Uplift Capacity of K-Series Open Web Steel Joist Seats

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Abstract

The uplift resistance of K-series open web steel joist seats was determined by physical testing of twenty-eight specimens to failure. The experimental data obtained from the physical testing was evaluated along with the mechanical properties of the steel material used in fabricating the joist seat test specimens. A simple analytical model was developed based on the experimental results using yield-line theory, which adequately predicts the ultimate uplift capacity of the joist seat. This ultimate strength model was modified to create simple AISC-ASD and AISC-LRFD design equations to be used in the analysis of K-series joist seats for uplift. Both the AISC-ASD and the AISC-LRFD design equations consider the following variables: Joist seat yield strength (nominally 50 ksi), anchorage weld length, seat length, and seat angle thickness.

Introduction

Net uplift due to wind loading is one key design consideration for open web steel joists used in roof systems. The uplift resistance of the joist seat itself, along with the capacity of the welds which connect the seat to the supporting structure, are vital links in the load path when considering wind uplift in a roof system.

For most joist manufacturers, the typical seat is 4 inches long, however 6-inch and 8-inch extended seat lengths are occasionally provided. The Steel Joist Institute (SJI) standard (Standard, 1994), in Paragraph 5.6 (End Anchorage) requires a minimum of “two 1/8 inch fillet welds 1 inch long” to the supporting structure, be it masonry, concrete, or steel. The paragraph goes on to state, “Where uplift forces are a design consideration, roof joists shall be anchored to resist such forces.” Current structural engineering practice has the structural engineer-of-record responsible for the design of the end bearing plate and the anchorage weld of the joist seat to the steel plate or beam, not the joist manufacturer. Wind loading may be a critical design consideration depending where a structure utilizing K-series joists is located. The minimum required anchorage weld or seat length may not be sufficient to resist the net uplift forces that may be applied to the structure during its design life.
Objectives and Scope

The objectives of this research were first to determine (or verify) that the nominal uplift resistance of lightweight and standard K-series joist seats, based on the current minimum design requirements as specified in the SJI Manual (Standard, 1994) could achieve or exceed two (2) kips and four (4) kips, respectively. Once this baseline was established, a series of “straight pull” tests was conducted on various configurations of joist seat angle size, angle thickness, angle length, and fillet weld length to determine the experimental uplift capacities. A typical experimental load-deformation response curve of one of the test specimens is shown in Figure 1 and its resulting failure mechanism shown in Figure 2. The test data was evaluated along with the failure patterns of the test specimens to develop a rational model to be used as a simple design method for properly designing the joist bearing seat and anchorage weld to resist a specified net uplift load due to wind forces acting on a steel roof joist.

![Figure 1. Load-Deformation Response of Test Specimen S3-4-1/8-3](image1)

![Figure 2. End View of Test Specimen S3-4-1/8-3 Showing Failure Mechanism](image2)
Development of Analytical Model

Visual observations of the failed joist seats indicated that a “yield line” mechanism formed in the horizontal seat leg as seen in Figures 3 and 4. Therefore, the use of a yield line analysis in the development of an analytical predictive model was felt to be appropriate. Yield line analysis is a recognized method of calculating the strength of plate-type structural elements such as those used to fabricate the joist bearing seats. The virtual work method of analysis is employed in the derivation given below leading to an ultimate strength prediction of the uplift capacity of the seat angles. In applying the virtual work method, the difference between the internal work, $W_I$, (plate bending) and the external work, $W_E$, (the applied load moving through a distance) is set equal to zero.

![Figure 3. Longitudinal View of Seat Angle After Test, Test Specimen S1-6-1/8-1](image)

![Figure 4. End View of Test Specimen S1-6-1/8-1 after Test](image)
Prior to employing the virtual work method, it was necessary to numerically describe the length of the yield lines that were formed. Typical yield line patterns observed during the tests are schematically illustrated in Figures 5 and 6. Angle seats with both short and long anchorage welds displayed elliptical shaped yield lines that were created as the horizontal legs were deformed into the inelastic range during the tests. It was decided that this shape yield line would be impractical to use in the analytical model so a simpler yield line pattern was developed that was still similar to the pattern observed in the tests.

![Figure 5. Plan View Schematic of Test Specimen Showing Typical Yield Line Pattern for Short Anchorage Welds](image1)

![Figure 6. Plan View Schematic of Test Specimen Showing Typical Yield Line Pattern for Long Anchorage Welds](image2)

The final simplified shape of the yield line pattern that was chosen is shown in Figure 7. The figure shows a single seat angle being loaded by one-half of the total uplift load. Referring to this figure, the external work, $W_E$, can be written as follows:

$$W_E = \left(\frac{P_u}{2}\right)\Delta$$

(1)

where: $P_u = \text{Predicted ultimate uplift load}$  
$\Delta = \text{Distance which the load moves through}$

Likewise, the internal work, $W_I$, can be written as:

$$W_I = M_p \theta \left(L_{YL}\right)$$

(2)
where: $M_p$ = Plastic moment capacity of plate, per unit length of plate  
= $F_y Z$  
$\theta$ = Angle through which the yield line rotates  
$L_{YL}$ = Length of the yield line where $L_{YL}$ is the lesser of  
$(L_w + \pi a)$ and $L_s$  
$L_w$ = Length of anchorage weld  
$L_s$ = Length of seat angle  
$F_y$ = Average 0.2% offset yield stress of the steel angle  
$Z$ = Plastic section modulus of unit length of plate which is  
$t^2 / 4$  
$t$ = Thickness of seat angle leg

Setting the difference between the external work and the internal work equal to zero gives:

$$(P_u / 2)\Delta - M_p\theta(L_{YL}) = 0$$  \hspace{1cm} (3)$$

From small angle theory, $\tan \theta \approx \theta$, therefore:

$$\theta = \Delta / a$$  \hspace{1cm} (4)$$

where: $a$ = The distance from the toe of the angle to the yield line

![Figure 7. Yield Line Analysis Model for Prediction of Uplift Capacity](image-url)
Substituting Equation (4) into Equation (3), and solving for $P_u$, gives:

$$P_u = \frac{2M_p L_{YL}}{a}$$

Equation 5 predicts the ultimate uplift load, $P_u$, which will yield the horizontal legs of the two seat angles that form the joist seat.

The test data was analyzed to obtain a yield line length that most closely fit the experimental data, while still being reasonably simple to apply for design purposes. The best fit was obtained when the distance, $a$, was assumed to be equal to $2.3t$. Table 1 shows that the assumption of $a = 2.3t$ provides a reasonably good prediction of the ultimate uplift strength of the joist bearing seat.

**Example 1**

For a 4-inch long seat, constructed of angles $L 1-1/2 \times 1-1/2 \times 1/8$, with 2-1/2” long anchorage welds, what is the predicted ultimate uplift resistance?

Assume $F_y = 50$ ksi.

- $Z = 0.125^2 / 4 = 0.00391$ in.$^3$/in.
- $a = 2.3 \times 0.125 = 0.2875$ in.
- $L_s = 4$ in.
- $L_w = 2.50$ in.
- $L_{YL} = 2.50 + \pi(0.2875) = 3.403$ in. < $L_a$
- $M_p = 50(0.00391) = 0.1953$ in-k
- $P_u = 2 \times 0.1953 \times 3.403 / 0.2875 = 4.62$ kips

**AISC-ASD Design Procedure**

The ultimate strength prediction given in Equation 5 can be easily modified for use with an Allowable Stress Design (ASD). The following procedure creates an equation set up in ASD terms, which is familiar to most design engineers. The following changes are necessary:

Let:

- $M_a = \text{Allowable elastic capacity of plate, per unit length of plate}$
- $F_b S = \frac{F_b S}{t^2/6}$
- $F_b = 0.75 F_y$ (per 9th Edition AISC-ASD Spec., Equation F 2-1)
- $S = \text{Elastic section modulus of a unit length of plate}$
- $P_a = \text{ASD allowable uplift capacity}$

Therefore, the allowable uplift capacity of the joist bearing seat becomes:

$$P_a = \frac{2M_a L_{YL}}{a}$$
**Example 2**
For the same seat configuration used in Example 1, calculate the ASD allowable uplift capacity.

\[
\begin{align*}
S &= 0.125^2 / 6 = 0.00260 \text{ in.}^3/\text{in.} \\
a &= 0.2875 \text{ in.} \\
L_s &= 4 \text{ in.} \\
L_{YL} &= 3.403 \text{ in.} < L_s \\
F_b &= 0.75 (50) = 37.5 \text{ ksi} \text{ (without } \frac{1}{3} \text{ stress increase)} \\
&\quad = 0.75 (50) (1.33) = 50.0 \text{ ksi} \text{ (with } \frac{1}{3} \text{ stress increase)} \\
M_a &= 37.5 (0.00260) = 0.0975 \text{ in-k} \text{ (w/o stress increase)} \\
&\quad = 50.0 (0.00260) = 0.1300 \text{ in-k} \text{ (w/ stress increase)} \\
Pa &= 2 (0.0975)(3.403) / 0.2875 = 2.31 \text{ kips} \text{ (w/o } \frac{1}{3} \text{ stress increase)} \\
&\quad = 2 (0.1300)(3.403) / 0.2875 = 3.08 \text{ kips} \text{ (w/ } \frac{1}{3} \text{ stress increase)} \\
\end{align*}
\]

**AISC-LRFD Design Procedure**

The ultimate strength prediction given by Equation 5 is formulated to calculate the predicted ultimate strength, \(P_u\). Equation 5 may be rewritten in LRFD format as:

\[
P_n = \frac{2M_p L_{YL}}{a} 
\]

where: \(P_n\) = Nominal predicted ultimate uplift load
\(\phi = 0.90\) (AISC-LRFD resistance factor for bending)

The AISC-LRFD factored load combinations would be used for the load effect.

**Example 3**
For the same seat configuration used in Example 1, calculate the factored nominal resistance of the joist seat to uplift.

\[
\begin{align*}
P_n &= 2 (0.1953) (3.403) / 0.2875 = 4.62 \text{ kips} \\
\phi P_n &= 0.90 (4.62) = 4.16 \text{ kips} \\
\end{align*}
\]

The factored nominal resistance, \(\phi P_n\), would be compared to the maximum load effect from the applicable LRFD load combinations.
Table 1. Experimental Test Load vs. Predicted Ultimate Resistance

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>$t_{avg}$</th>
<th>$L_{w avg}$</th>
<th>$L_s avg$</th>
<th>$P_{test}$</th>
<th>$F_p$</th>
<th>$a_{predicted}$</th>
<th>$L_{YL}$</th>
<th>$P_{u (Eq. 4.5)}$</th>
<th>$P_{test}$</th>
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<tr>
<td>S1-4-1/8-1</td>
<td>0.105</td>
<td>1.250</td>
<td>4.085</td>
<td>2.5</td>
<td>55.8</td>
<td>0.251</td>
<td>2.39</td>
<td>2.01</td>
<td>2.56</td>
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<td>S1-4-1/8-3</td>
<td>0.111</td>
<td>3.750</td>
<td>4.095</td>
<td>4.6</td>
<td>55.9</td>
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<td>5.970</td>
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<td>6.015</td>
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<td>51.8</td>
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<td>2.79</td>
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<td>0.118</td>
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<td>1.485</td>
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<td>0.794</td>
<td>4.60</td>
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<td>2.770</td>
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<td>S3-8-1/8-5</td>
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<td>8.165</td>
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<td>1.485</td>
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<td>0.634</td>
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<td>6.82</td>
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</table>

Summary and Conclusions

An equation for predicting the ultimate uplift strength of a K-series open web steel joist seat was developed from basic engineering mechanics principles and based on experimental observations. This ultimate strength prediction equation was modified to create the following Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) equations:

**ASD:**

$$P_a = \frac{2M_{a} L_{YL}}{a}$$  \hspace{1cm} (6)

**LRFD:**

$$P_n = \frac{2M_{p} L_{YL}}{a}$$  \hspace{1cm} (7)
Considering the parameters of the experimental test program, the following limitations exist in applying these design equations:

(1) The joist seat must be welded to the steel anchorage plate or supporting steel beam or joist girder with approximately equal length fillet welds on each side. The fillet weld must have a minimum equivalent throat equal to that of a $\frac{5}{32}$ inch equal leg fillet weld. While this exceeds the SJI minimum $\frac{1}{8}$ inch leg weld, in practice most field applied anchorage welds exceed this minimum. Each weld provided must be a minimum of one (1”) inch long.

(2) The maximum thickness of the horizontal (bearing) leg of the seat angle must not exceed $\frac{1}{4}$ inch. It is unknown whether the $\frac{5}{32}$ inch nominal fillet weld is adequate to develop the yield line mechanism for thicker seats based on the scope of this research.

(3) The joist seat length must be a minimum four (4”) inches long, and must not exceed eight (8”) inches in length.

(4) For seat configurations where the seat angles overlap the top chord angles, the seat angles must be welded to the top chord from both the inside and outside. The result of not providing the outside weld is clearly illustrated in Figure 8. This outside weld is necessary to prevent rigid body rotation of the seat angles that will prevent development of the yield line mechanism.

![Figure 8. Rigid Body Rotation of Joist Seat with No Outside Weld Provided](image)

**Acknowledgment**

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References

SJI (1994), Standard Specifications for Open Web Steel Joists, K-Series, Steel Joist Institute, Myrtle Beach, SC.