U_{exp}$ [$F_{u1}$] | $U_{exp}$ [$F_{u2}$] | $U_{exp}$ [$F_{u3}$] | $U_{exp}$ [$F_{u1}$] | $U_{exp}$ [$F_{u2}$] | $U_{exp}$ [$F_{u3}$] |
| 1 | 50-4-311 | L | L | L | H | H | H |
| 2 | 50-4-312 | L | L | L | H | H | H |
| 3 | 50-4-313 | L | L | L | H | H | E |
| 4 | 50-4-314 | L | L | L | H | H | L |
| 5 | 50-4-315 | L | L | L | H | H | H |
| 6 | 50-4-411 | H | L | L | H | H | L |
| 7 | 50-4-412 | H | L | L | H | H | L |
| 8 | 50-4-413 | H | L | L | H | H | L |
| 9 | 50-4-414 | H | L | L | H | H | L |
| 10 | 50-4-415 | H | L | L | H | H | L |
| 11 | 50-6-311 | H | L | L | H | H | H |
| 12 | 50-6-312 | L | L | L | H | H | H |
| 13 | 50-6-313 | L | L | L | H | H | H |
| 14 | 50-6-314 | L | L | L | H | H | H |
| 15 | 50-6-315 | L | L | L | H | H | H |
| 16 | 50-6-411 | H | L | L | H | H | L |
| 17 | 50-6-412 | H | L | L | H | H | L |
| 18 | 50-6-413 | H | L | L | H | H | L |
| 19 | 50-6-414 | L | L | L | H | L | L |
| 20 | 50-6-415 | H | L | L | H | L | L |
| 21 | 75-6-311 | L | L | L | H | H | H |
| 22 | 75-6-312 | H | H | L | H | H | H |
| 23 | 75-6-313 | H | L | L | H | H | H |
| 24 | 75-6-314 | L | L | L | H | H | H |
| 25 | 75-6-315 | L | L | L | H | H | H |
| 26 | 75-6-316 | H | H | L | H | H | H |

The meaning of "H" in Table 8 is the value of shear lag which is got from experimental program higher than the shear lag which is defined from AISC (2010), "L" means the value of shear lag from experimental program lower than the value of AISC (2010) and "E" means both values are equal.

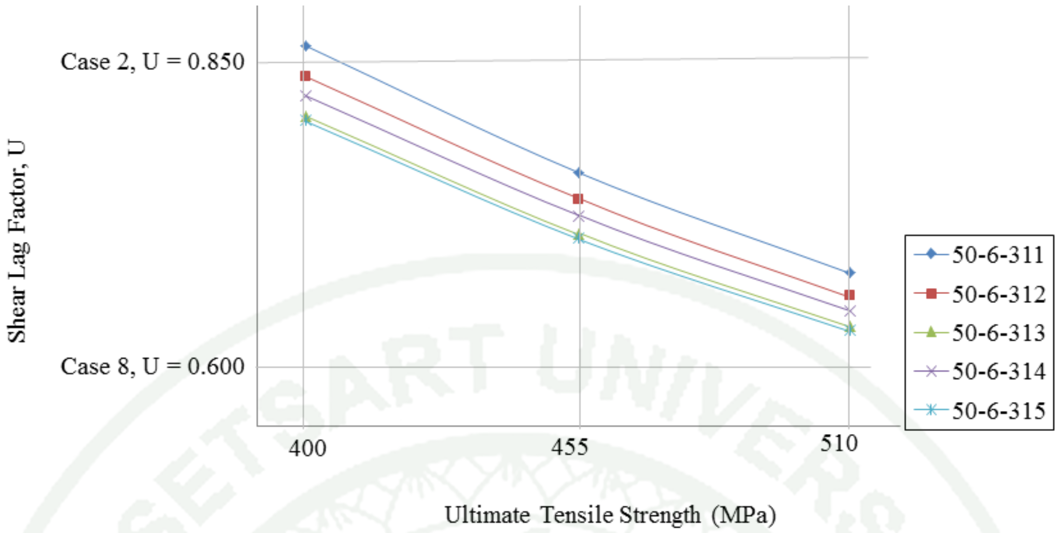



*(a)*

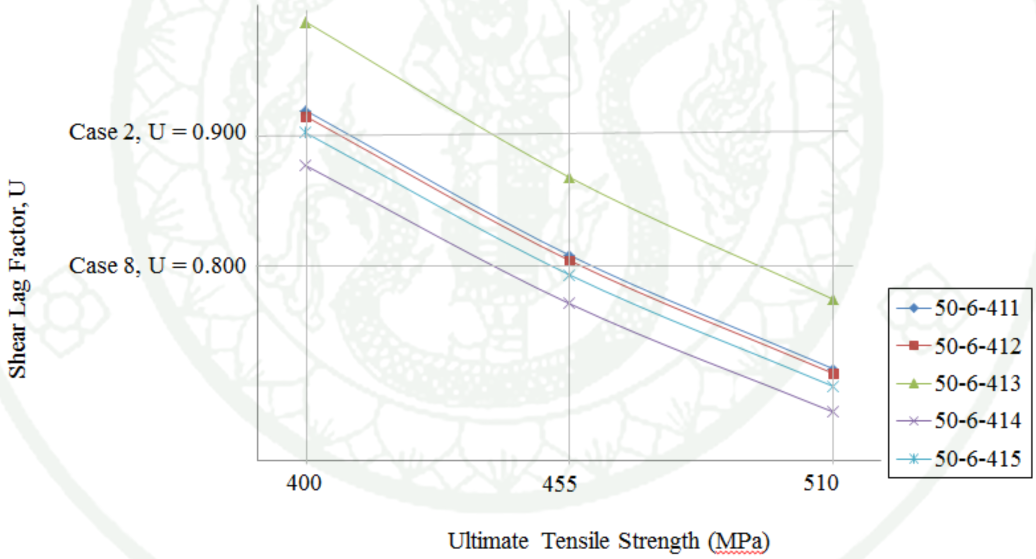



*(b)*

**Figure 25** Shear lag factor-Ultimate strength plots

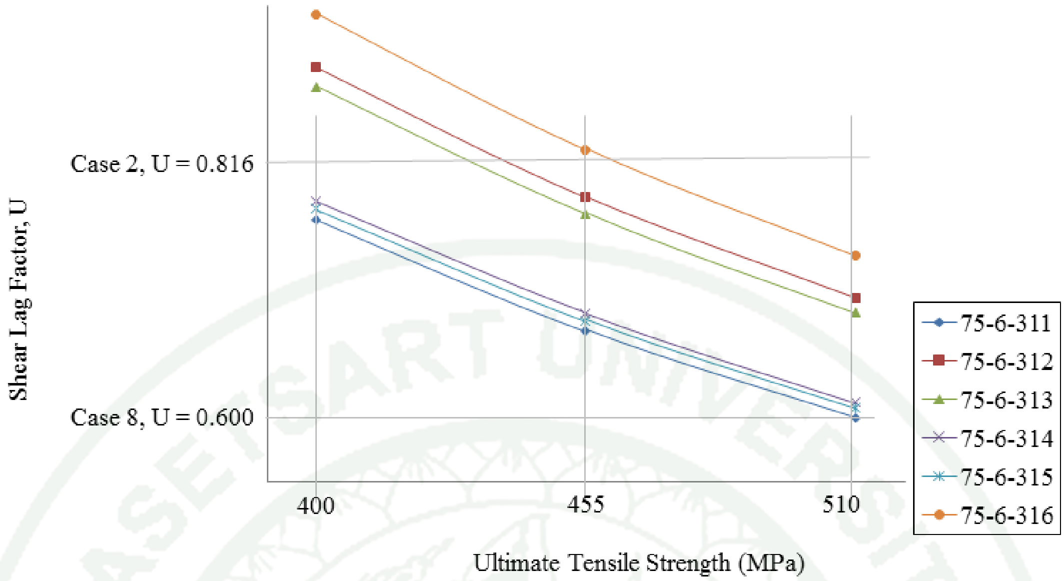



*(c)*




*(d)*

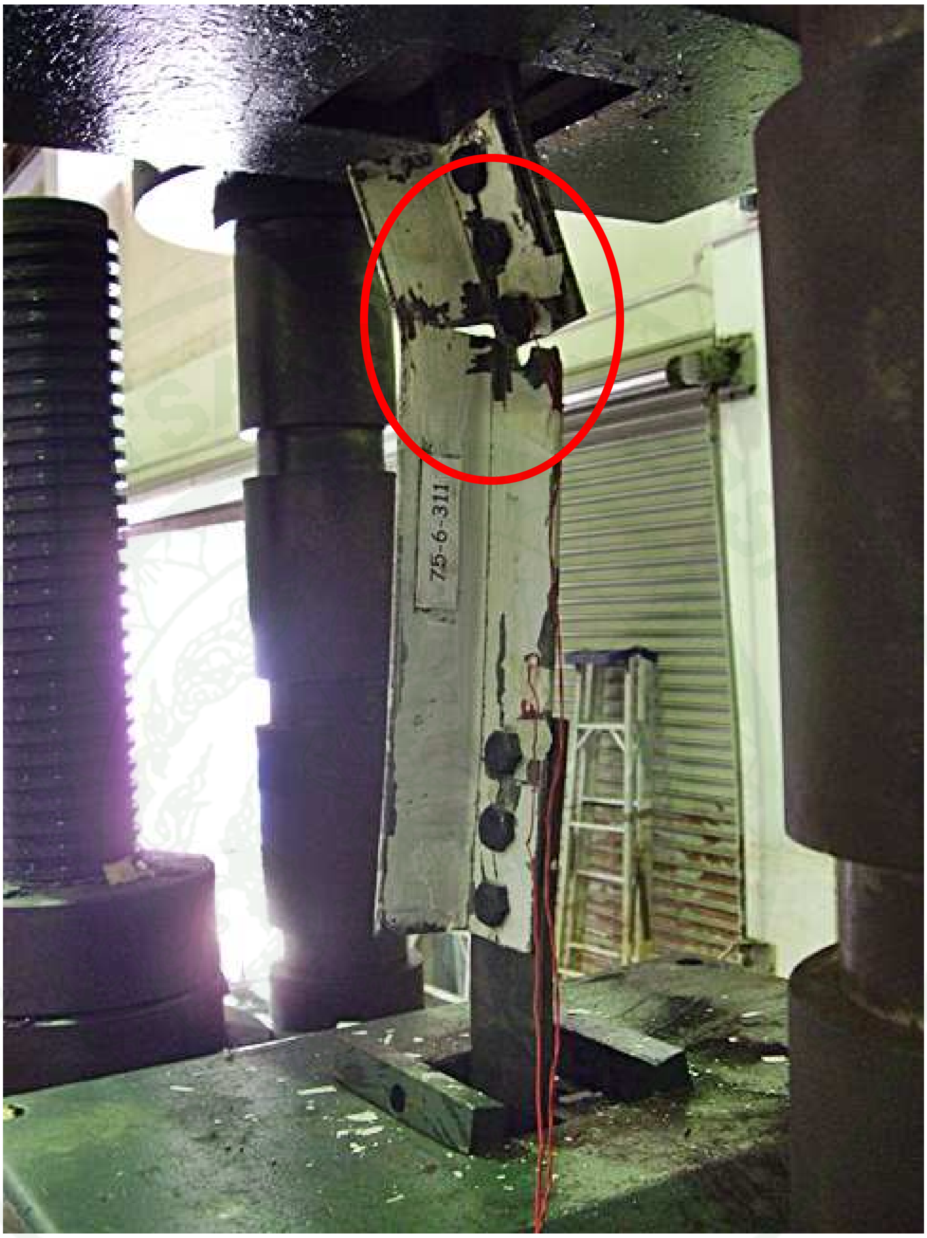
**Figure 25** (Continued).




*(e)*

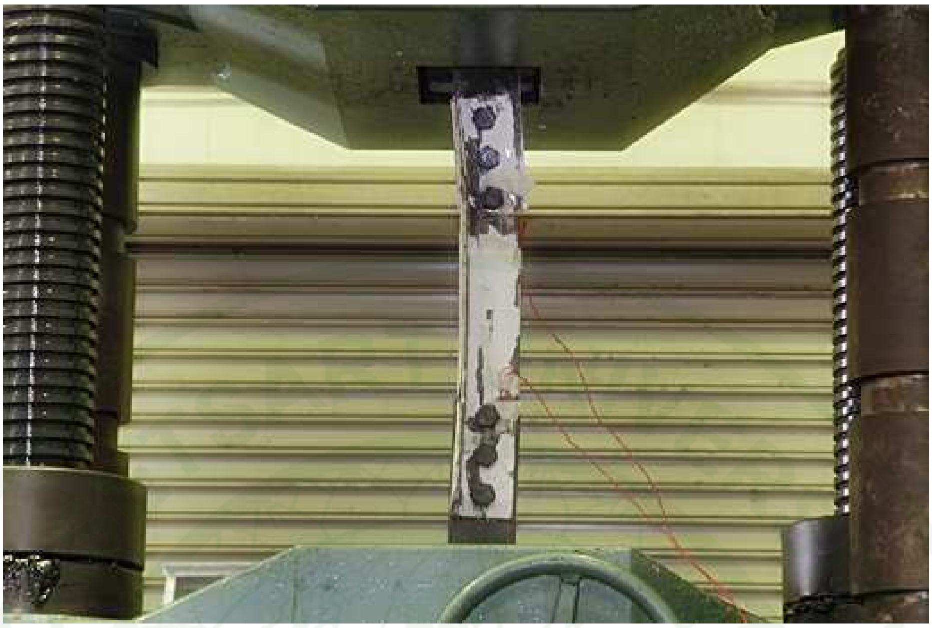
**Figure 25** (Continued).

From Table 8 and Figure 25, it is obvious that, AISC 2010 Case 2 still gives safe design (Table 5, show $P_{exp}$ and $0.75P_n$). It is concluded that 400 MPa should be selected because it always gives safe design. Therefore AISC (2010) is correct for shear lag factor (U).




*(a)* Failure of specimen tested

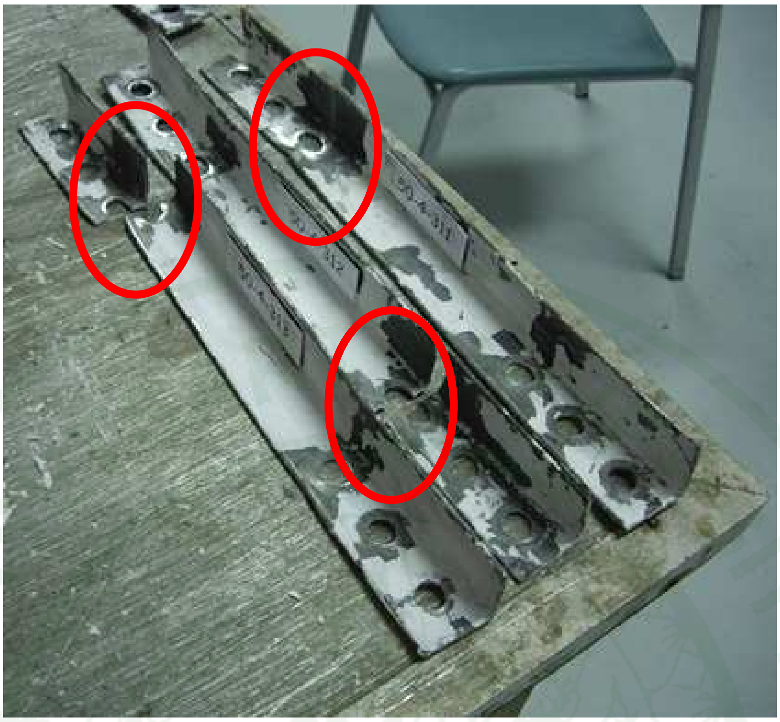
**Figure 26** Experimental results.



*(b)* Unavoidable bending

*(c)* Bent gusset plate during the test

**Figure 26** (Continued).




*(d)* Failure of the specimens


*(e)* Failure of the specimens

**Figure 26** (Continued).

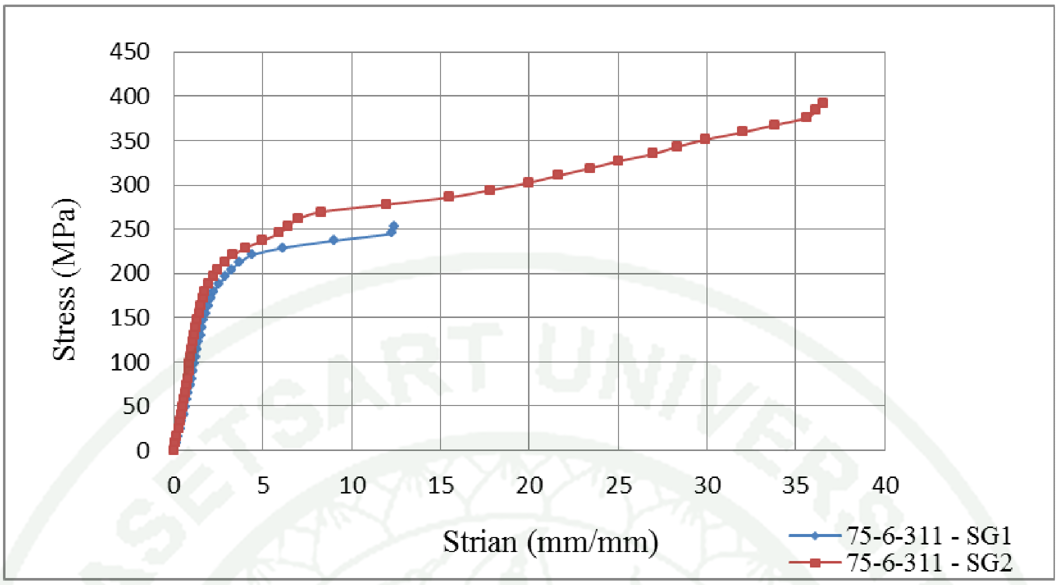



**Figure 27** Stress-Strain curve plots from 75-6-311 specimen tested

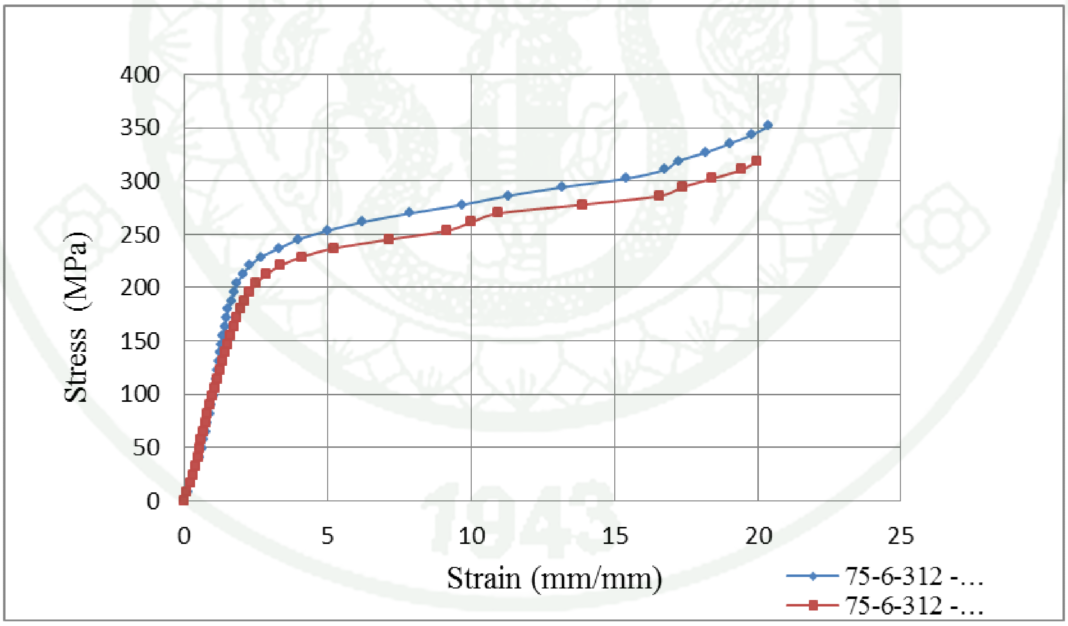



**Figure 28** Stress-Strain curve plots from 75-6-312 specimen tested

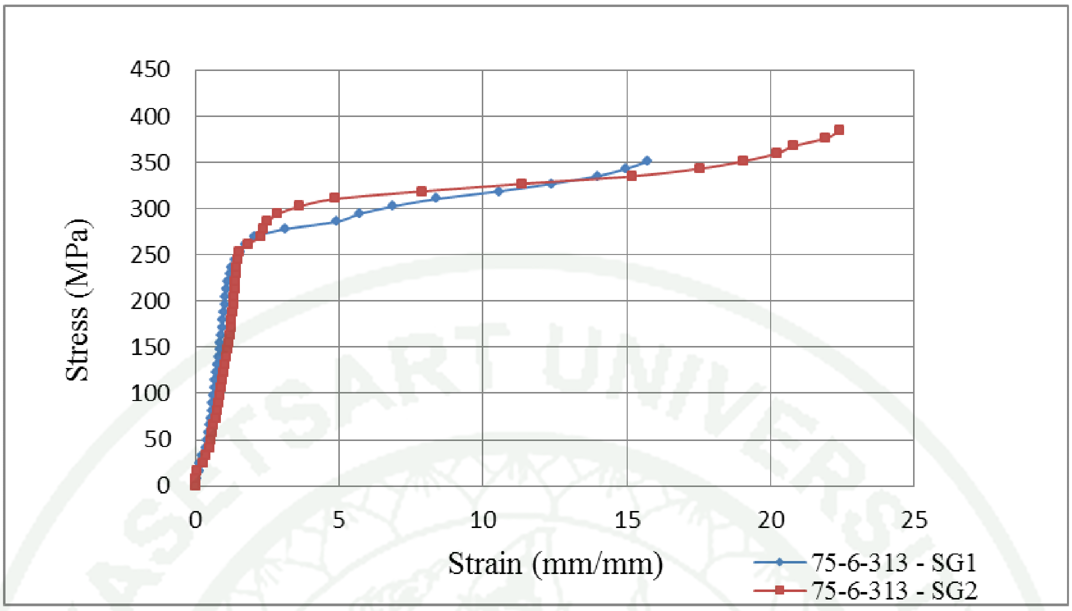



**Figure 29** Axial force – Displacement plots from 75-6-313 specimen tested

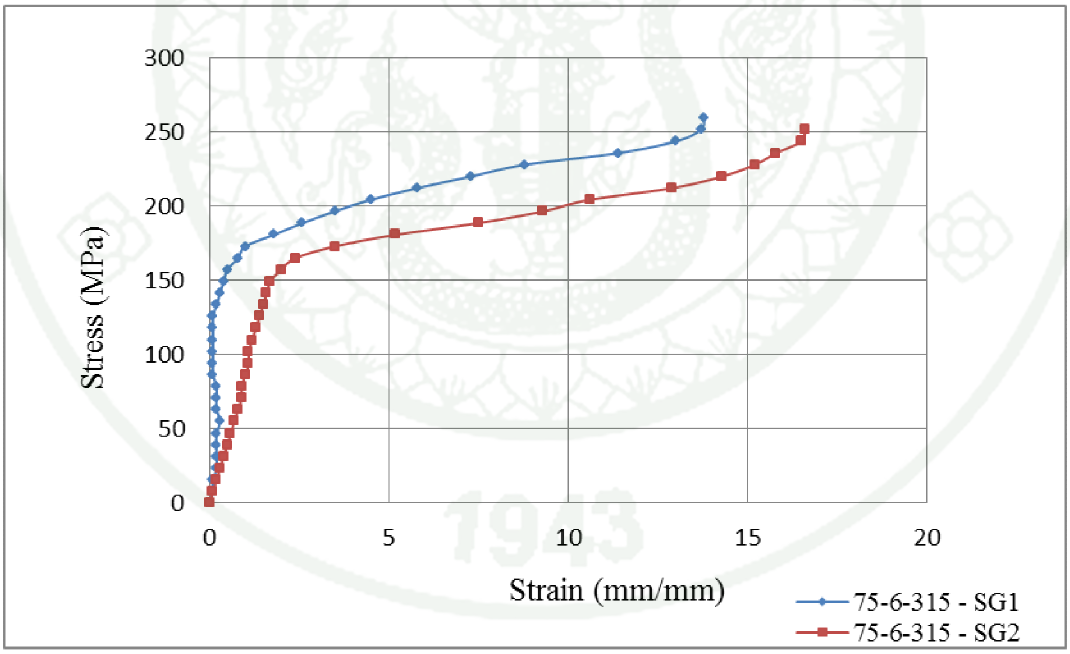



**Figure 30** Stress-Strain curve plots from 75-6-315 specimen tested

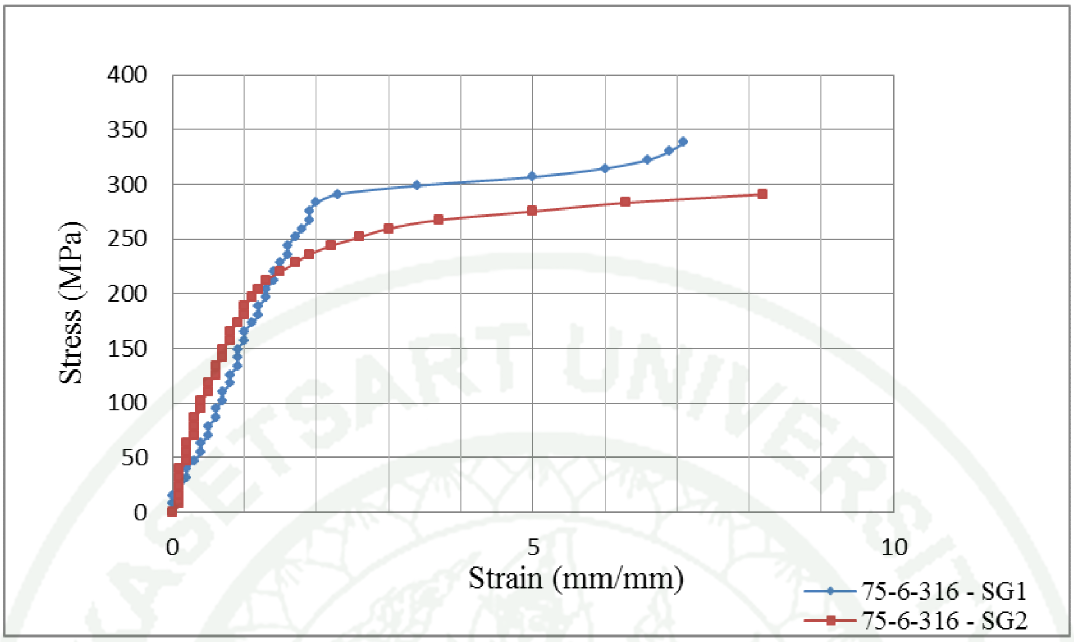



**Figure 31** Stress-Strain curve plots from 75-6-316 specimen tested

# CONCLUSION AND RECOMMENDATION

1. Shear lag effect depends on number of bolts, connection length, size/cross section of steel angles and ultimate tensile strength of material.

2. The shear lag factor resulted from the experiment are within the range between the values provided by AISC Case 2 to Case 8 depended on the values of ultimate tensile strength ($F_u$). The use of reduction factor given by AISC 2010, Case 8 seems to be conservative and recommended for higher ultimate tensile strength ($F_u$).

3. Properly chosen value of ultimate tensile strength ($F_u$) is important. Choosing the smallest value of $F_u$ is always safe and recommended for designer. Further study should be focused on how to pick up the $F_u$ value for economical design.

4. The strength reduction factor "$\phi$" of 0.75 is necessary to compute the tensile strength of angle section for safety reason.

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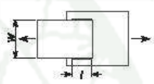
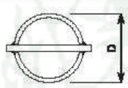
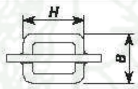
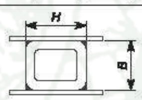
# APPENDIX

## TABLE D3.1
## Shear Lag Factors for Connections to Tension Members

| Case | Description of Element | | Shear Lag Factor, $U$ | Example |
|---|---|---|---|---|
| 1 | All tension members where the tension load is transmitted directly to each of the cross-sectional elements by fasteners or welds (except as in Cases 4, 5 and 6). | | $U = 1.0$ | —— |
| 2 | All tension members, except plates and HSS, where the tension load is transmitted to some but not all of the cross-sectional elements by fasteners or longitudinal welds or by longitudinal welds in combination with transverse welds. (Alternatively, for W, M, S and HP, Case 7 may be used. For angles, Case 8 may be used.) | | $U = 1 - \bar{x}/l$ |  |
| 3 | All tension members where the tension load is transmitted only by transverse welds to some but not all of the cross-sectional elements. | | $U = 1.0$ and $A_n$ = area of the directly connected elements | —— |
| 4 | Plates where the tension load is transmitted by longitudinal welds only. | | $l \geq 2w \ldots U = 1.0$<br>$2w > l \geq 1.5w \ldots U = 0.87$<br>$1.5w > l \geq w \ldots U = 0.75$ |  |
| 5 | Round HSS with a single concentric gusset plate | | $l \geq 1.3D \ldots U = 1.0$<br>$D \leq l < 1.3D \ldots U = 1 - \bar{x}/l$<br>$\bar{x} = D/\pi$ |  |
| 6 | Rectangular HSS | with a single concentric gusset plate | $l \geq H \ldots U = 1 - \bar{x}/l$<br>$\bar{x} = \dfrac{B^2 + 2BH}{4(B+H)}$ |  |
| | | with two side gusset plates | $l \geq H \ldots U = 1 - \bar{x}/l$<br>$\bar{x} = \dfrac{B^2}{4(B+H)}$ |  |
| 7 | W, M, S or HP Shapes or Tees cut from these shapes. (If $U$ is calculated per Case 2, the larger value is permitted to be used.) | with flange connected with 3 or more fasteners per line in the direction of loading | $b_f \geq 2/3d \ldots U = 0.90$<br>$b_f < 2/3d \ldots U = 0.85$ | —— |
| | | with web connected with 4 or more fasteners per line in the direction of loading | $U = 0.70$ | —— |
| 8 | Single and double angles (If $U$ is calculated per Case 2, the larger value is permitted to be used.) | with 4 or more fasteners per line in the direction of loading | $U = 0.80$ | —— |
| | | with 3 fasteners per line in the direction of loading (With fewer than 3 fasteners per line in the direction of loading, use Case 2.) | $U = 0.60$ | —— |

$l$ = length of connection, in. (mm); $w$ = plate width, in. (mm); $\bar{x}$ = eccentricity of connection, in. (mm); $B$ = overall width of rectangular HSS member, measured 90° to the plane of the connection, in. (mm); $H$ = overall height of rectangular HSS member, measured in the plane of the connection, in. (mm)

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**Appendix Figure 1** Table D3.1 shear lag factor for connections to tension members AISC (2010)

## JIS G3101 SS400 steel plate/sheet for general purpose structural steels

JIS G3101 SS400 steel plate/sheet,JIS G3101 SS400 steel plate/sheet, under JISG3101 standard, we can regard SS400 steel plate/sheet for general purpose structural steel.

JIS G3101 SS400 is a technical delivery conditions for general purpose structural steel.JIS G3101 SS400 is a type of steel sheet under JIS standard which is used to build ship, bridge, belongs to high strength sheet. JIS G3101 SS400 is equivalent to DIN:St37-2,EN S235JR,ASTM:A283C and UNI:FE360B.

| | Comparision of steel grades | |
|---|---|---|
| SS400<br>JIS3101 | BS 4360 | 40(A)B |
| | CSAG40-21 | 230 G |
| | IS | IS 226 |
| | JIS 3106 | SM 400 A |
| | ISO 630 | Fe 360 B |
| | ASTM | A 36/A 283 C |

Chemical Composition

| Grade | Chemical Composition, % by weight | | | | |
|---|---|---|---|---|---|
| | C. max | Si. max | Manganese | P. max | S. max |
| SS400 | - | - | - | 0.050 | 0.050 |

Mechnical Propertites

| Grade | Yield Strength min. (Mpa) | | Tensile Strength MPa | Elongation min. % | | | Impact Resistance min.[J] |
|---|---|---|---|---|---|---|---|
| | Thickness <16 mm | Thickness ≥16mm | | Thickness <5mm | Thickness 5-16mm | Thickness ≥16mm | |
| SS400 | 245 | 235 | 400-510 | 21 | 17 | 21 | - |

**Appendix Figure 2** JIS3101 Grade SS400 material properties

**Appendix Table** Calculation of “U” which give from experimental program

| Test | Angle denomination | $P_{exp}$ (kN) | $A_n$ (mm2) | $F_{u1}$ (Mpa) | $F_{u2}$ (Mpa) | $F_{u3}$ (Mpa) | $U_{exp}$ [$F_{u1}$] $P_{exp}/(F_{u1}.A_n)$ | $U_{exp}$ [$F_{u2}$] $P_{exp}/(F_{u2}.A_n)$ | $U_{exp}$ [$F_{u3}$] $P_{exp}/(F_{u3}.A_n)$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 50-4-311 | 104.49 | 317.2 | 400 | 455 | 510 | 0.824 | 0.724 | 0.646 |
| 2 | 50-4-312 | 100.28 | 317.2 | 400 | 455 | 510 | 0.790 | 0.695 | 0.620 |
| 3 | 50-4-313 | 97.00 | 317.2 | 400 | 455 | 510 | 0.765 | 0.672 | 0.600 |
| 4 | 50-4-314 | 93.56 | 317.2 | 400 | 455 | 510 | 0.737 | 0.648 | 0.578 |
| 5 | 50-4-315 | 102.34 | 317.2 | 400 | 455 | 510 | 0.807 | 0.709 | 0.633 |
| 6 | 50-4-411 | 123.76 | 317.2 | 400 | 455 | 510 | 0.975 | 0.858 | 0.765 |
| 7 | 50-4-412 | 121.82 | 317.2 | 400 | 455 | 510 | 0.960 | 0.844 | 0.753 |
| 8 | 50-4-413 | 121.62 | 317.2 | 400 | 455 | 510 | 0.959 | 0.843 | 0.752 |
| 9 | 50-4-414 | 120.81 | 317.2 | 400 | 455 | 510 | 0.952 | 0.837 | 0.747 |
| 10 | 50-4-415 | 125.63 | 317.2 | 400 | 455 | 510 | 0.990 | 0.870 | 0.777 |
| 11 | 50-6-311 | 157.55 | 456.4 | 400 | 455 | 510 | 0.863 | 0.759 | 0.677 |
| 12 | 50-6-312 | 152.96 | 456.4 | 400 | 455 | 510 | 0.838 | 0.737 | 0.657 |
| 13 | 50-6-313 | 147.06 | 456.4 | 400 | 455 | 510 | 0.806 | 0.708 | 0.632 |
| 14 | 50-6-314 | 150.11 | 456.4 | 400 | 455 | 510 | 0.822 | 0.723 | 0.645 |
| 15 | 50-6-315 | 146.35 | 456.4 | 400 | 455 | 510 | 0.802 | 0.705 | 0.629 |
| 16 | 50-6-411 | 167.84 | 456.4 | 400 | 455 | 510 | 0.919 | 0.808 | 0.721 |
| 17 | 50-6-412 | 167.02 | 456.4 | 400 | 455 | 510 | 0.915 | 0.804 | 0.718 |
| 18 | 50-6-413 | 180.27 | 456.4 | 400 | 455 | 510 | 0.987 | 0.868 | 0.774 |
| 19 | 50-6-414 | 160.12 | 456.4 | 400 | 455 | 510 | 0.877 | 0.771 | 0.688 |
| 20 | 50-6-415 | 164.71 | 456.4 | 400 | 455 | 510 | 0.902 | 0.793 | 0.708 |
| 21 | 75-6-311 | 235.44 | 764.7 | 400 | 455 | 510 | 0.770 | 0.677 | 0.604 |
| 22 | 75-6-312 | 274.68 | 764.7 | 400 | 455 | 510 | 0.898 | 0.789 | 0.704 |
| 23 | 75-6-313 | 269.78 | 764.7 | 400 | 455 | 510 | 0.882 | 0.775 | 0.692 |
| 24 | 75-6-314 | 240.35 | 764.7 | 400 | 455 | 510 | 0.786 | 0.691 | 0.616 |
| 25 | 75-6-315 | 235.44 | 764.7 | 400 | 455 | 510 | 0.770 | 0.677 | 0.604 |
| 26 | 75-6-316 | 240.35 | 764.7 | 400 | 455 | 510 | 0.786 | 0.691 | 0.616 |

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