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Fatigue Categorization of Obliquely Oriented Welded Attachments

Robert J. Connor,
Purdue University, rconnor@purdue.edu

Cem Korkmaz,
Purdue University, ckorkmaz@purdue.edu

Abstract

In current bridge design specifications and evaluation manuals from the American Association of State Highway and Transportation Officials (AASHTO LRFD)(AASHTO, 2018), the detail category for base metal at the toe of transverse stiffener-to-flange fillet welds and transverse stiffener-to-web fillet welds to the direction of the web and hence, the primary stress) is Category C′. In skewed bridges or various other applications, there is sometimes a need to place the stiffener or a connection plate at an angle that is not at 90 degrees to the web. As the plate is rotated away from being 90 degrees to the web, the effective "length" of the stiffener in the longitudinal direction increases. However, AASHTO is currently silent on how to address the possible effects on fatigue performance for other angles in between these two extremes. This report summarizes an FEA study that was conducted in order to investigate and determine the fatigue category for welded attachments that are placed at angles other than 0 or 90 degrees for various stiffener geometries and thicknesses. Recommendations on how to incorporate the results into the AASHTO LRFD Bridge Design Specifications are included in this report.

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1. Introduction

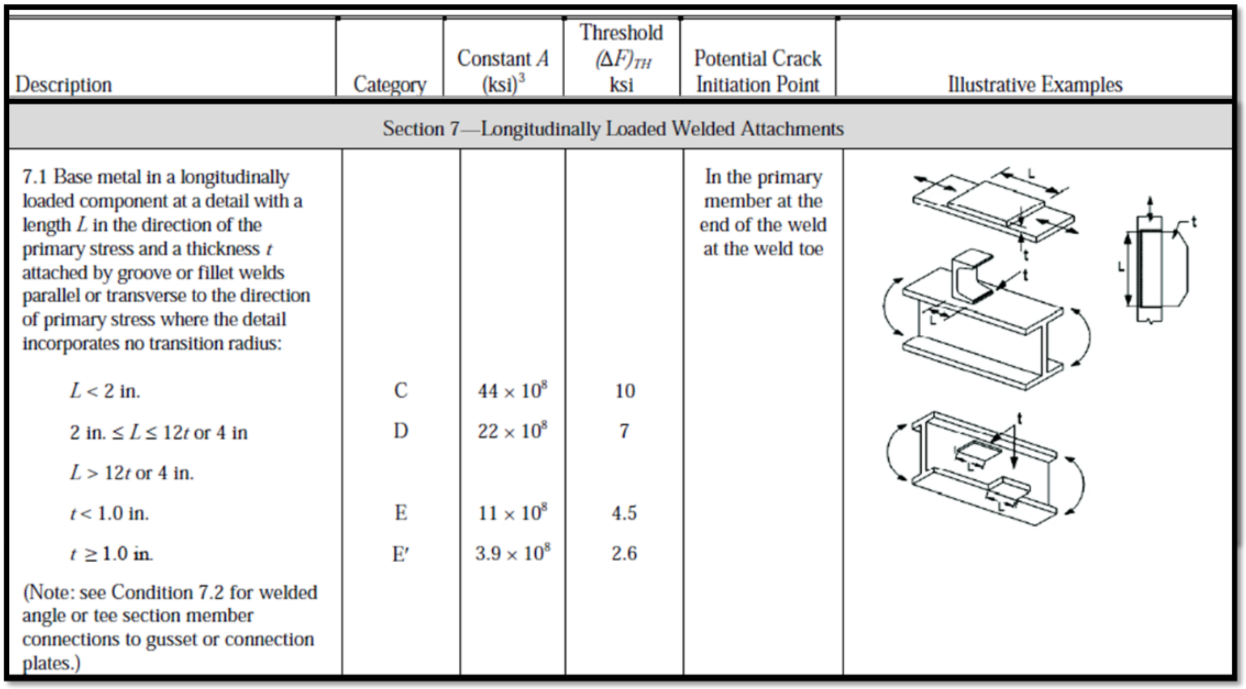
In current bridge design specifications and evaluation manuals from the American Association of State Highway and Transportation Officials (AASHTO LRFD) (AASHTO, 2018), the detail category for base metal at the toe of transverse stiffener-to-flange fillet welds and transverse stiffener-to-web fillet welds (fillet welded stiffeners perpendicular (i.e., 90 degrees) to the direction of the web and hence, the primary stress) is Category C′. These are commonly referred to as short attachments as their length in the direction of the primary stress range is very small, but always less than 2 inches since details longer than 2 inches would be classified as category C. It is noted there is some ambiguity as to when Category C′ vs. C would be appropriate if one simply considers the length of the attachment. For example, a typical stiffener is on the order of 1/2 thick inch. But a bearing stiffener that is say, 1-1/4-inch thick, plus the length added by the fillet welds is almost 2 inches long. It would seem that thicker stiffeners (e.g., bearing stiffeners) would be better classified as Category C, however AASHTO does not have any such commentary on this issue. A close study of the AASHTO illustrative examples reveals a few other inconsistencies regarding fatigue category classification vs attachment length. Nevertheless, it is not the objective of this study to address such issues.

In skewed bridges or various other applications, there is sometimes a need to place the stiffener or a connection plate at an angle that is not at 90 degrees to the web. As the plate is rotated away from being 90 degrees to the web, the effective "length" of the stiffener in the longitudinal direction increases. The extreme case would be when the stiffener is rotated a full 90 degrees and is fully parallel to the primary stress range. In this case, the detail category for base metal at the termination of welded attachments that are greater than 4 inches long and thinner than 1 inch, are classified as Category E. Clearly, if one were to rotate the stiffener fully, it would effectively become identical to the long attachment or in other words, Category E. However, AASHTO is currently silent on how to address the possible effects on fatigue performance for other angles in between these two extremes.

This report summarizes an FEA study that was conducted in order to investigate and determine the fatigue category for welded attachments that are placed at angles other than 0 or 90 degrees for various stiffener geometries and thicknesses. Recommendations on how to incorporate the results into the AASHTO LRFD Bridge Design Specifications are included in this report.

2. Background

Fatigue life of welded attachments is well known to be affected by several factors, some of which are difficult to quantify. Local stress concentrations, the effect of weld toe imperfections, residual stresses, and other factors all influence the fatigue life of a given detail. For the attachments that are considered herein, weld toe cracking is the dominant mode of cracking of interest. Since weld toe cracking is consistent whether the detail is oriented longitudinally or transversely, the influences of residual stress and local weld toe imperfections are effectively identical independent of the angle. However, the local stress concentrations at the weld toe are very different, as evidenced by the reduction in fatigue resistance observed in Figure 2.1 taken from AASHTO LRFD Table 6.6.1.2.3-1 Condition 7.1 (AASHTO, 2018). It is noted that for the welded details shown, the fatigue resistance of the detail decreases from Category C to E simply due to an increase in length. However, the residual stresses and defect distribution at the weld toe itself remain the same. Thus, the primary factor influencing the fatigue resistance of these details is the stress concentration factor (SCF) at the weld toe as the detail length increases.



Description	Category	Constant A (ksi)^3	Threshold $(\Delta F)_{TH}$ ksi	Potential Crack Initiation Point	Illustrative Examples
Section 7—Longitudinally Loaded Welded Attachments					
7.1 Base metal in a longitudinally loaded component at a detail with a length L in the direction of the primary stress and a thickness t attached by groove or fillet welds parallel or transverse to the direction of primary stress where the detail incorporates no transition radius:				In the primary member at the end of the weld at the weld toe	
$L < 2$ in.	C	44×10^8	10		
2 in. $\leq L \leq 12t$ or 4 in	D	22×10^8	7		
$L > 12t$ or 4 in.					
$t < 1.0$ in.	E	11×10^8	4.5		
$t \geq 1.0$ in.	E′	3.9×10^8	2.6		
(Note: see Condition 7.2 for welded angle or tee section member connections to gusset or connection plates.)					

Figure 2.1 Longitudinally loaded welded attachment (AASHTO, 2018).

As stated, when the welded attachment is rotated 90 degrees, the SCF will also change and transition from the observed fatigue behavior that is consistent with say Category C (or C′) to that characterized by Category E. A challenge of course is the estimation of the "true" SCF at the weld toe for the details of interest. Fortunately, experimental data exist at the two extremes of the angles of consideration, i.e., Category C (or C′) at 90 deg. and Category E at 0 deg. Since all other factors that affect the fatigue resistance remain constant (i.e., weld toe imperfections, residual stresses, etc.), one can use the ratios between the fatigue resistance curves for Category C (or C′) and E as “anchors” to which FEA results can be calibrated.

3. Methodology

3.1 The Ratio Between the Estimated SCFs

In this study, analyses of refined FE models in which the angle of the welded attachment was varied from 0 degrees to 90 degrees were performed and an *estimate* of the SCF was made. A mesh convergence study was performed to ensure that the *ratio* between the estimated SCFs for Category C′ and E were constant. Again, it is not important to know the *exact* SCF but rather, to be able to predict the same ratio in fatigue life as exhibited between the two categories that effectively “anchor” the extreme geometries and are based on experimental test data. As can be seen in Equation 3.1 below, the detail constant “A” is the only variable used to define the difference in the fatigue resistance of the various AASHTO details. Since the other factors affecting fatigue life remain constant as discussed, the ratio of the cube root of the detail constants is a strong indicator of the change in the SCF associated with Category C and E for a given value of N. This ratio is presented in Table 3.1 normalized to Category C (C′).

$$\frac{(\Delta F)_X}{(\Delta F)_{C'}} = \frac{(SCF)_X}{(SCF)_{C'}} = \left(\frac{A_x/N}{A_{C'}/N}\right)^{1/3} = \frac{{A_x}^{1/3}}{{A_{C'}}^{1/3}} \quad \text{Eq. 3.1}$$

Table 3.1 Ratio between the estimated SCFs from experimental data for detail categories normalized to Category C and C′

Category	**Threshold (ksi)**	**Constant, A Times 10^8 (ksi^3)**	**$A^{1/3}$ (ksi)**	**Ratio of $A_X^{1/3}$ / $A_{C'}^{1/3}$**
C′	12.0	44.0	1639	1.00
C	10.0	44.0	1639	Determined according to 1.95-inch-thick welded attachment (See Section 4)
D	7.0	22.0	1301	1.26
E	4.5	11.0	1032	1.59

While the actual SCFs remain unknown, Table 3.1 suggests that the SCF for Category E is about 1.6 times that associated with Category C in the finite life portion of the S-N curve. Thus, the ratio of the SCFs can be obtained.

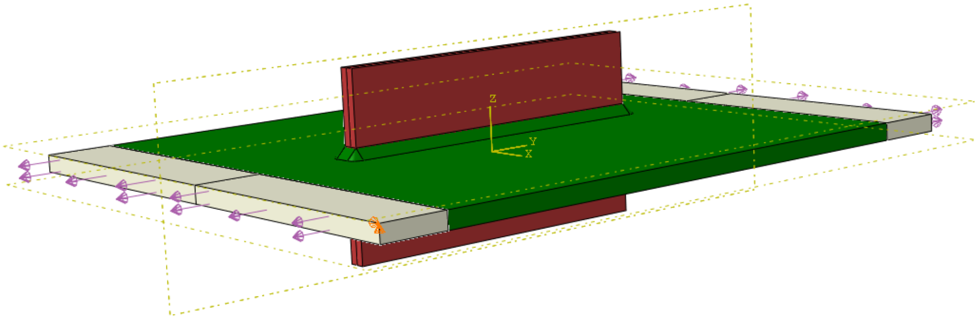
3.2 Finite Element Analysis

The first step in a parametric study is the selection of the specimen geometry to be studied. While a variety of plate sizes could be studied, it was decided to use components that were comparable with the specimens using in previous NCHRP studies by Fisher et al. (1974). Specifically, the following plate sizes were modeled.

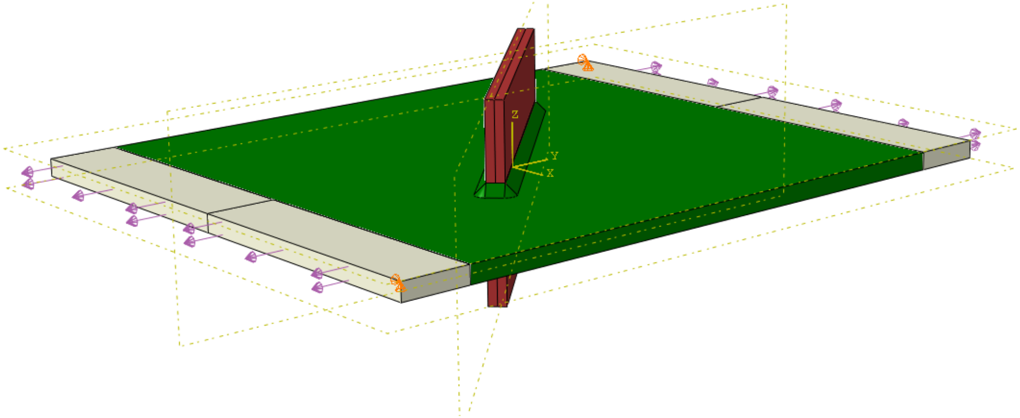
Plate component sizes used in FEA:

- Flange Width: 16 inches
- Flange Thickness: 0.5 inch (9/32" was used in the original NCHRP experimental program)
- Flange Length: 20 inches
- Attachment (stiffener) Widths: 8, 10 and 12 inches (transverse to web at 90 deg.)
- Attachment (stiffener) Thickness: 0.5 inch
- Weld Thickness: 5/16 inch

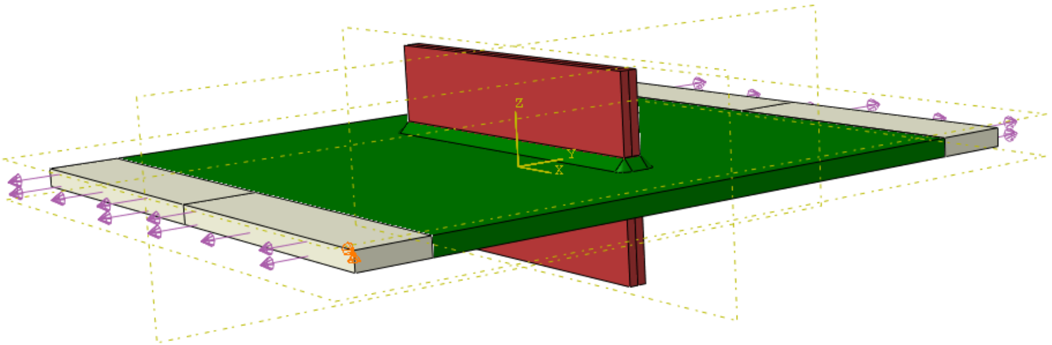
The typical configuration is shown in Figure 3.1. As can be seen in the figure, the attachment was then rotated to evaluate the effect on the estimated SCF. The angles evaluated included 0, 15, 30, 45, 60, 75, 90 degrees.



(a) Category E at 0 deg



(b) Unknown Category at 45 deg



(c) Category C’ at 90 deg

Figure 3.1 Annotated sketches of attachments with different orientations modeled.

The finite element models of the aforementioned geometries were created and analyzed using ABAQUS. All geometries were subjected to a gross section tensile stress of 1 ksi along the length of the plates. The constructed models are three-dimensional and are subjected to quasi-static implicit analysis in which large deformation theory is used.

A mesh convergence study was performed with the objective of identifying a mesh in which the ratio between the various estimated SCFs became constant. Table 3.2 presents the estimated SCFs for the various meshes for longitudinal stresses of 8-inch-wide stiffener, although in the final analysis, 8-, 10-, and 12-inch-wide stiffeners were evaluated. (*It is noted that the authors also evaluated the ratios of the SCF using principal stresses and the results were found to be the same.*

It was found that further refinements in the mesh size continued to result in larger estimates of the actual SCF as expected. But, as discussed, the actual value of the SCF is not of interest. Rather, the ratio between the various SCF factors is of importance. Thus, the mesh size was deemed to be acceptable when the ratio of the SCFs became nearly constant as the mesh size was varied.

Table 3.2 Estimated SCF for the various meshes for longitudinal stresses of 8-inch-wide stiffener

Angle (Degree)	0.150″ Elements SCF (ksi) Longit. Stress Range	0.125″ Elements SCF (ksi) Longit. Stress Range	0.100″ Elements SCF (ksi) Longit. Stress Range
0	2.374	2.651	2.847
15	2.397	2.576	2.795
30	2.381	2.443	2.594
45	1.939	2.122	2.299
60	1.779	1.802	1.980
75	1.668	1.746	1.880
90	1.630	1.722	1.854

Table 3.3 Ratio between the estimated SCFs for the various meshes for an 8-inch-wide stiffener. Each angle is normalized to Category C′ (90 degrees)

Angle (Degree)	0.150″ Elements Ratio to C′ (90 degree)	0.125″ Elements Ratio to C′ (90 degree)	0.100″ Elements Ratio to C′ (90 degree)
0	1.456	1.539	1.536
15	1.471	1.496	1.508
30	1.461	1.419	1.399
45	1.190	1.232	1.240
60	1.091	1.046	1.068
75	1.023	1.014	1.014
90	1.000	1.000	1.000

Table 3.4 Difference between 0.125″ mesh and 0.1″ mesh for an 8-inch-wide stiffener

Angle (Degree)	0.125″ Elements Ratio to C′ (90 degree)	0.100″ Elements Ratio to C′ (90 degree)	|Difference| (%)
0	1.539	1.536	0.253
15	1.496	1.508	0.771
30	1.419	1.399	1.398
45	1.232	1.240	0.645
60	1.046	1.068	2.014
75	1.014	1.014	0.009
90	1.000	1.000	0.000

It is apparent by reviewing Table 3.3 and Table 3.4 that the ratio of the estimated SCFs becomes effectively constant at a mesh size of 0.1 inch. With a mesh of this size, the average difference was 0.65% and the maximum difference was 2%. Therefore, this mesh size was deemed sufficient for the purpose of this study.

Figure 3.2 illustrates the mesh details of a typical configuration. The type of finite elements utilized were 20-node quadratic brick elements with reduced integration (C3D20R, per ABAQUS designation). The quadratic formulation is classically utilized in the calculation of large strain gradients, such as the ones occurring at stress risers, in elastic problems.

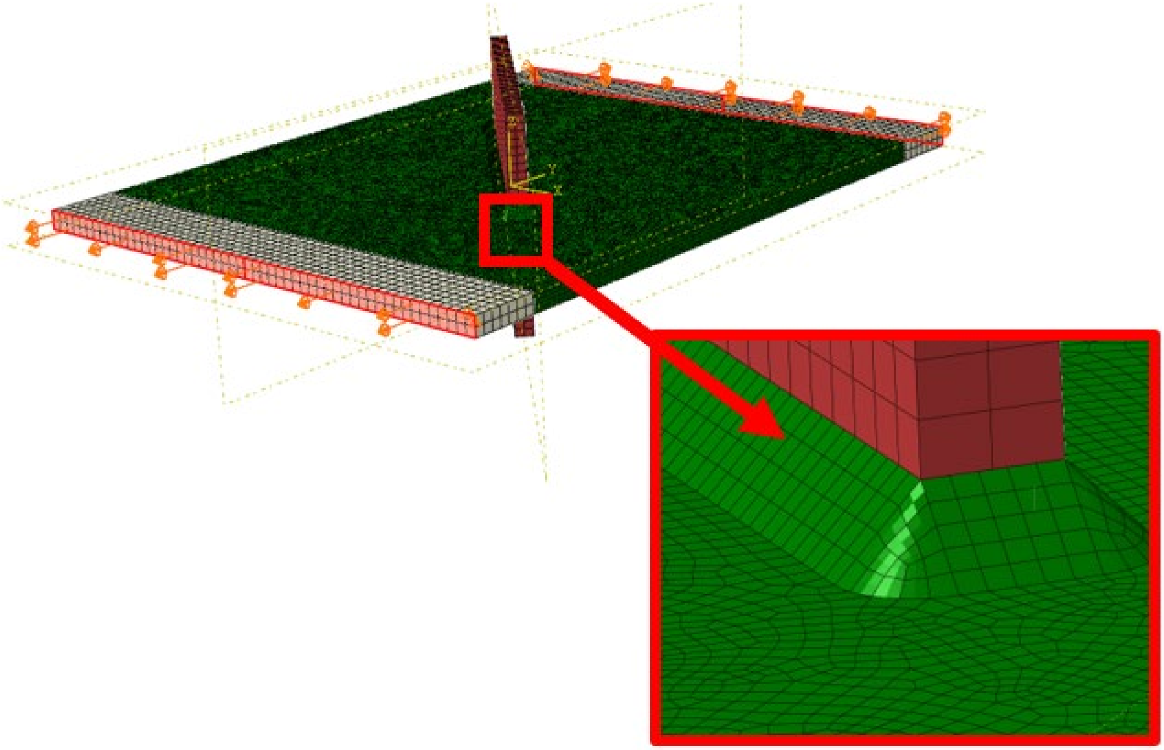


Figure 3.2 Solid model (C3D20R) of the specimens.

Maximum longitudinal stresses were obtained in the flange through finite element analysis as shown in Figure 3.3. Due to the fact that normal applied stresses were equal to 1 ksi, the stress concentration factor was equal to the maximum FE longitudinal stress (*i.e., in contrast to principal SCFs. It is noted that the authors evaluated the ratios in the SCF for principal stresses and the results were found to be the same.)*

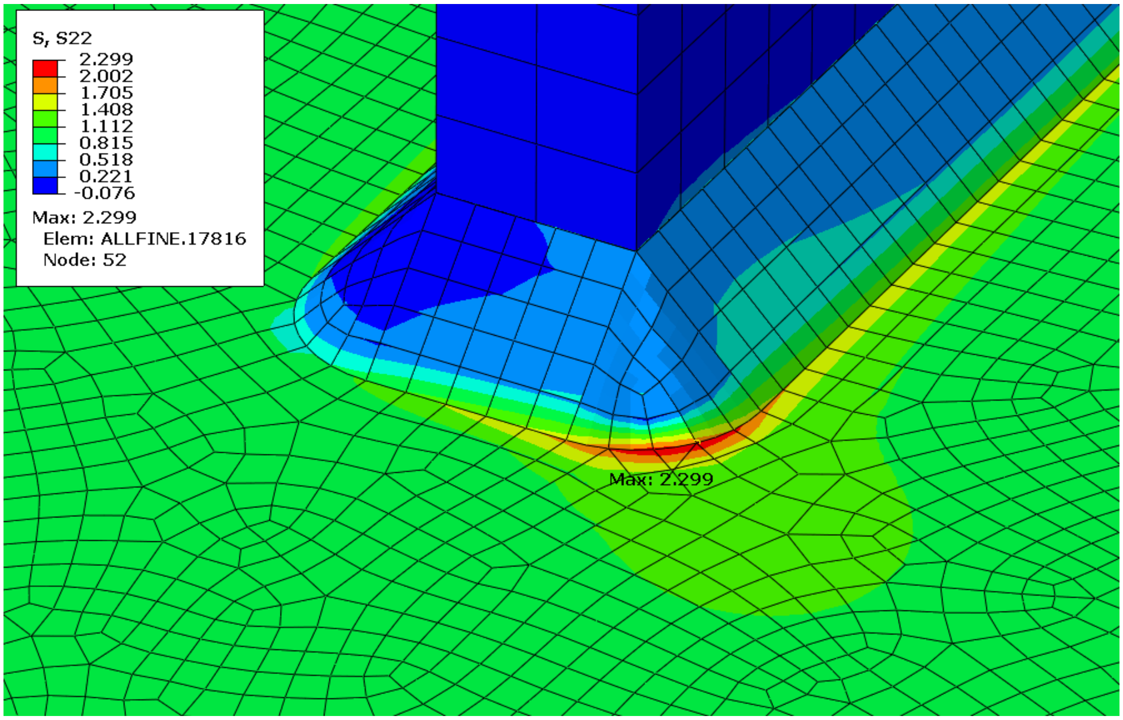


Figure 3.3 Solid model maximum longitudinal stresses of the specimens.

4. Results

As stated, the objective of the current study is to determine the fatigue category of obliquely loaded welded attachments by comparing the ratio between the estimated SCFs to that associated with Category C′ (90 degrees perpendicular to the applied stresses). Other variables such as residual stresses due to weld defects etc. do not need to be taken into account explicitly since these are effectively constant regardless of the angle of the attachment. Further, it is recognized that there will be some effects of welds that wrap around the stiffener or those that do not and other small geometric effects that are not included in this study. Since these effects are not significant enough to be included in the current AASHTO fatigue illustrations, they were also deemed to be insignificant in this study. Therefore, the load-induced fatigue performance of these details may be characterized by comparing these ratios to that associated with the known fatigue resistance of welded stiffener connections transverse to the direction of primary stress (Category C′) and longitudinally loaded welded attachments (Category E).

The following variables are calculated for each geometry analyzed:

- *Longitudinal stress range, σ_L:* Total longitudinal force divided by the cross-sectional area of the plate without taking the hole into account. For all models this equals the applied traction of 1 ksi.
- *Estimated stress concentration factor (SCF):* Stress concentration factors are the maximum longitudinal stresses (σ_L) obtained from FEA models adjacent to the weld toe.
- *Ratio of calculated SCF to Category C′ SCF (Ratio):* This ratio is obtained according to SCF for each angle divided by the SCF of Category C′ (90 degrees).

$$\text{Ratio} = \frac{SCF_{Angle}}{SCF_{90\ (Category\ C')}}$$

- *Principal, σ_P stress ranges:* Stress concentration factors and ratios are also obtained for the stress ranges of σ_P that are obtained from the FEA models for comparison purposes.

Since the other factors affecting fatigue life remain constant as discussed, the ratio of the cube root of the detail constants is a strong indicator of the change in the SCF associated with Category C and E for a given value of N. This ratio is presented in Table 3.1 normalized to Category C (C′).

Figure 4.1 presents (1) the ratio of $A_X^{1/3}$ / $A_{C'}^{1/3}$ based on the experimental data, and (2) the ratio of the estimated SCF from the FEA study normalized to the Category C & C′ curve. The dashed horizontal lines correspond to the experimental data while the blue curving line is the ratio of the SCFs obtained from the FEA as the angle of the stiffener was changed. Where the data intersect provides a reasonable estimate of the angle at which the fatigue resistance becomes the next lower category. In other words, all SCF values below the Category E dashed line, but above the Category D dashed line would best be classified as Category E. The same is true between Category C/C′ and Category D.

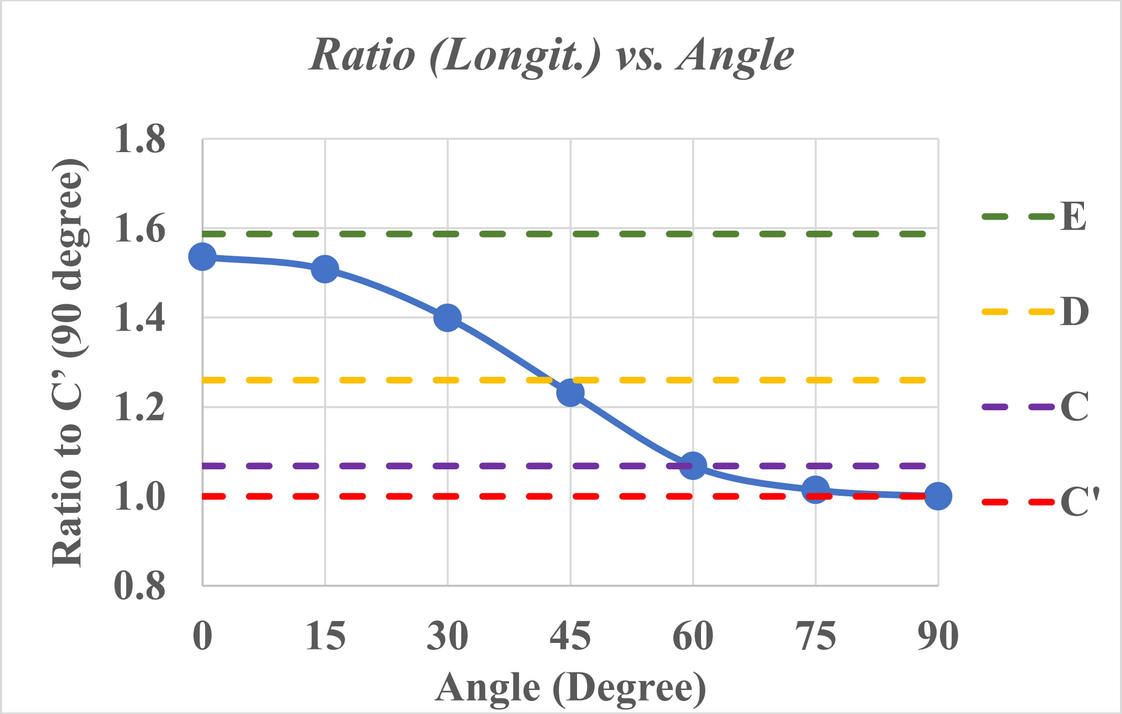


Figure 4.1 Ratio of the estimated SCF from the FEA study vs. experimental data.

From Figure 4.1, the ratio in the SCF corresponding to Category D is approximately 1.26. Based on the FEA, Table 4.1 was generated and includes the estimated SCFs for the various angles, stiffener widths (8, 10, and 12 inches) and stresses (i.e., longitudinal, and principal). As can be seen in Table 4.1, varying the length has negligible effect.

Table 4.2 next presents the range of SCF ratios for the various angles and stiffener widths considered (These data are also plotted in Figure 4.1 for SCF ratios based on longitudinal stresses.) normalized to 90 degrees which corresponds to the angle of a typical transverse stiffener. As can be seen, at about 45 degrees, the ratio in the SCF is nearly 1.26, when longitudinal stresses are considered (i.e., 1.232) and almost exactly 1.26 for when various stiffener widths and principal stresses are considered. Hence, it is concluded that when the stiffener is at 45 degrees, Category D should provide a reasonable estimate of the fatigue life. It is also apparent that there is excellent agreement when considering the data for Category E.

Table 4.1 Estimated SCF values for various angles and stiffener lengths based on FEA

Angle (Degree)	8″ Wide Stiffener Longitudinal Stresses (ksi)	8″ Wide Stiffener Principal Stresses (ksi)	10″ Wide Stiffener Longitudinal Stresses (ksi)	10″ Wide Stiffener Principal Stresses (ksi)	12″ Wide Stiffener Longitudinal Stresses (ksi)	12″ Wide Stiffener Principal Stresses (ksi)
0	2.847	3.188	2.901	3.295	2.924	3.299
15	2.795	3.041	2.862	3.180	2.871	3.182
30	2.594	2.821	2.664	2.954	2.660	2.999
45	2.299	2.503	2.314	2.580	2.344	2.596
60	1.980	2.144	1.985	2.186	2.001	2.201
75	1.880	2.031	1.881	2.063	1.892	2.076
90	1.854	2.027	1.870	2.045	1.880	2.055

Table 4.2 Ratio estimated SCF values for various angles based on FEA normalized to 90 degrees

Angle (Degree)	8″ Wide Stiffener Longitudinal Stresses (ksi)	8″ Wide Stiffener Principal Stresses (ksi)	10″ Wide Stiffener Longitudinal Stresses (ksi)	10″ Wide Stiffener Principal Stresses (ksi)	12″ Wide Stiffener Longitudinal Stresses (ksi)	12″ Wide Stiffener Principal Stresses (ksi)
0	1.539	1.573	1.551	1.611	1.555	1.605
15	1.496	1.500	1.530	1.555	1.527	1.548
30	1.419	1.392	1.425	1.444	1.415	1.459
45	1.232	1.235	1.237	1.262	1.247	1.263
60	1.046	1.058	1.061	1.069	1.064	1.071
75	1.014	1.002	1.006	1.009	1.006	1.010
90	1.000	1.000	1.000	1.000	1.000	1.000

It is noted that the data however suggest that as soon as the stiffener is even slightly angled, Category D would apply since the actual SCF increases, albeit very little. Further, as soon as the angle is at say, 44 degrees, Category E applies. While this is not as critical when switching from Category D to E (as few bridges have such sharp angles), it is a very severe penalty when falling below Category C′. In order to add another "step" to the transition, the authors looked at incorporating Category C into the approach.

Based on the AASHTO fatigue illustrations, Category C is applicable to "short" attachments that are 2 inches or less in length. While Category C and C′ share the same finite life characteristics, the CAFL (constant-amplitude fatigue threshold) for Category C′ is slightly higher. This is because Category C′ details are generally shorter than 2 inches and possess a slightly lower SCF. Note, the residual stresses and defect distribution at the weld toe would be expected to be the same for both C and C′. Thus, while the finite life portion can be estimated easily, the authors attempted to identify the angle at which the SCF of a stiffener (i.e., C′) equals that associated with C. This was done by comparing the estimated SCFs as the length of the attachment approached up to 2.0 inches in length. Figure 4.2 illustrates the model used to obtain this estimated SCF.

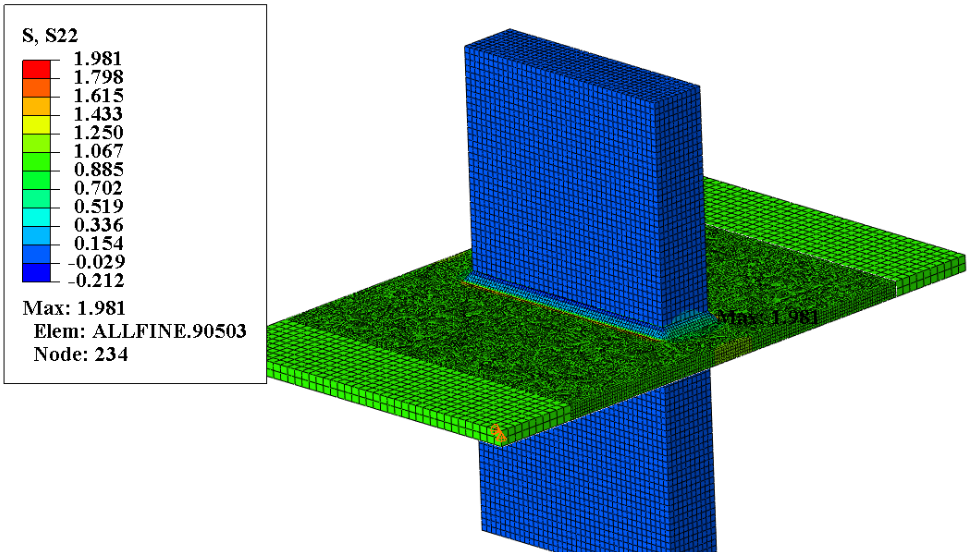


Figure 4.2 FE model of 1.95-inch-thick attachment to estimated SCF for category C.

Table 4.3 presents the estimated SCF for two transverse stiffeners or attachments of different thickness. While the 0.5-inch thick stiffener corresponds to Category C′, the 1.95-inch-thick stiffener corresponds to Category C. In other words, the SCF of 1.981 for the 1.95-inch-long attachment effectively represents that associated with Category C (i.e., a detail that is almost 2 inches long and hence at the limit of Category C). By taking the ratio of these two SCFs and plotting the value on Figure 4.1, the angle at which Category C will apply can be obtained. As can be seen, this angle corresponds to about 60 degrees. It is also apparent from the data in Table 4.2 and as plotted in Figure 4.1, that between 90 degrees and about 75 degrees, there is only about a 1.5% change in the ratio when normalized to the SCF of Category C′. Hence, there is really no need to drop below Category C′ for stiffeners angled between 90 and 75 degrees. Category C would then apply between 75 and 60 degrees. Based on these observations and the data above, recommendations on how to incorporate these findings into AASHTO were developed and are presented in Section 5.

Table 4.3 Comparison of SCF obtained from FEA for 0.5 and 1.95-inch thick attachments

Angle (Degree)	**0.5″ Thick SCF (ksi)**	**1.95″ Thick SCF (ksi)**
90	1.854	1.981

$$Category\ C\ (SCF) = \frac{1.981}{1.854} = 1.068$$

5. Conclusions and Recommendations

In the current FEA study, all stiffeners were 0.5-inch-thick, since this thickness is widely used in steel bridge girders. It is also comparable to the stiffeners thickness used in the original NCHRP studies (9/32 inches). The length of the stiffener was also varied from 8, 10, and 12 inches. It is important to note that the NCHRP results (which focused on 0.5-inch-thick stiffeners) have been extended and used for other stiffeners that are greater than 0.5 inches thick. The authors have looked at a few other stiffener thicknesses analytically (up to 1 inch) during this study. As a result, the proposed specification presented herein is only applicable up to this thickness (i.e., 1 inch). For stiffeners thicker than this and/or angled, it seems additional FEA and possibly additional experimental data would be needed. One possibility is to simply adjust the recommendations given below one category when thicker stiffeners are used, but the authors believe this would require additional FEA and discussion with T-14.

Based on the results of the current study, the following addition to the end of Condition 7.1 in Section 7 (Longitudinally Loaded Welded Attachments) of Table 6.6.1.2.3-1—Detail Categories, for Load-Induced Fatigue in the AASHTO LRFD Bridge Design Specification (AASHTO, 2018) is suggested, as shown in Table 5.1. This material may also be incorporated into Detail 4.1 related to transverse stiffeners. Where best to potentially incorporated these recommendations will be left to the AASHTO T-14 committee to decide. It is noted that the “break point” between category C and C’ was best represented at an angle of 75 degrees. However, after discussions with AASHTO T-14, to accommodate the existing AASHTO provisions which permits skewed connection plates up to 70 degrees (i.e., 20 degrees from normal), it was decided to make the step at 70 degrees instead of 75 degrees. This was deemed to be a reasonable accommodation, though slight unconservative.

It is noted that the table above and throughout this report, the references to the skew angle are opposite from that typically used in AASHTO. Hence, Table 5.2 would likely be more appropriate for direct implementation as it references the skew angle consistently with the AASHTO LRFD BDS.

Table 5.1 Recommended AASHTO provisions for skewed plates based on the angle as referenced in this report

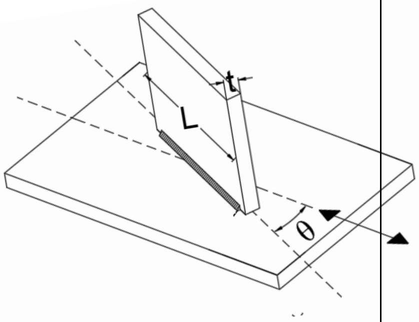
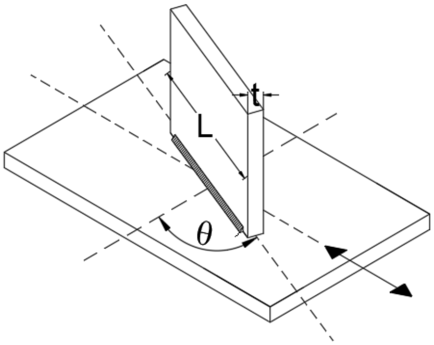
Description	Category	Constant A (ksi^3)	Threshold $(\Delta F)_{TH}$ (ksi)	Potential Crack Initiation Point	Illustrative Examples
Base metal in a longitudinally loaded component at an obliquely oriented detail with an effective length $L > 4$ in. and a thickness t less than 1 in. attached by groove or fillet welds.				In the primary member at the weld toe	
90° > θ ≥ 70°	C′	44 × 10^8	12		
70° > θ ≥ 60°	C	44 × 10^8	10		
60° > θ ≥ 45°	D	22 × 10^8	7		
0° < θ < 45°	E	11 × 10^8	4.5		

Table 5.2 Recommended AASHTO provisions for skewed plates based on the skew angle as referenced in the AASHTO LRFD BDS

Description	Category	Constant A (ksi^3)	Threshold $(\Delta F)_{TH}$ (ksi)	Potential Crack Initiation Point	Illustrative Examples
Base metal in a longitudinally loaded component at an obliquely oriented detail with an effective length $L > 4$ in. and a thickness t less than 1 in. attached by groove or fillet welds.				In the primary member at the weld toe	
θ ≤ 20°	C′	44 × 10^8	12		
20° < θ ≤ 30°	C	44 × 10^8	10		
30° < θ ≤ 45°	D	22 × 10^8	7		
45° < θ < 90°	E	11 × 10^8	4.5		

References

AASHTO. (2018). *AASHTO guide specifications for analysis and identification of fracture critical members and system redundant members.* American Association of State Highway and Transportation Officials.

Fisher, J. W., Pedro, A. A., Yen, B. T., Klingerman, D. J., & Mcnamee, B. M. (1974). *Fatigue strength of steel beams with welded stiffeners and attachments* (NCHRP Synthesis 147). National Academy Press.