

# Recommendations for Shear Lag Factors for Longitudinally Welded Tension Members

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## ABSTRACT

Section J2.2b of the 2010 AISC *Specification for Structural Steel Buildings* requires the length of longitudinal welds, used to connect flat plate tension members, to be greater than the distance between the longitudinal welds. Currently, weld lengths less than the distance between the welds are not permitted for connections of flat plate members. The procedure for the calculation of the shear lag factor,  $U$ , for this type of connection is given by Case 4 in Table D3.1 of the AISC *Specification*, where  $U$  is a function of the length of the longitudinal weld and the width of the plate. Although Case 4 is explicitly defined for plates only, the generally accepted practice in the design of similar welded connections of angles, channels, tees and wide flange members is to apply the same limitation on weld length, and calculate the effect of shear lag as  $1 - \bar{x}/l$  as given by Case 2 in Table D3.1 of the AISC *Specification*, while ignoring shear lag effects with weld lengths between one and two times the distance between the welds. Furthermore, for connection geometries meeting those for Case 2 or Case 4, there is no guideline for considering connection strengths where the longitudinal welds on each side of the member have unequal lengths (e.g., skewed web members or braces) or weld lengths less than the distance between the welds.

This paper presents recommendations for a generalized design procedure for welded connections of plate, angle, channel and tee tension members regardless of the length of the weld or if the length of the longitudinal welds are unequal. A summary of the treatment of various current building codes/specifications (AISC and CSA) on this topic is presented along with the results of several published experimental research projects that evaluated the behavior of these types of connections. Two analytical models are presented, and recommendations for changes to the current AISC *Specification* are made, followed by an example problem illustrating the practical application of the recommendations.

**Keywords:** shear lag, longitudinal welds.

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In November 2005, a task group was formed under the AISC Committee on Specifications to evaluate Table D3.1 of the 2005 AISC *Specification for Structural Steel Buildings*. One of the tasks assigned to the group was to evaluate shear lag coefficients for longitudinally welded flat plate connections, shown as Case 4 in Table D3.1, for cases where the weld length,  $l$ , is less than the width,  $w$ , of the connected plate. Since then, the same question was posted in the Steel Interchange section of the June 2009 edition of *Modern Steel Construction*. While reviewing the provisions for Case 4, the authors of this paper decided to evaluate the potential of revising Case 4 to address longitudinally welded end connected members in a more general fashion and to address similar connections, as shown in Case 2 for angles, channels, wide flange and WT sections.

Case 4 shown in Table D3.1 provides direction for end-connected plate material. The limitations for this condition

are (1) only plates are considered, (2) both edges of the plate must be welded, (3) the longitudinal welds on each side of the plate must be of equal length, and (4) the length of the welds must be equal to or greater than the distance between the welds. Presented in this paper are recommendations for generalizing Case 4 in Table D3.1, while incorporating conditions where the length of the welds are less than the distance between them, and for conditions where the weld lengths are unequal (e.g., skewed brace or web connections).

## SUMMARY OF CURRENT DESIGN PROVISIONS

The AISC *Specification* (2010) and *Design of Steel Structures* (Canadian Standards Association, 2009) were reviewed. The following is a summary of the treatment of longitudinally welded tension members as presented in the two codes/specifications.

### 2010 AISC *Specification* (ANSI/AISC 360-10)

$$A_e = A_n U = w t U \quad (D3-1)$$

where

$A_e$  = effective cross-sectional area

$A_n$  = net cross-sectional area

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$t$  = thickness of plate  
 $w$  = width of plate  
 $U$  = shear lag factor

Shear lag factor,  $U$ ; Table D3.1 (Case 4)

For  $l \geq 2w$

$$U = 1.0$$

$$\therefore A_e = wt$$

For  $2w > l \geq 1.5w$

$$U = 0.87$$

$$\therefore A_e = 0.87wt$$

For  $1.5w > l \geq w$

$$U = 0.75$$

$$\therefore A_e = 0.75wt$$

For  $w > l$

Per AISC Specification Section J2.2b, the length of the

welds shall not be less than the perpendicular distance between the welds.

$\therefore l < w$  is not permitted.

In all of the preceding expressions,  $l$  is the length of each longitudinal weld.

#### CSA-2009 (Section 12.3.3.3)

$$A_{ne} = A_{n1} + A_{n2} + A_{n3}$$

For elements connected with transverse welds,

$$A_{n1} = wt$$

(Note that this type of weld is outside the scope of this paper.)

For elements connected with a pair of parallel longitudinal welds,

For  $L \geq 2w$

$$A_{n2} = 1.00wt$$

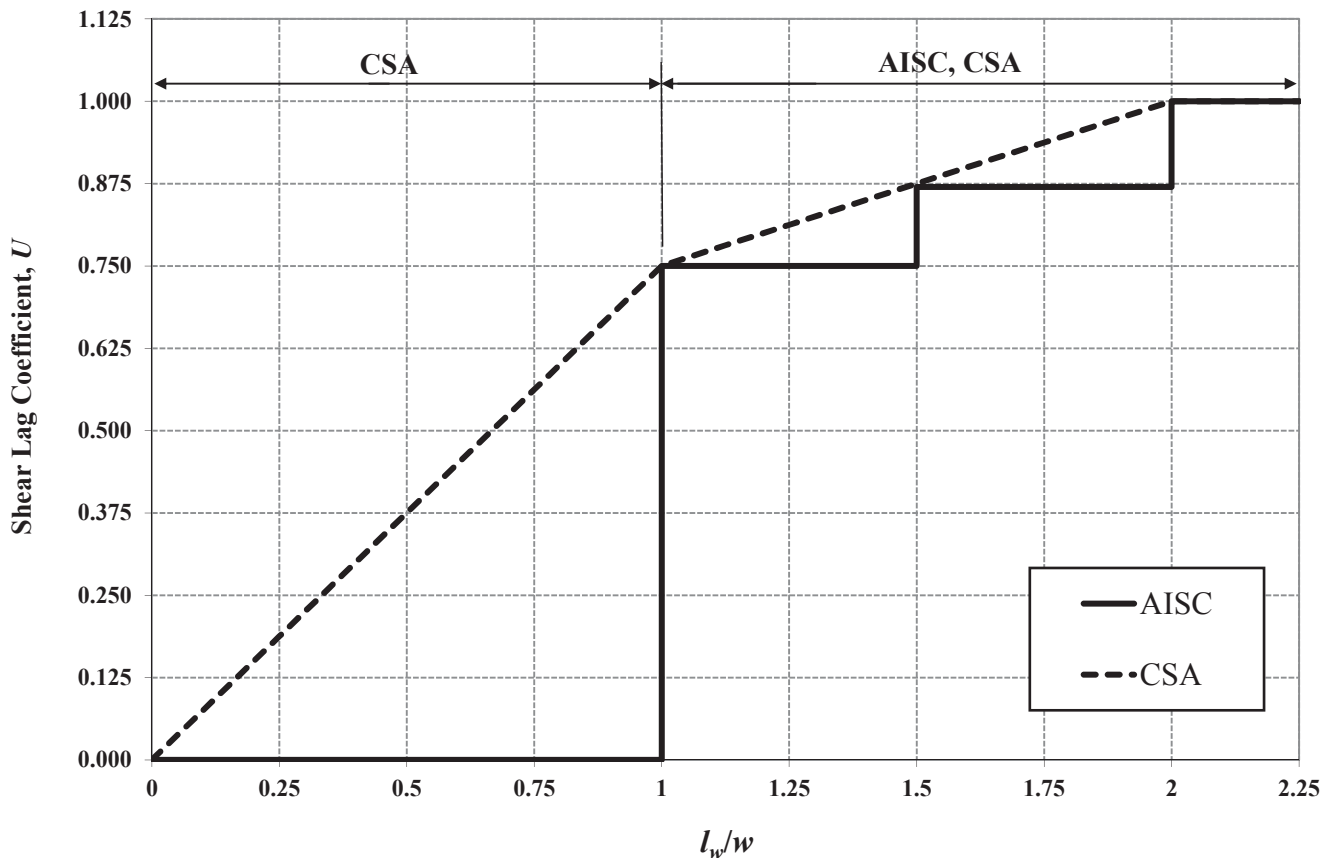


Fig. 1. Comparison of AISC and CSA shear lag requirements for plates connected with a pair of parallel longitudinal welds ( $l_w$  = length of weld).

For  $2w > L \geq 1.0w$

$$A_{n2} = 0.5wt + 0.25Lt$$

For  $w > L$

$$A_{n2} = 0.75Lt$$

(Note that these provisions are CSA's counterpart to AISC's provisions for plate tension members connected with longitudinal welds.)

For elements connected by a single line of weld,

$$A_{n3} = \left(1 - \frac{\bar{x}}{L}\right)wt$$

(Note that AISC does not have such a provision.)

where

$A_{n1}$  = net cross-sectional area of an element connected with a transverse weld

$A_{n2}$  = net cross-sectional area of an element connected by a pair of parallel longitudinal welds

$A_{n3}$  = net cross-sectional area of an element connected with a single longitudinal weld line

$w$  = the width of the element being considered

$t$  = the thickness of the element being considered

$L$  = length of longitudinal weld

$\bar{x}$  = the distance from the connected edge to the centroid of the area of the element

### Evaluating AISC 360-10 Against CSA-2009

The CSA provisions for calculating the effective area,  $A_{n2}$ , are CSA's method for computing shear lag effects in longitudinally welded plates. The CSA  $A_{n2}$  provisions are evaluated and compared to AISC's provisions for longitudinally welded plates.

Substituting  $w$  for  $L$  in the CSA equation for  $A_{n2}$ , it can be seen that the CSA provisions are the same as AISC for  $w \leq L < 2w$ . Note that the Canadian Standard uses  $L$  to denote weld length.

$$A_e = A_{n2}$$

For  $L \geq 2w$

$$A_{n2} = 1.00wt = A_e = wt \quad (\because \text{AISC and CSA equal})$$

For  $2w > L \geq 1.0w$

$$A_{n2} = 0.5wt + 0.25Lt$$

At  $L = 2w$

$$A_{n2} = 0.5wt + 0.25(2w)t = 1.0wt$$

(at  $L = 2w$ ,  $\therefore$  AISC and CSA equal)

At  $l_w = 1.5w$

$$A_{n2} = 0.5wt + 0.25(1.5w)t = 0.875wt$$

(at  $L = 1.5w$ ,  $\therefore$  AISC and CSA equal)

At  $l_w = w$

$$A_{n2} = 0.5wt + 0.25(1.0w)t = 0.75wt$$

(at  $L = w$ ,  $\therefore$  AISC and CSA equal)

For  $w > L$

$$A_{n2} = 0.75Lt = 0.75\alpha wt$$

where  $\alpha = L/w < 1.0$

So, there are two differences between AISC and CSA standards relative to plates used as tension members, and connected with longitudinal welds. Refer to Figure 1.

1. When  $2w > L \geq w$ , the reduction varies linearly in the CSA standard where the AISC standard has a step function with the steps located at  $L = 1.5w$  and  $L = 2w$ .
2. When  $L < w$ , AISC does not permit this condition. The CSA standard allows this condition, and strength reduction varies linearly from  $U = 0$  at  $L = 0$  to  $U = 0.75$  at  $L = w$ .

### Rationale for CSA Provisions

Figure 2 is an illustration of a possible schematic representing the CSA shear lag model for plates connected with a pair of longitudinal welds (i.e.,  $A_{n2}$ ). Referring to Figure 2, the following equations are developed.

#### Assumptions:

1. Only cross-sectional area contained within  $w'$  is effective in resisting tension.
2. Stress acting on the effective cross-sectional area is uniformly distributed with magnitude of  $F_u$ .
3. The effective width,  $w'$ , varies bi-linearly from  $l_w = 0$  to  $l_w = w$  and from  $l_w = w$  to  $l_w = 2w$ , as shown in Figure 2, where  $l_w$  = length of weld.

For  $l_w \geq 2w$

$$w' = w$$

$$A_n = wt$$

For  $2w > l_w \geq 1.0w$

$$\frac{w'}{2} = \frac{3w}{8} + \frac{0.125w}{w}(l_w - w)$$

$$w' = 0.5w + 0.25l_w$$

$$A_n = (0.5w + 0.25l_w)t$$

For  $w > l_w$

$$\frac{3w}{8w} = \frac{w'}{2l_w}$$

$$w' = 0.75l_w$$

$$A_n = 0.75l_w t$$

Conclusion: this model is the same model as AISC with the exceptions that (1) the effective width varies linearly from  $l_w = w$  to  $l_w = 2w$  in the CSA model, where the AISC model has step functions at  $l_w/w$  ratios of 1.0, 1.5 and 2.0, and (2) the CSA model allows  $w > l_w$  where AISC currently does not.

### Fixed-Fixed Beam Model

Figure 3 illustrates the theoretical deformed shape of a welded tension member over the connected region. As axial tension load is applied, longitudinal and transverse strain is induced over the connected region resulting from a combination of axial tension and bending resulting from the Poisson effect. The following derivation neglects Poisson's effect, but it assumes that normal longitudinal stresses develop in the plate during bending; are approximately equal to the normal stresses in the transverse direction, resulting from bending in an assumed fixed-fixed beam with a uniformly distributed load along the width of the plate; and are equal to  $T/w$ , where  $T$  is the applied axial load and  $w$  is the width of the plate.

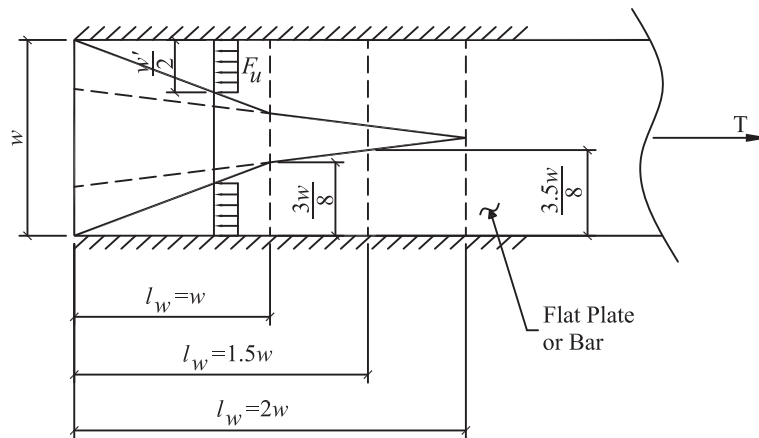


Fig. 2. Representation of CSA shear lag model for welded flat-plate tension members.

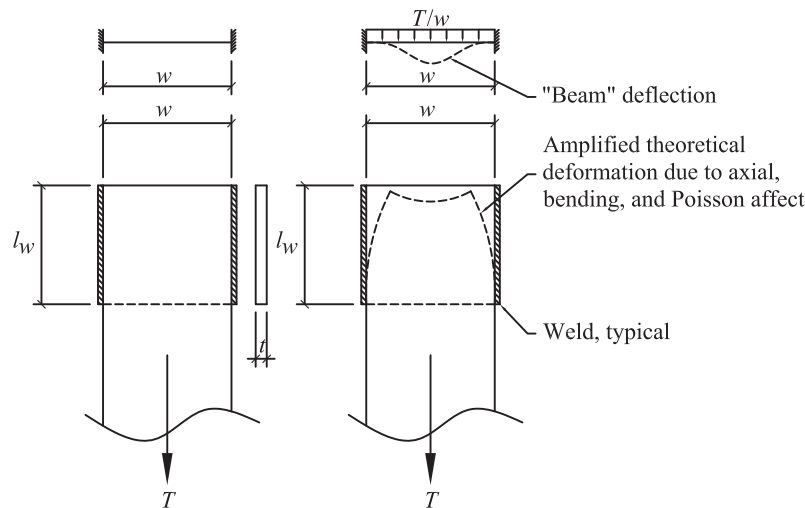


Fig. 3. Fixed-fixed beam shear lag model.



Assuming a fixed-fixed beam with a uniformly distributed load along its length and plastic hinges formed at locations of maximum positive and negative moments, the required nominal flexural strength,  $M_r$ , and flexural capacity,  $M_c$ , at the weld is

$$M_r = \frac{Tw}{16} \quad (1)$$

$$M_c = F_y Z = \frac{F_y t l_w^2}{4} \quad (2)$$

Similarly, the required nominal axial strength,  $P_r$ , and tensile capacity,  $P_c$ , is

$$P_r = T \quad (3)$$

$$P_c = F_u t w \quad (4)$$

Using the moment-axial interaction equation of AISC Section H1.1, and assuming that  $P_r/P_c > 0.2$ , for uniaxial bending,

$$\frac{P_r}{P_c} + \frac{8M_r}{9M_c} = 1.0 = \frac{T}{F_u w t} + \frac{8}{9} \frac{Tw}{16 F_y t l_w^2} \quad (5)$$

$$1.0 = \frac{T}{F_u w t} + \frac{2Tw}{9F_y t l_w^2} \quad (6)$$

Rearranging Equation 6 to take the form of  $T = F_u A_n U = F_u t w U$

$$T = F_u w t \left( \frac{1}{1 + \frac{2}{9} \left( \frac{F_u}{F_y} \right) \left( \frac{w}{l_w} \right)^2} \right) \quad (7)$$

Conservatively taking  $F_u/F_y$  approximately equal to 1.5, the shear lag factor reduces to

$$U = \frac{1}{1 + \frac{1}{3} \left( \frac{w}{l_w} \right)^2} \quad (8)$$

As can be seen in Figure 4, the shear lag model defined

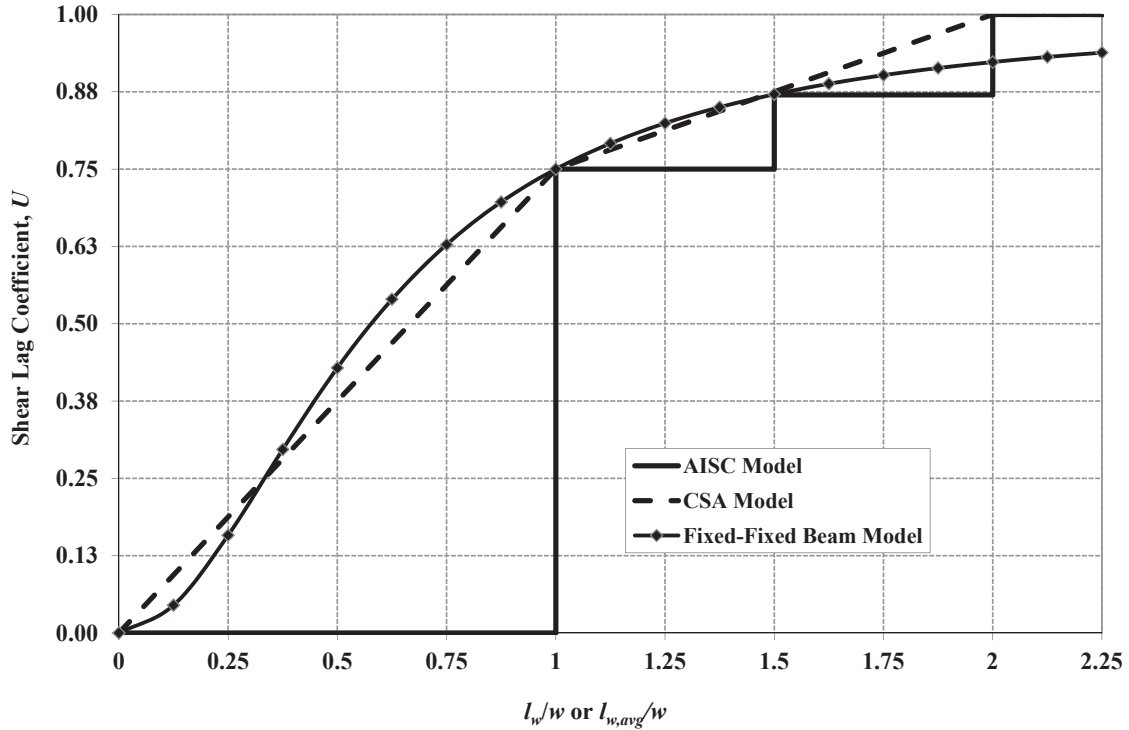


Fig. 4. Comparison of fixed-fixed beam model to current AISC and CSA models used for plates connected with a pair of longitudinal welds.

by Equation 8 is a good approximation to the CSA model currently used for plates connected with a pair of longitudinal welds. Comparing Equation 8 to the current AISC model, Equation 8 is a good approximation if the step functions are neglected. Note that the fixed-fixed beam model, surprisingly because of its simplicity, intersects with the AISC model at  $l_w/w$  values of 1.0 and 1.5.

In regard to the fixed-fixed beam model presented, it is worth noting that the authors evaluated several different beam models assuming various boundary conditions (fixed or pinned), loading conditions (uniform or concentrated) and beam stress distributions (elastic or plastic), as well a plane stress lower bound solution. The fixed-fixed beam with a uniformly distributed load along the width of the plate has the best correlations with the AISC and CSA models, as well as the experimental data, as will be presented in the following section.

This fixed-fixed beam model, which closely follows both the AISC and CSA models, gives a continuous curve that is a function of  $l_w$  and  $w$  for  $U$  rather than a series of four discrete straight lines. This is much simpler to use relative to the current AISC and CSA procedures and will be part of the recommendations given in this paper.

### THE SHEAR LAG FACTOR, $U$

The shear lag factor used in AISC procedures,  $U$ , is generally thought to be a factor applied to the main member and not the weld—and not the connection region either. But, equally generally understood is that the weld arrangement in a welded connection, such as that considered in this paper, affects both the main member and the weld. The Poisson effect, for example, results in stresses on the welds over the connection region that are not accounted for in the usual weld strength calculations, where only longitudinal stress is considered. The beam models presented previously in this paper, although not exact models that describe the structural mechanics occurring, are generated in an effort to at least capture the phenomena that occur in the connection region.

The discussion in this paper is based on the authors' assertion that the shear lag factor is more accurately used to capture the strength reduction of the system, rather than simply the member. It is also important to recognize that the strength of the weld is usually the controlling limit state in the design of a longitudinally welded tension member. Commonly, these types of connections are designed based on a given load, which is usually less than the tensile strength of the member ( $F_u A_g$ ). For a longitudinally welded tension member, where the connection is designed to resist a given load, it should be expected that the failure of such a system would be a weld failure because the weld strength is controlling limit state. However, consider a welded connection designed to resist the tensile strength of the member.

Assume a  $\frac{3}{8}$ -in.  $\times$  6-in. A36 plate is used as a tension

member and is connected using 6-in.-long longitudinal welds on each side of the plate. The design would be set up as shown in the following.

The design tensile yielding strength of the plate is

$$\phi P_{ny} = \phi F_y A_g = (0.9)(36 \text{ ksi})(\frac{3}{8} \text{ in.})(6 \text{ in.}) = 72.9 \text{ kips}$$

The weld required to resist this load is

$$1.392 D L n = 72.9 \text{ kips}$$

$$n = 2$$

$$L = 6 \text{ in. (given)}$$

$$D = \frac{72.9 \text{ kips}}{(1.392)(6 \text{ in.})(2)} = 4.36 \text{ sixteenths}$$

The design tensile rupture strength of the plate is

$$U = 0.75$$

$$\begin{aligned} \phi P_{nu} &= \phi F_u U A_n \\ &= (0.75)(58 \text{ ksi})(0.75)(\frac{3}{8} \text{ in.})(6 \text{ in.}) \\ &= 73.4 \text{ kips} \end{aligned}$$

The weld required to resist this load is

$$1.392 D L n = 73.4 \text{ kips}$$

$$n = 2$$

$$L = 6 \text{ in. (given)}$$

$$D = \frac{73.4 \text{ kips}}{(1.392)(6 \text{ in.})(2)} = 4.39 \text{ sixteenths}$$

Thus, a  $\frac{5}{16}$ -in. weld 6 in. long will be used.

The nominal strengths of the plate and weld are

$$\text{Plate yield: } R_{ny} = (36 \text{ ksi})(\frac{3}{8} \text{ in.})(6 \text{ in.}) = 81 \text{ kips}$$

$$\text{Plate rupture: } R_{nu} = (58 \text{ ksi})(\frac{3}{8} \text{ in.})(6 \text{ in.}) = 131 \text{ kips}$$

$$\text{Weld: } R_w = \frac{(1.392)(2)(5)(6)}{0.75} = 111 \text{ kips}$$

Considering the calculated nominal strengths, the weld will fail prior the plate reaching rupture strength. Generally speaking, it should be no surprise that weld failure occurs in these types of connections.

**Table 1. Summary of Test Specimens**

| No. | Researcher                              | Specimen Type   | Quantity | Weld Length        |
|-----|-----------------------------------------|-----------------|----------|--------------------|
| 1   | Easterling and Giroux (1993)            | Flat plates     | 7        | Equal              |
|     |                                         | Double angles   | 3        | Equal (balanced)   |
|     |                                         | Double channels | 6        | Equal              |
|     |                                         | Double tees     | 4        | Equal              |
| 2   | Structural Steel Welding Society (1931) | Flat plates     | 151      | Equal              |
| 3   | Gibson and Wake (1942)                  | Single angles   | 4        | Unequal (balanced) |

The following sections of this paper discuss previous physical research projects evaluating the strength of longitudinally welded tension members. In these research reports, the researchers report failure loads where weld failures occur. The data points of these specimens are included in the data points presented in this paper. For example, as is presented in the following section, 151 longitudinally welded plate specimens were tested by the Structural Steel Welding Committee (1931). Of the 151 data points presented, 149 of the specimens were reported as weld failures at the reported failure load. Of the 149 specimens reported as having weld failures, 126 of these specimens have calculated weld strengths, using AISC 360-10 strength equations, greater than the reported failure load. In most cases, the calculated weld strengths vary from 2 to 10 times larger than the weld size that would be required to produce the reported failure load. Although apparently contrary to prevailing opinion (which assumes that shear lag is limited to the member), referring to these SSWC results and also to the preceding example calculations where a weld size of at least a  $R_{nu}/5R_w = 131/(5)(111) = 3/8$  in. fillet weld would be needed to cause the member to fail first, it is the authors' assertion that the 151 SSWC tests are all valid data points for evaluating the shear lag phenomena.

## PREVIOUS RESEARCH

To evaluate the potential for generalizing the shear lag model for the various shapes discussed in this paper, a literature review was conducted to gather all possible pertinent experimental data. The following is a discussion and summary of experimental data collected from past research reports.

Three research projects, as shown in Table 1, were evaluated for load capacities of longitudinally welded tension members. Specimens meeting the configuration as shown in Cases 2 and 4 of Table D3.1 were included in the evaluation. Measured  $U$  factors,  $P_{fail}/F_uA_{net}$ , plotted against the ratio of weld length to width ( $l_w/w$ ), were determined for each of the specimens reported in the three research projects considered.  $P_{fail}$  is the reported load at which the specimen

failed, and  $F_uA_{net}$  is the calculated net tension capacity using (1) measured material properties for research projects Nos. 1 and 2 and (2) mill test reported values for research project No. 3.

Considering that flat plate connections have negligible eccentricity in the direction normal to the axis of the member, whereas angles, channels and tees have eccentricity, connections of flat plate members and connections of members with out-of-plane eccentricity are considered separately.

## Welded Flat Plates

The measured shear lag factors,  $U$ , for Easterling and Giroux (7 specimens) and the Structural Steel Welding Committee (SSWC) (151 specimens) are plotted in Figure 5. Referring to Figure 5, for  $l_w/w \geq 1$ , the majority of the tensile strengths measured by the SSWC fall below the model currently adopted by AISC; all specimen strengths measured by Easterling and Giroux are larger than the current models. Evaluating the SSWC test data, all current specifications are unconservative, but conservative compared to the Easterling and Giroux results.

For  $l_w/w < 1$ , only two values were considered in the SSWC project (0.67 and 0.80). At  $l_w/w = 0.67$ , 78 specimen results are available; 8 specimens at  $l_w/w = 0.80$ . As can be seen in Figure 5, the CSA model is conservative from  $l_w/w = 0$  up to  $l_w/w = 1.0$ . Note that the SSWC tested multiple numbers of the same specimen type, and many data points exist in the same space.

Also noteworthy is that the stepped model adopted by AISC has a better correlation with the experimental results relative to the CSA straight line functions for  $l_w/w$  values greater than 1.0.

## Members with Eccentricity (Out-of-Plane Unconnected Elements)

AISC procedures account for out-of-plane eccentricity by reducing tensile strength by  $(1 - \bar{x}/l)$ , where  $\bar{x}$  is the distance from the connection surface to the centroid of the connected member and  $l$  is the length of the connection (in the context

| Table 2. Comparison of Measured Shear Lag to AISC Requirements (Uni-planar Model) |                      |         |                                 |                         |                           |                                     |                      |              |                                 |                         |                           |
|-----------------------------------------------------------------------------------|----------------------|---------|---------------------------------|-------------------------|---------------------------|-------------------------------------|----------------------|--------------|---------------------------------|-------------------------|---------------------------|
| Double Angles (Easterling and Giroux)                                             |                      |         |                                 |                         |                           | Single Angles (Gibson and Wake)     |                      |              |                                 |                         |                           |
| Test                                                                              | $P_{fail}$<br>(kips) | $I_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $1 - x/l$<br>$U_{AISC}$ | $U_{exp}/U_{AISC}$<br>(%) | Test                                | $P_{fail}$<br>(kips) | $I_w, avg/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $1 - x/l$<br>$U_{AISC}$ | $U_{exp}/U_{AISC}$<br>(%) |
| L-L1                                                                              | 50.0                 | 2.25    | 0.81                            | 0.89                    | 91.4                      | 1                                   | 80.8                 | 1.95         | 1.28                            | 0.90                    | 142                       |
| L-L2                                                                              | 50.5                 | 2.25    | 0.82                            | 0.89                    | 92.2                      | 2                                   | 78.2                 | 1.95         | 1.23                            | 0.90                    | 138                       |
| L-L3                                                                              | 50.4                 | 2.25    | 0.82                            | 0.89                    | 92.7                      | 3                                   | 77.3                 | 1.45         | 1.22                            | 0.86                    | 142                       |
|                                                                                   |                      |         |                                 |                         |                           | 4                                   | 76.8                 | 1.28         | 1.21                            | 0.84                    | 144                       |
| Double Channels (Easterling and Giroux)                                           |                      |         |                                 |                         |                           | Double Tees (Easterling and Giroux) |                      |              |                                 |                         |                           |
| Test                                                                              | $P_{fail}$           | $I_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $1 - x/l$<br>$U_{AISC}$ | $U_{exp}/U_{AISC}$<br>(%) | Test                                | $P_{fail}$<br>(kips) | $I_w/W$      | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $1 - x/l$<br>$U_{AISC}$ | $U_{exp}/U_{AISC}$<br>(%) |
| C-L-1a                                                                            | 79.9 <sup>†</sup>    | 2.16    | 0.84                            | 0.93                    | 90.2                      | T-L-1a                              | 71.7 <sup>†</sup>    | 1.41         | 0.55                            | 0.75                    | 73.4                      |
| C-L-1b                                                                            | 87.0 <sup>‡</sup>    | 1.66    | 0.89                            | 0.91                    | 97.9                      | T-L-1b                              | 85.3                 | 1.65         | 0.80                            | 0.90                    | 88.6                      |
| C-L-2a                                                                            | 85.0 <sup>†</sup>    | 2.16    | 0.92                            | 0.93                    | 98.5                      | T-L-2                               | 85.1 <sup>†</sup>    | 1.65         | 0.82                            | 0.90                    | 90.4                      |
| C-L-2b                                                                            | 86.7 <sup>‡</sup>    | 1.65    | 0.90                            | 0.91                    | 98.3                      | T-L-3                               | 86.5                 | 1.65         | 0.79                            | 0.90                    | 87.2                      |
| C-L-3a                                                                            | 76.3 <sup>†</sup>    | 2.16    | 0.83                            | 0.93                    | 89.4                      |                                     |                      |              |                                 |                         |                           |
| C-L-3b                                                                            | 86.9 <sup>‡</sup>    | 1.65    | 0.92                            | 0.91                    | 100.8                     |                                     |                      |              |                                 |                         |                           |

<sup>†</sup> Test stopped due to weld failure.

<sup>‡</sup> Test stopped due to cross-sectional rupture away from connection region.

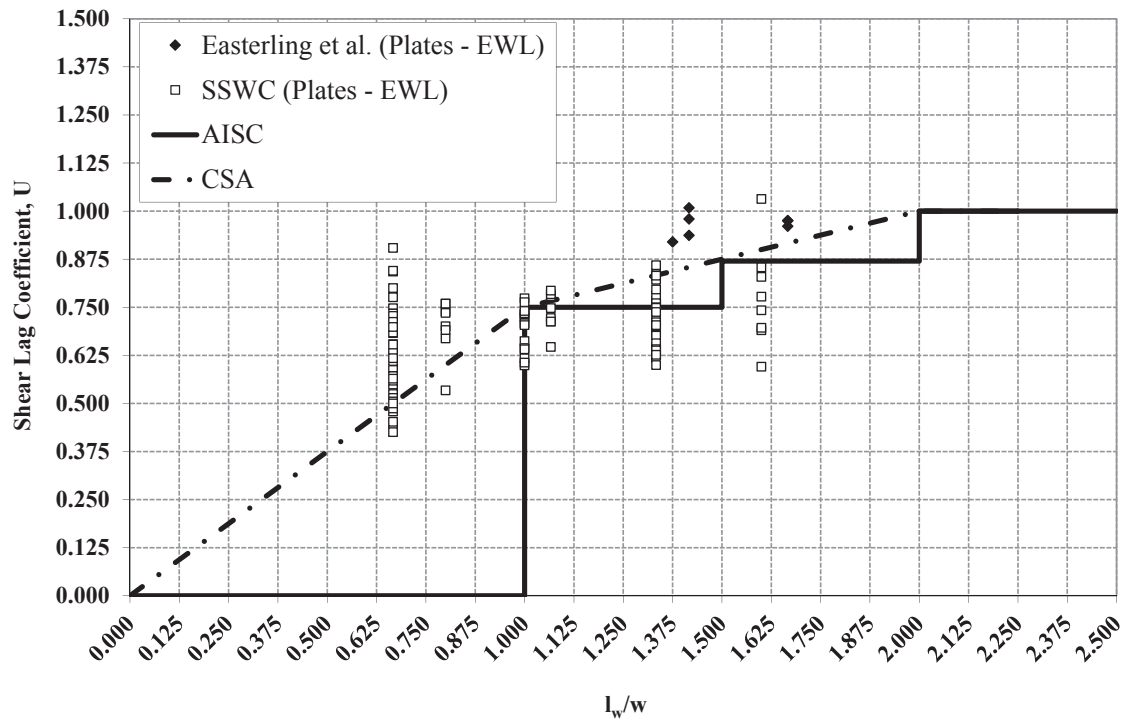


Fig. 5. Data for plates with equal-length longitudinal welds.

of this paper, the length of the weld). Note that previous versions of the the AISC *Specification* limited the upper bound of  $U$  to 0.9 for reductions calculated using the  $(1 - \bar{x}/l)$  term (the fixed-fixed beam model described previously for flat plate members reaches 0.9 at  $l_w/w \approx 2.0$ ). Consider a WT connected with longitudinal welds at the flange only. Currently, the AISC procedure accounts for shear lag effect of the out-of-plane eccentricity but does not account for the length of the weld (in-plane shear lag effect). The following is an evaluation to determine if eccentricity due to out-of-plane effects, as well as the in-plane effects, should be considered. Note that this evaluation is for members where not all of the member's elements are connected.

Easterling and Giroux (1993) tested several welded tension members consisting of double angles, double channels and double tees. A total of 13 specimens were reported; three, six, and four specimens, respectively. All specimens

had equal length longitudinal welds. The longitudinal welds used for the angles were sized appropriately to create balanced connections.

Table 2 summarizes the shear lag factors measured for each of the specimens and compares those values to the shear lag calculated using the current AISC procedure. As can be seen in Table 2, the experimental data results in a larger strength reduction compared to the procedure currently required by AISC. On average, the AISC procedure would result in connection strength approximately 10% larger than what is reported by Easterling and Giroux (1993). It should be noted that several of the failure loads reported for the channels and tees are a result of weld failures. Refer to the footnotes to the table.

Referring to the results shown in Table 2, the experimental strengths are less than the strength predicted with  $(1 - \bar{x}/l)$  (with the exception of the single angles).

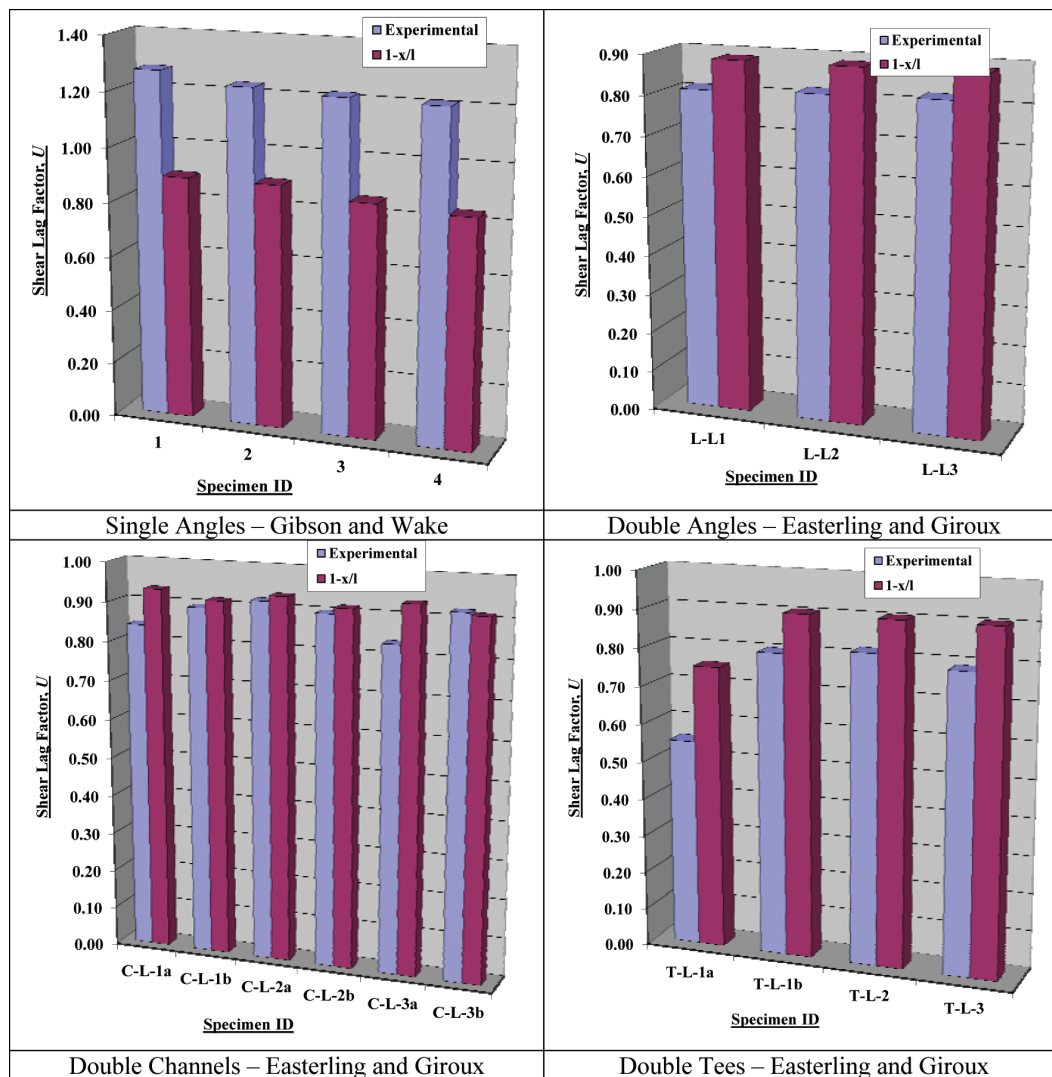


Fig. 6. Comparison of measured shear lag to AISC current procedures.

Considering that the effect of the in-plane shear lag is not considered in the values shown, the following discussion evaluates the need for accounting for the in-plane effects.

Figure 6 shows a graphical representation of the data shown in Table 2. As can be seen in the figure, the experimentally measured strengths for all specimens, except for the single angles, are less than the strength predicted using the current AISC procedure (i.e.,  $1 - \bar{x}/l$ ). This may be a result of not considering the in-plane shear lag effect resulting from the length of the connection. However, consider that several of the specimens shown in Table 2 have weld lengths greater than two times the width of the connected element. For these connection lengths, consideration of weld length will not have an impact if no strength reduction is taken for weld lengths equal to or greater than two times the distance between the welds.

### Unequal-Length Welds and Unconnected Elements

A generalized procedure for determining shear lag in tension members should consider welded connections where the longitudinal welds are not equal in length. Very little experimental evidence was able to be located during the literature review. Gibson and Wake (1942) tested four single-angle tension members connected with unequal length longitudinal welds. For each of the four tests, the angles were connected with different size, unequal-length welds, and

proportioned appropriately to achieve a balanced connection. Table 2 also summarizes the results of those four tests. As can be seen in Table 2, the measured failure load was considerably larger than the strength computed using the current AISC procedure. The measured failure load is, on average, 42% larger than what the AISC procedure allows.

It is also worth noting that the CSA shear lag provisions explicitly provide direction for determining strength reduction in tension members connected with longitudinal welds on some, but not all, of the elements that make up the member cross-section.

### Effects of Shear Lag in Two Planes

As discussed previously, shear lag is considerably different in the connected region of a plate as opposed to angles, channels and tee sections. This is an effect primarily due to the eccentricity of the geometric centroid relative to the faying surface of the connected element of the member. The total shear lag is a combination of the in-plane shear lag effect in the connected element and the out-of-plane shear lag effect associated with the unconnected element of the section. Referring to Figure 7, the total shear lag in an end-connected plate is fully due to the in-plane shear lag effect, whereas the total shear lag in angles, channels and tees is a combination of the in-plane and out-of-plane effects.

The contribution to the total shear lag effect in the

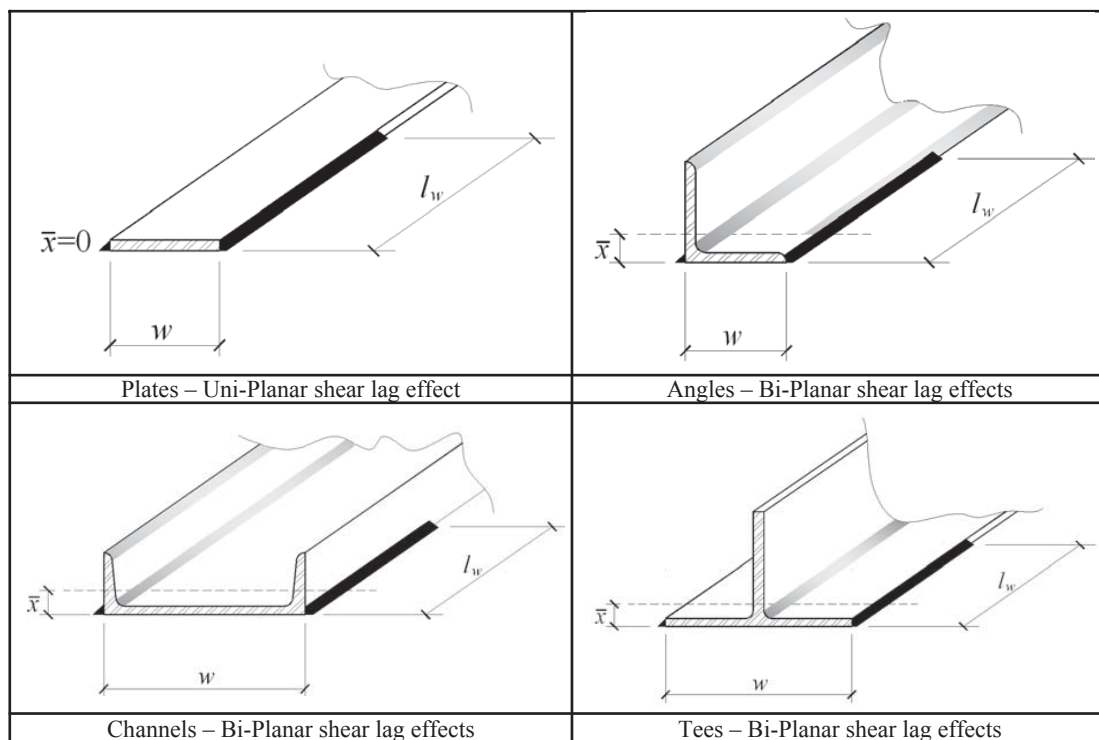


Fig. 7. Examples of shear lag effects in one and two planes.



connected element, due to in-plane effects, may be assumed to be captured using the guidelines of the AISC *Specification* for plates (Case 4), as given in Equation 9, where  $U_{CE}$  is the shear lag factor for the connected element (similar to  $A_{n2}$  used by CSA).

$$U_{CE} = f(l_w, w) = \begin{cases} 1.0 & \text{for } l_w \geq 2w \\ 0.875 & \text{for } 1.5w \leq l_w < 2w \\ 0.75 & \text{for } 1.0w \leq l_w < 1.5w \\ 0.75 \left( \frac{l_w}{w} \right) & \text{for } l_w < w \end{cases} \quad (9)$$

The contribution to the total shear lag effect in the unconnected element, due to out-of-plane effects, may be assumed to be captured using the guidelines of the AISC *Specification* for tension members (Case 2) as given in Equation 10, where  $U_{OE}$  is the shear lag factor for the unconnected (out-standing) element(s).

$$U_{OE} = 1 - \frac{\bar{x}}{l_w} \quad (10)$$

The combined effect of Equations 9 and 10 can be approximated as the product of the two component effects as

$$U = U_{CE} U_{OE} = \left( f(l_w, w) \right) \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (11)$$

Equation 11 is the method proposed in this paper for combining Cases 2 and 4 of Table D3.1 of the current AISC Specification (2005) for welded connections. This is referred to subsequently as the bi-planar model. As will be discussed later in this paper, two bi-planar models are recommended: the bi-planar (AISC method) model, which uses current AISC provisions for determining the shear lag effect of the connected element, and the bi-planar (beam method), which uses the proposed fixed-fixed beam model to account for the shear lag effect in the connected element.

Evaluating the stepped function of the AISC shear lag model for the four regions defined by Equation 9 results in four shear lag equations as a function of the  $l_w/w$  ratio, as given in Equations 12 through 15. Note that current AISC provisions do not permit weld lengths less than the width of the connected element. However, as the following equations are part of the development of the recommendations made in this paper, Equation 15 provides for a strength reduction similar to the CSA provisions for weld lengths in that range.

For weld lengths where  $l_w \geq 2w$ ,

$$U = 1.0 \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (12)$$

For weld lengths where  $1.5w \leq l_w < 2w$ ,

$$U = 0.875 \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (13)$$

For weld lengths where  $1.0w \leq l_w < 1.5w$ ,

$$U = 0.75 \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (14)$$

For weld lengths where  $l_w < w$ ,

$$U = 0.75 \left( \frac{l_w}{w} \right) \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (15)$$

Figures 8 and 9 illustrate the shear lag factors that the bi-planar (AISC method) model produces. In these figures, the shear lag factor is plotted against the  $l_w/w$  ratio. To produce the plots, an assumption must be made regarding the width of the connected element,  $w$ . Widths of 4 and 24 in. were selected, respectively, to cover a range of conditions that illustrate the range of the proposed model. The eccentricity of the connection,  $\bar{x}$ , is chosen to range from  $\bar{x} = 0$  to  $\bar{x} = 16$  in. From  $\bar{x} = 0$  to  $\bar{x} = 1.00$  in., the eccentricity increases in 8-in. increments. These ranges were chosen to illustrate the difference between relatively narrow connections with large eccentricities to that of relatively wide connections with small eccentricities.

Figure 8 presents the shear lag factors for a 4-in.-wide connection (i.e.,  $w = 4$  in.). As expected, if the eccentricity of the connection is zero, the member is a flat plate, and the  $1 - \bar{x}/l$  term in the bi-planar model is 1.0, leaving the shear lag factor a function of only the  $l_w/w$  ratio. As the eccentricity increases slightly, the out-of-plane term decreases from 1.0, reducing the strength of the connection. When the eccentricity is as large as the width of the connection (e.g.,  $\bar{x} = 4.0$  in.), the strength reduction becomes more severe, penalizing the strength. If the eccentricity is as much as four times the width of the connection (i.e.,  $\bar{x} = 16$  in.), the connection has no calculable strength regardless of the length of the welds.

Figure 9 presents the shear lag factors for a 24-in.-wide connection (i.e.,  $w = 24$  in.). As expected, if the eccentricity of the connection is zero, the member is a flat plate, and the  $1 - \bar{x}/l$  term in the bi-planar model is 1.0, leaving the shear lag factor a function of only the  $l_w/w$  ratio. As the eccentricity increases slightly, the out-of-plane term decreases from 1.0, reducing the strength of the connection. Although the trend of strength reduction for the wide connection is similar to that of the narrow connection shown in Figure 6, the penalty for eccentricity is less severe relative to a narrow connection.

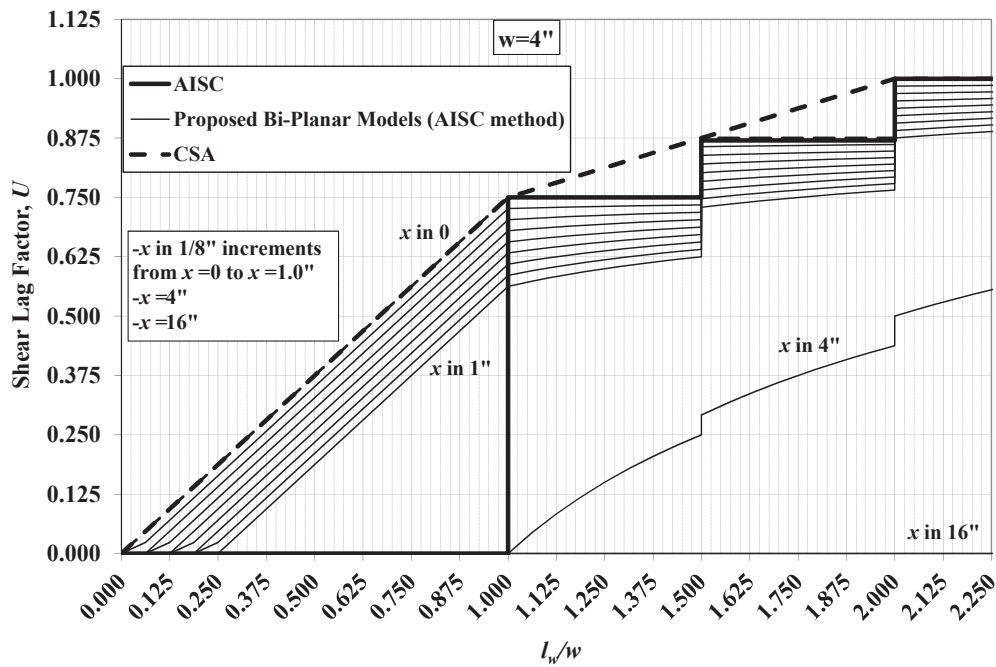


Fig. 8. Comparison of proposed bi-planar model to current AISC model (width of connected element equal to 4 in.).

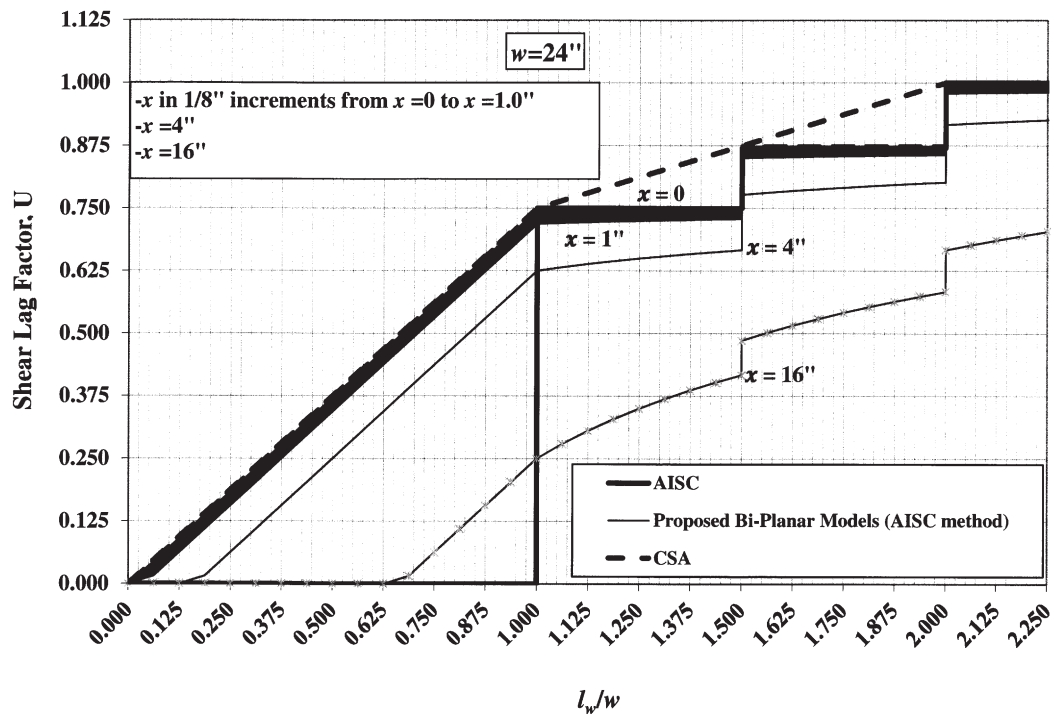


Fig. 9. Comparison of proposed bi-planar model to current AISC model (width of connected element equal to 24 in.).



**Table 3. Comparison of Measured Shear Lag to AISC Requirements  
(Bi-Planar Model Using AISC Method for Connected Element)**

| Double Angles (Easterling and Giroux)   |                   |         |                                 |                            |                                                           | Single Angles (Gibson and Wake)     |                   |              |                                 |                            |                                                           |
|-----------------------------------------|-------------------|---------|---------------------------------|----------------------------|-----------------------------------------------------------|-------------------------------------|-------------------|--------------|---------------------------------|----------------------------|-----------------------------------------------------------|
| Test                                    | $P_{fail}$        | $l_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) | Test                                | $P_{fail}$        | $l_w, avg/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) |
| L-L1                                    | 50.0              | 2.25    | 0.81                            | 0.89                       | 91.4                                                      | 1                                   | 80.8              | 1.95         | 1.28                            | 0.82                       | 163                                                       |
| L-L2                                    | 50.5              | 2.25    | 0.82                            | 0.89                       | 92.2                                                      | 2                                   | 78.2              | 1.95         | 1.23                            | 0.78                       | 157                                                       |
| L-L3                                    | 50.4              | 2.25    | 0.82                            | 0.89                       | 92.7                                                      | 3                                   | 77.3              | 1.45         | 1.22                            | 0.64                       | 189                                                       |
|                                         |                   |         |                                 |                            |                                                           | 4                                   | 76.8              | 1.28         | 1.21                            | 0.63                       | 192                                                       |
| Double Channels (Easterling and Giroux) |                   |         |                                 |                            |                                                           | Double Tees (Easterling and Giroux) |                   |              |                                 |                            |                                                           |
| Test                                    | $P_{fail}$        | $l_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) | Test                                | $P_{fail}$        | $l_w, avg/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) |
| C-L-1a                                  | 79.9 <sup>†</sup> | 2.16    | 0.84                            | 0.93                       | 90.2                                                      | T-L-1a                              | 71.7 <sup>†</sup> | 1.41         | 0.55                            | 0.56                       | 97.9                                                      |
| C-L-1b                                  | 87.0 <sup>‡</sup> | 1.66    | 0.89                            | 0.68                       | 131                                                       | T-L-1b                              | 85.3              | 1.65         | 0.80                            | 0.68                       | 118                                                       |
| C-L-2a                                  | 85.0 <sup>†</sup> | 2.16    | 0.92                            | 0.93                       | 98.5                                                      | T-L-2                               | 85.1 <sup>†</sup> | 1.65         | 0.82                            | 0.68                       | 120                                                       |
| C-L-2b                                  | 86.7 <sup>‡</sup> | 1.65    | 0.90                            | 0.68                       | 131                                                       | T-L-3                               | 86.5              | 1.65         | 0.79                            | 0.68                       | 116                                                       |
| C-L-3a                                  | 76.3 <sup>†</sup> | 2.16    | 0.83                            | 0.93                       | 89.4                                                      |                                     |                   |              |                                 |                            |                                                           |
| C-L-3b                                  | 86.9 <sup>‡</sup> | 1.65    | 0.92                            | 0.68                       | 134                                                       |                                     |                   |              |                                 |                            |                                                           |

<sup>†</sup> Test stopped due to weld failure.

<sup>‡</sup> Test stopped due to cross-sectional rupture away from connection region.

Similar plots as shown in Figures 8 and 9 were generated to illustrate the strength reduction due to shear lag when the shear lag effect of the connected element is determined using the fixed-fixed beam model. Those plots are shown in Figures 10 and 11. Note that the resulting strength reduction between the two methods is similar. The primary difference is that the bi-planar (beam method) model is simpler to apply due to the continuous function through the  $l_w/w$  range. That is, the  $l_w/w$  ratio does not need to be evaluated when using the beam method. One other difference is that the beam method requires approximately a 10% strength reduction for weld lengths equal to or greater than  $2w$ , where the AISC method requires no strength reduction for the same range. Although the beam method is asymptotic to 1.0, the weld length needs to be approximately six times the width of the connected region to mathematically achieve no strength reduction. The mathematical model used for the beam method uses the general equation shown in Equation 11. However, the function  $f(l_w, w)$  is computed using Equation 8. Equation 16 gives the bi-planar (beam method) model.

$$U = f(l_w, w) \left( 1 - \frac{\bar{x}}{l_w} \right) = \left( \frac{1}{1 + \frac{1}{3} \left( \frac{w}{l_w} \right)^2} \right) \left( 1 - \frac{\bar{x}}{l_w} \right) \quad (16)$$

Tables 3 and 4 summarize the comparisons of the experimental shear lag factors to the bi-planar models. The same experimental data as presented in Table 2 is given in this table. However, the percent difference in the experimental data is compared to the shear lag factors computed using the bi-planar models. Referring to Tables 3 and 4, the bi-planar models provide a conservative estimate of strength reduction relative to the current AISC procedure, with the exception of the double angles tested by Easterling and Giroux (1993). Note that because the  $l_w/w$  ratio for the double angles is greater than 2.0, the  $U_{CE}$  term in the bi-planar models is 1.0. Thus, the uni-planar and bi-planar models yield the same shear lag factor. Figures 12 and 13 present graphical representations of the shear lag comparisons summarized in Tables 3 and 4, respectively.

Of the recommended bi-planar models considered in Tables 3 and 4, the beam method is closer to predicting the failure load than is the AISC method, except for one case (T-L-1a). Considering the 17 tests listed in Tables 3 and 4, the

AISC method of Table 3 results in an average  $\frac{U_{exp}}{U_{plane} U_{1-\bar{x}/l}}$

of 124%, whereas the beam method of Table 4 results in an

**Table 4. Comparison of Measured Shear Lag to AISC Requirements  
(Bi-Planar Model Using Fixed-Fixed Beam Method for Connected Element)**

| Double Angles (Easterling and Giroux)   |            |         |                                 |                            |                                                           | Single Angles (Gibson and Wake)     |            |              |                                 |                            |                                                           |
|-----------------------------------------|------------|---------|---------------------------------|----------------------------|-----------------------------------------------------------|-------------------------------------|------------|--------------|---------------------------------|----------------------------|-----------------------------------------------------------|
| Test                                    | $P_{fail}$ | $l_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) | Test                                | $P_{fail}$ | $l_w, avg/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) |
| L-L1                                    | 50.0       | 2.25    | 0.81                            | 0.83                       | 97.5                                                      | 1                                   | 80.8       | 1.95         | 1.28                            | 0.82                       | 155                                                       |
| L-L2                                    | 50.5       | 2.25    | 0.82                            | 0.83                       | 98.3                                                      | 2                                   | 78.2       | 1.95         | 1.23                            | 0.78                       | 157                                                       |
| L-L3                                    | 50.4       | 2.25    | 0.82                            | 0.83                       | 98.8                                                      | 3                                   | 77.3       | 1.45         | 1.22                            | 0.64                       | 189                                                       |
|                                         |            |         |                                 |                            |                                                           | 4                                   | 76.8       | 1.28         | 1.21                            | 0.63                       | 192                                                       |
| Double Channels (Easterling and Giroux) |            |         |                                 |                            |                                                           | Double Tees (Easterling and Giroux) |            |              |                                 |                            |                                                           |
| Test                                    | $P_{fail}$ | $l_w/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) | Test                                | $P_{fail}$ | $l_w, avg/W$ | $P_{fail}/F_u A_g$<br>$U_{exp}$ | $U_{plane}$<br>$U_{1-x/l}$ | Bi-Planar Model<br>$U_{exp}/U_{plane}$<br>$U_{1-x/l}$ (%) |
| C-L-1a                                  | †79.9      | 2.16    | 0.84                            | 0.87                       | 96.6                                                      | T-L-1a                              | †71.7      | 1.41         | 0.55                            | 0.64                       | 85.8                                                      |
| C-L-1b                                  | ‡87.0      | 1.66    | 0.89                            | 0.81                       | 110                                                       | T-L-1b                              | 85.3       | 1.65         | 0.80                            | 0.81                       | 99.4                                                      |
| C-L-2a                                  | †85.0      | 2.16    | 0.92                            | 0.87                       | 106                                                       | T-L-2                               | †85.1      | 1.65         | 0.82                            | 0.81                       | 101                                                       |
| C-L-2b                                  | ‡86.7      | 1.65    | 0.90                            | 0.81                       | 110                                                       | T-L-3                               | 86.5       | 1.65         | 0.79                            | 0.81                       | 97.9                                                      |
| C-L-3a                                  | †76.3      | 2.16    | 0.83                            | 0.87                       | 95.8                                                      |                                     |            |              |                                 |                            |                                                           |
| C-L-3b                                  | ‡86.9      | 1.65    | 0.92                            | 0.81                       | 113                                                       |                                     |            |              |                                 |                            |                                                           |

† Test stopped due to weld failure.

‡ Test stopped due to cross-sectional rupture away from connection region.

average  $\frac{U_{exp}}{U_{plane} U_{1-x/l}}$  of 115%, an improvement in prediction accuracy of 7.8%.

### Wide Flange Shapes

Although reports of experimental studies investigating welded connections of wide flange tension members were not able to be found, the bi-planar shear lag models can be easily adopted. Where only the flanges or web of a W-shape are connected with longitudinal welds, the  $U_{CE}$  term can be determined based on the length of the welds, and the  $U_{OE}$  term computed by considering the eccentricity of the shape's corresponding T-shape (see Case 2 of Table D3.1 in the AISC *Specification*).

### SUMMARY

The objective of this work was to develop a generalized procedure for computing shear lag in plate, angle, channel and tee members connected with longitudinal welds. The procedure was to include consideration of connections with welds lengths less than the distance between them and where unequal weld lengths are permitted. Of the three research projects presented, only the SSWC project considered weld lengths less than the distance between them; a total of 86 specimens were evaluated. A large majority of

the experimental strengths are larger than the strengths using the CSA procedure. In regard to unequal weld lengths, only four specimens were tested (Gibson and Wake). The experimental results have significant variation, as can be seen in Figure 14. Although both the AISC and CSA appear to capture average test result values, AISC's stepped model better captures the experimental results. This is especially true for  $l_w/w$  ratios greater than 1.0.

Two analytical uni-planar models were investigated: the effective width model and the fixed-fixed beam model. The effective width model is identical to the CSA procedure, and unlike the AISC procedure, includes  $l_w/w$  ratios less than 1.0. The fixed-fixed beam model correlates very well with the CSA procedure up to  $l_w/w = 1.5$  and is conservative beyond ratios greater than 1.5. However, it is important to recognize that these two models consider only shear lag within the plane of the connected element, and therefore are only appropriate for flat plate tension members.

The bi-planar models can be used in a general sense regardless of the type of tension member discussed in this paper. For typical connection widths and out-of-plane eccentricities, the bi-planar model is somewhat conservative but has the advantage of easy adoption for flat plate, angle, channel or tee tension members. The current AISC procedure does not account for bi-planar effects of shear lag in welded connected elements of angle, channel, wide flange and tee tension members. Not accounting for the bi-planar

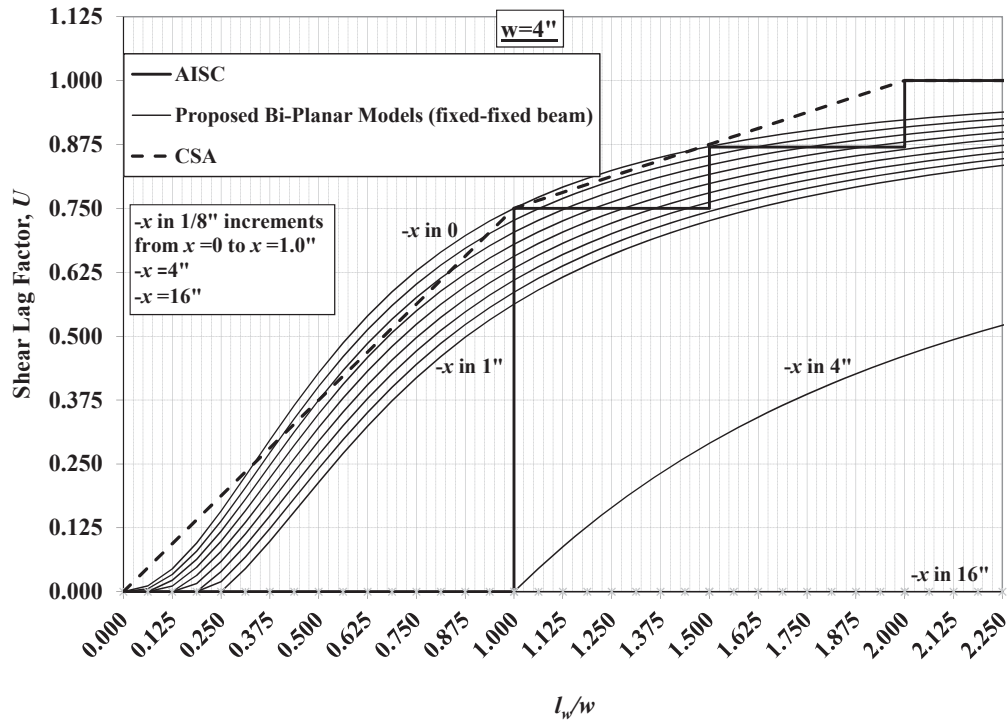


Fig. 10. Comparison of proposed beam bi-planar model to current AISC model (width of connected element equal to 4 in.).

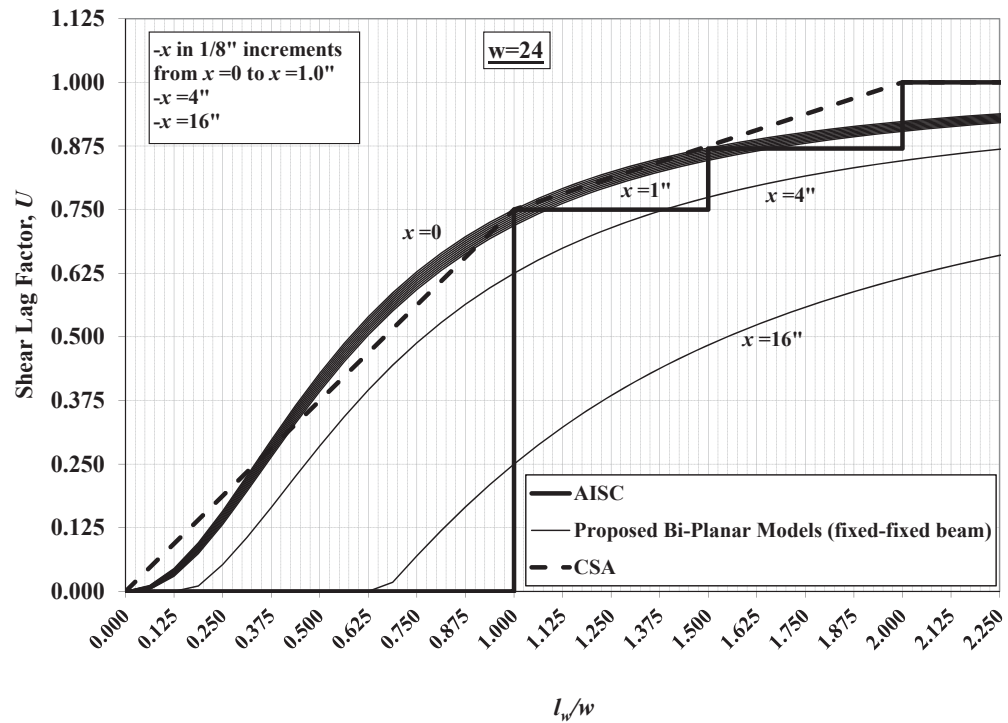


Fig. 11. Comparison of proposed beam bi-planar model to current AISC model (width of connected element equal to 24 in.).

affect tends to overestimate the connection strength relative to the experimental results presented.

## RECOMMENDATIONS

**Recommendation No. 1:** The bi-planar model using stepped functions for the connected element as currently used by AISC.

The following are recommendations for revisions of AISC 360-10 regarding shear lag in longitudinally welded tension members,

1. Recommended changes to Table D3.1 of the AISC Specification:

Replace the description for Case 2 with the following:

“All tension members, except HSS, where the tension load is transmitted to some but not all of the cross-sectional elements by fasteners. Alternatively, Case 7 may be used for W, M, S, and HP shapes.”

Replace Case 4 with that shown in Figure 15.

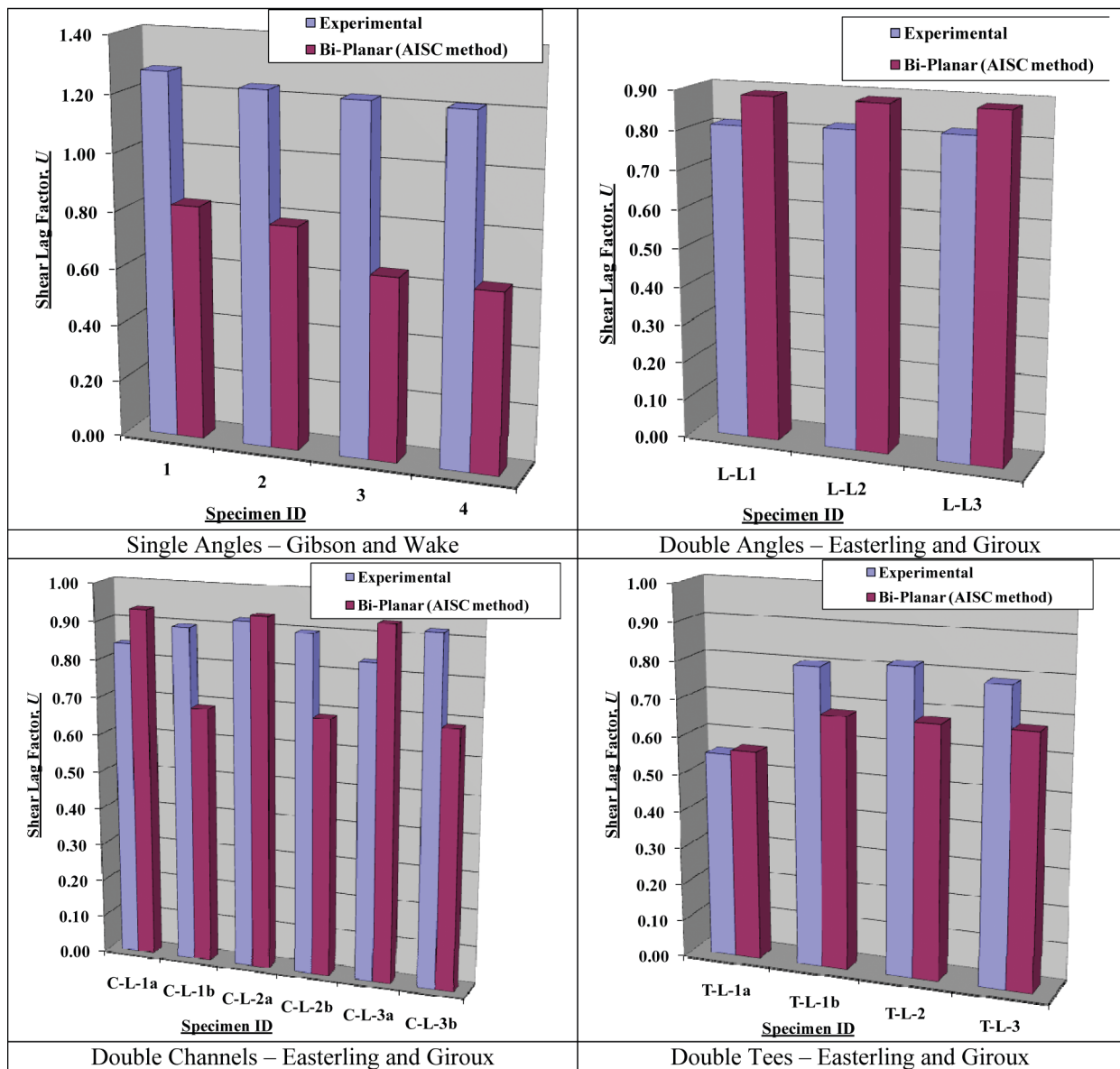


Fig. 12. Comparison of measured shear lag to proposed bi-planar model using AISC method for connected element.

- Remove the portion of *Specification* paragraph J2.2(b) that states, “If longitudinal fillet welds are used alone in end connections of flat-bar tension members, the length of each fillet weld shall not be less than the perpendicular distance between them.”
- Remove the fourth paragraph of Commentary to J2.2(b), which states that the length of longitudinal fillet welds must be equal to or greater than the distance between them.

**Recommendation No. 2:** The bi-planar model using the continuous fixed-fixed beam model for the connected element. This recommendation is the same as Recommendation

No. 1, with the exception that Case 4 is replaced with that shown in Figure 16.

### EXAMPLE PROBLEM — UNEQUAL LENGTH WELDS AND UNCONNECTED ELEMENTS

The following is an example evaluation of a skewed angle, used as a web member of a truss, connected to the truss chord using unequal length welds. First, assume that the internal member is a 2-L4×4×2; and second, assume the internal member is back-to-back 4-in.-wide by ½-in.-thick flat bars. Compute the shear lag factor using

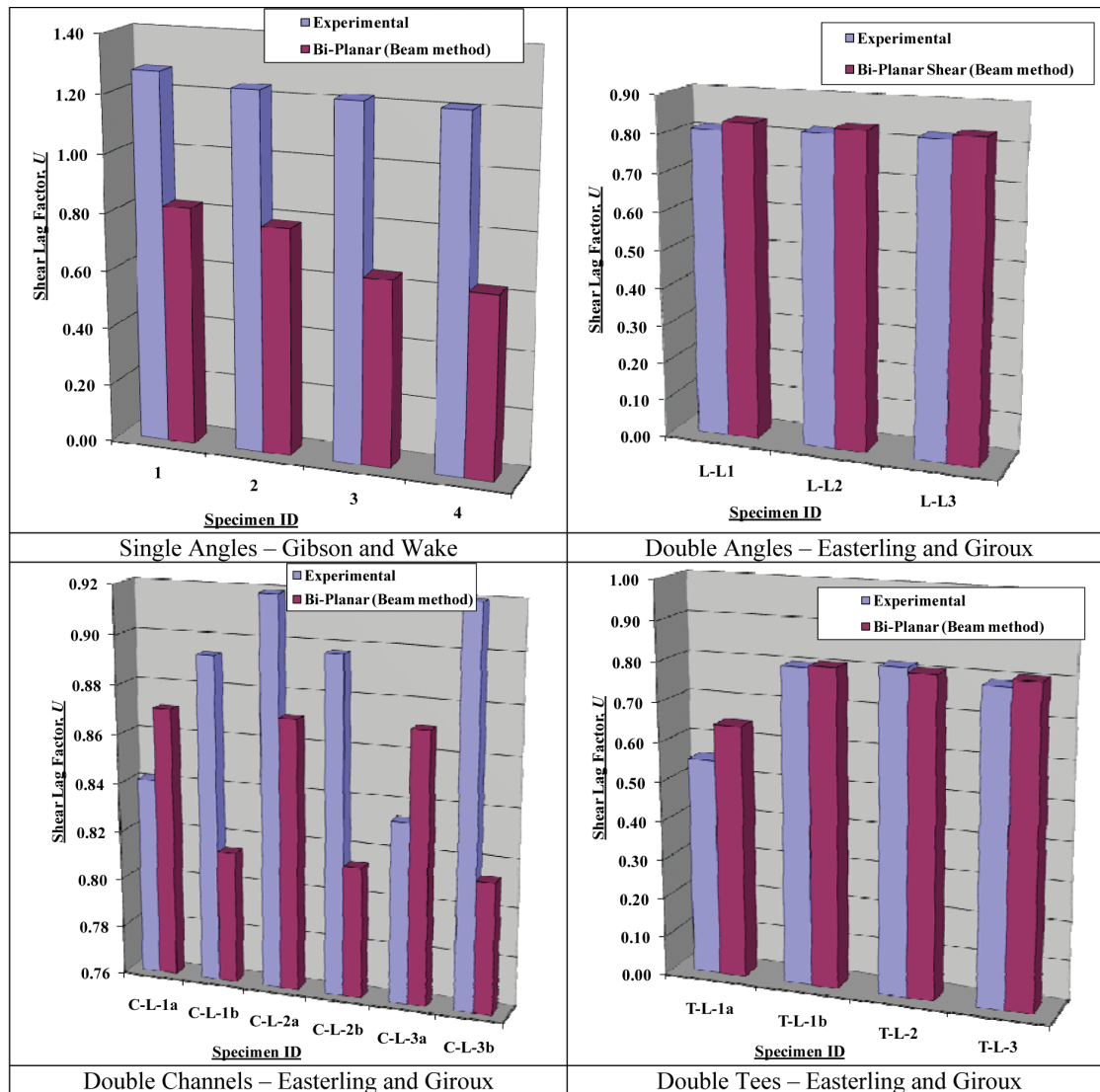


Fig. 13. Comparison of measured shear lag to proposed bi-planar model using beam method for connected element.



1. The current specified AISC procedure.
2. The current practice AISC procedure
3. The current CSA procedure.
4. The procedure as given in Recommendation No. 1.
5. The procedure as given in Recommendation No. 2.

Figure 17 shows the connection details. Given for a L4×4×2:  
 $\bar{x} = 1.18$  in.

Although the following example demonstrates the procedure for a plate and angle member, the procedure can be easily applied to channels and WT sections where not all of the elements of the member are connected (with perpendicular or skewed orientation). Furthermore, this example problem illustrates the procedure considering unequal length welds, having a weld length less than the distance perpendicular to the line of the welds.

## Double Angles

### Part 1: Current Specified AISC Procedure

This connection is not permitted. Therefore,  $U = 0$ .

### Part 2: Current Practice AISC Procedure

The current AISC procedure requires Case 2 be used to compute the shear lag factor,  $U$ . However, unequal length welds are not addressed currently nor is the in-plane effect. Because there are no guidelines currently, the length of the connection,  $l$ , will be taken as the average weld length ( $l = 5.00$  in.), because this is what would probably be assumed in practice. Neglecting that one of the weld lengths is less than the width of the connected part, and therefore, would not be permitted using current procedures,

$$U = 1 - \frac{1.18 \text{ in.}}{5.00 \text{ in.}} = 0.764$$

### Part 3: Current CSA Procedure

The portion of the shear lag accounted for in the connected leg of the angle is:

$$l = \frac{3.00 \text{ in.} + 7.00 \text{ in.}}{2} = 5.00 \text{ in.}$$

$$2w = 2(4.00 \text{ in.}) = 8.00 \text{ in.} > 5.00 \text{ in.}$$

$$w = 4.00 \text{ in.} < 5.00 \text{ in.}$$

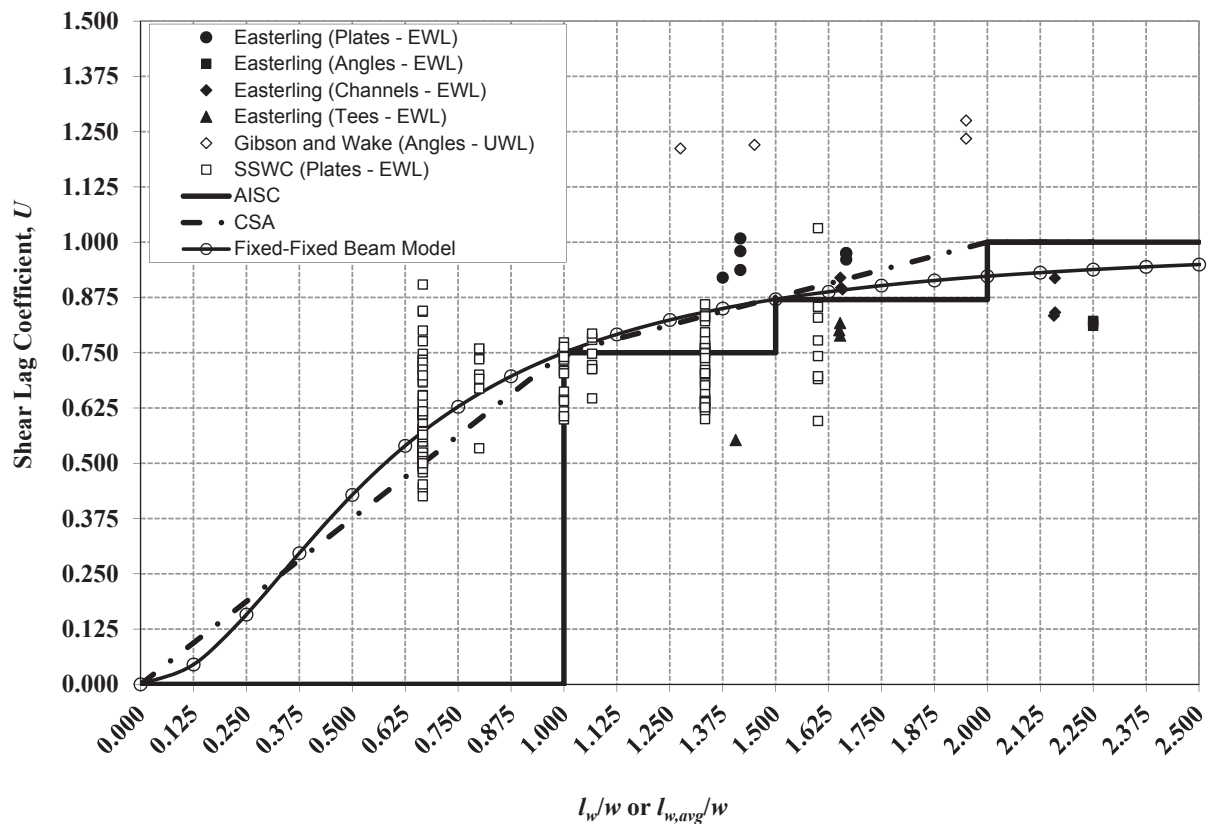


Fig. 14. Comparison of fixed-fixed beam model to current design models and experimental data.



Because  $l$  is less than  $2w$  but greater than  $w$ ,

$$\begin{aligned} A_{n2} &= 0.5wt + 0.25Lt \\ &= (0.5)(4.00 \text{ in.})(0.500 \text{ in.}) \\ &\quad + (0.25)(5.00 \text{ in.})(0.500 \text{ in.}) \\ &= 1.63 \text{ in.}^2 \end{aligned}$$

The portion of the shear lag accounted for in the unconnected (or outstanding) leg of the angle is:

$$\begin{aligned} A_{n3} &= wt \left( 1 - \frac{\bar{x}}{l} \right) \\ \bar{x} &= 0.500 \text{ in.} + \left( \frac{4.00 \text{ in.} - 0.5 \text{ in.}}{2} \right) \\ &= 2.25 \text{ in.} \\ A_{n3} &= (4.00 \text{ in.} - 0.500 \text{ in.})(0.500 \text{ in.}) \left( 1 - \frac{2.25 \text{ in.}}{5.00 \text{ in.}} \right) \\ &= 0.963 \text{ in.}^2 \end{aligned}$$

Taking a shear lag factor,  $U$ , which is not used in the CSA

treatment, as the sum of the cross-sectional areas of the elements divided by the gross area of the member,

$$U = \frac{A_{n2} + A_{n3}}{A_g} = \frac{1.63 \text{ in.}^2 + 0.963 \text{ in.}^2}{3.75 \text{ in.}^2} = 0.691$$

#### Part 4: Recommendation No. 1

This recommended procedure takes into account shear lag in both planes, as well as explicit treatment of the unequal weld lengths, and weld lengths less than  $w$ .

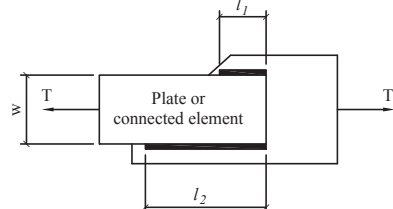
$$U = U_{CE} \left( 1 - \frac{\bar{x}}{l} \right)$$

$$l_{avg} = \frac{7.00 \text{ in.} + 3.00 \text{ in.}}{2} = 5.00 \text{ in.}$$

$$\frac{l}{w} = \frac{5.00 \text{ in.}}{4.00 \text{ in.}} = 1.25 \quad \therefore U_{CE} = 0.75$$

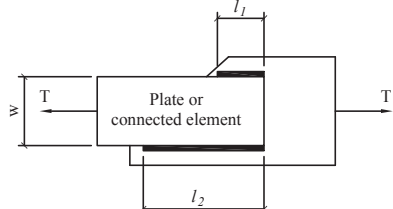
$$U_{OE} = 1 - \frac{\bar{x}}{l} = 1 - \frac{1.18 \text{ in.}}{5.00 \text{ in.}} = 0.764$$

$$U = U_{CE} U_{OE} = (0.75)(0.764) = 0.573$$

|                |                                                                                                                                            |                                                                                                                                                                                                                                        |                                                                                      |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| 4 <sup>x</sup> | Plates; and angles, channels, tees, and W shapes with connected elements; where the tension load is transmitted by longitudinal welds only | $U = U_{CE} \left( 1 - \frac{\bar{x}}{l} \right)$<br>$l \geq 2w \dots \dots \dots U_{CE} = 1.0$<br>$2w > l \geq 1.5w \dots U_{CE} = 0.87$<br>$1.5w > l \geq w \dots \dots U_{CE} = 0.75$<br>$w > l \dots \dots \dots U_{CE} = 0.75l/w$ |  |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|

<sup>x</sup>Weld lengths  $l_1$  and  $l_2$  must be non-zero,  $(l_1, l_2)_{\min} = 4$  times weld size; where  $l_1 = l_2$ ,  $l = l_1 = l_2$ ; where  $l_1 \neq l_2$ ,  $l = \frac{l_1 + l_2}{2}$ .

Fig. 15. Recommended revision to Table D3.1 (Recommendation No. 1)

|                |                                                                                                                                            |                                                                                                                        |                                                                                      |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| 4 <sup>x</sup> | Plates; and angles, channels, tees, and W shapes with connected elements; where the tension load is transmitted by longitudinal welds only | $U = U_{CE} \left( 1 - \frac{\bar{x}}{l} \right)$<br>$U_{CE} = \frac{1}{1 + \frac{1}{3} \left( \frac{w}{l} \right)^2}$ |  |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|

<sup>x</sup>Weld lengths  $l_1$  and  $l_2$  must be non-zero,  $(l_1, l_2)_{\min} = 4$  times weld size; where  $l_1 = l_2$ ,  $l = l_1 = l_2$ ; where  $l_1 \neq l_2$ ,  $l = \frac{l_1 + l_2}{2}$ .

Fig. 16. Recommended revision to Table D3.1 (Recommendation No. 2).

**Part 5:** Recommendation No. 2

This recommended procedure takes into account shear lag in both planes, as well as explicit treatment of the unequal weld lengths, and weld lengths less than  $w$ .

$$\begin{aligned}
 U &= U_{CE} \left( 1 - \frac{\bar{x}}{l} \right) \\
 &= \left( \frac{1}{1 + \frac{1}{3} \left( \frac{w}{l} \right)^2} \right) \left( 1 - \frac{\bar{x}}{l} \right) \\
 &= \left( \frac{1}{1 + \frac{1}{3} \left( \frac{4.00 \text{ in.}}{5.00 \text{ in.}} \right)^2} \right) \left( 1 - \frac{1.18 \text{ in.}}{5.00 \text{ in.}} \right) \\
 &= 0.630
 \end{aligned}$$

**Flat Plates**

**Part 1:** Current Specified AISC Procedure

This connection is not permitted. Therefore,  $U = 0$ .

**Part 2:** Current Practice AISC Procedure

The current AISC procedure requires Case 4 be used to compute the shear lag factor,  $U$ . However, unequal length welds are not addressed currently, so the length of the connection,

$l$ , will be taken as the average weld length ( $l = 5.0 \text{ in.}$ ), because this is what would probably be assumed in practice. Neglecting that one of the weld lengths is less than the width of the connected part, and therefore, would not be permitted using current procedures:

$$\begin{aligned}
 \frac{l}{w} &= \frac{5.00 \text{ in.}}{4.00 \text{ in.}} = 1.25 \\
 \therefore U &= 0.75
 \end{aligned}$$

**Part 3:** Current CSA Procedure

Because  $l = 5 \text{ in.}$  is between  $w$  and  $2w$ ,

$$\begin{aligned}
 A_2 &= 0.5wt + 0.25Lt \\
 &= (0.5)(4.00 \text{ in.})(0.500 \text{ in.}) \\
 &\quad + (0.25)(5.00 \text{ in.})(0.500 \text{ in.}) \\
 &= 1.63 \text{ in.}^2
 \end{aligned}$$

Taking a shear lag factor,  $U$ , which is not used in the CSA treatment, as the ratio of  $A_{n2}$  divided by the gross cross-sectional area of the plate,

$$U = \frac{A_{n2}}{A_g} = \frac{1.63 \text{ in.}^2}{(4.00 \text{ in.})(0.500 \text{ in.})} = 0.815$$

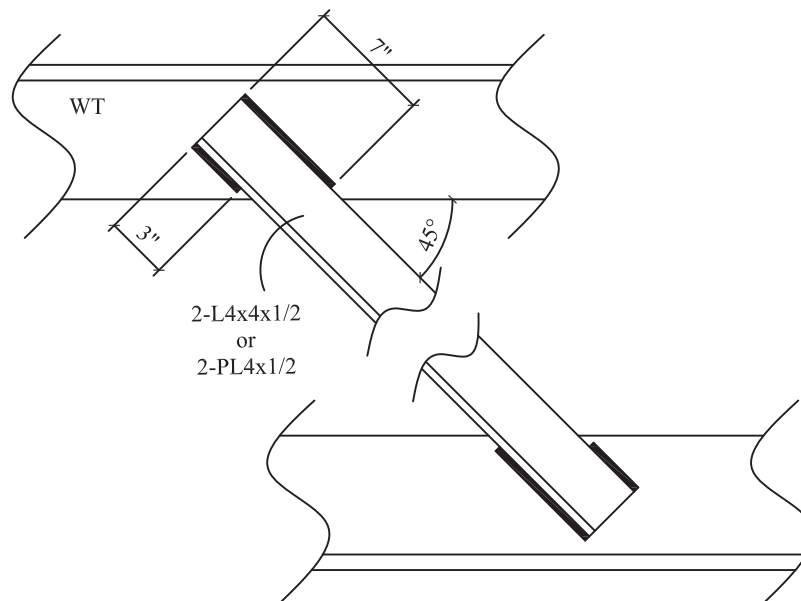


Fig. 17. End connection illustration for example problem.

Table 5. Summary of Example Problem Results

| Member       | Current Specified<br>AISC Procedure <sup>a</sup><br>(Part 1) | Current Practice<br>AISC Procedure <sup>b</sup><br>(Part 2) | Current CSA<br>Procedure<br>(Part 3) | Recommendation<br>No. 1<br>(AISC Method)<br>(Part 4) | Recommendation<br>No. 2<br>(Beam Method)<br>(Part 5) |
|--------------|--------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Double angle | 0                                                            | 0.76                                                        | 0.69                                 | 0.57                                                 | 0.63                                                 |
| Flat plate   | 0                                                            | 0.75                                                        | 0.81                                 | 0.75                                                 | 0.82                                                 |

<sup>a</sup> The current AISC provisions do not allow for unequal weld lengths. Additionally, one of the welds is only 3 in. long, which is less than the width of the connected element. Therefore, the connection would have to be considered as having no strength.

<sup>b</sup> The shear lag factors shown for this category neglect that AISC provisions do not currently permit unequal weld lengths. The weld length is taken as the average of the lengths of the two longitudinal welds.

#### Part 4: Recommendation No. 1 [Bi-Planar (AISC Method)]

The recommended procedure takes into account shear lag in both planes, as well as explicit treatment of the unequal weld lengths and weld lengths less than  $w$ . In the case of a plate,

$\bar{x} = 0$ , so the  $1 - \frac{\bar{x}}{l}$  term is 1.0.

$$U = U_{CE} \left( 1 - \frac{\bar{x}}{l} \right) = U_{CE}$$

$$l_{avg} = \frac{7.00 \text{ in.} + 3.00 \text{ in.}}{2} = 5.00 \text{ in.}$$

$$\frac{l}{w} = \frac{5.00 \text{ in.}}{4.00 \text{ in.}} = 1.25 \quad \therefore U_{CE} = 0.75$$

$$U = U_{CE} = 0.75$$

#### Part 5: Recommendation No. 2 [Bi-Planar (Beam Method)]

$$U = \frac{1}{1 + \frac{1}{3} \left( \frac{4.00 \text{ in.}}{5.00 \text{ in.}} \right)^2} = 0.824$$

Table 5 summarizes the results of the example problem. Note that because the parameters of the example problem are not currently addressed by the AISC procedure, assumptions regarding connection length were required. Without the assumptions (ignoring that the 3-in. length is less than the width of the angle leg and using the average weld length

of 5 in.), the current specified AISC procedure (Part 1 of the example problems above) yields no estimated strength. The bi-planar (AISC method) model is more conservative than that of the bi-planar (beam method). It is worth considering that although the bi-planar (beam method) is less than conservative than the bi-planar (AISC method), the beam method has better correlation with the experimental data and the CSA model.

Also note that the current AISC procedure and the bi-planar (AISC method) procedure give the same shear lag factor for the plate. This is expected, considering that there is no out-of-plane eccentricity in the plate (i.e., the  $(1 - \bar{x}/l)$  term is zero).

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