APPENDIX A

T AND CORNER JOINT CRITICAL FLAW SIZE

A.1 T and Corner Joints Loaded Parallel to Weld

T and corner joints loaded parallel to the weld and flange were evaluated for critical flaw sizes considering fatigue loading and fracture. Since the stress in these members is parallel to the weld, there are negligible stress concentration effects due to the geometry as determined through FE analysis performed by the Research Team. Due to this, T and corner CJP welds loaded parallel to the weld are similar to equal thickness butt welds except for any effect from the geometry on the stress intensity factor (K_I) values due to the change in thickness at the weld reinforcement and flange.

This effect was investigated through 3D finite element analysis using the commercial solver ABAQUS. FE models of T joints were developed with various cracks perpendicular to the stress (i.e., perpendicular to the weld). The cracks were placed in the root of the CJP welds, offset at approximately the ¼ point of the web, on the surface of the web at the toe of the weld reinforcement, and on the surface of the weld reinforcement. The K_I values around the crack were computed and compared to classical K_I values for embedded and surface cracks in flat plates in order to determine if the T joints can be simplified into a flat plate with an equivalent thickness. If so, the equal thickness CJP weld critical crack sizes could then be used for the T and corner joints loaded parallel to the weld and flange.

The models of the cracks at the root of the CJP weld were developed by taking advantage of the symmetry condition along the centerline of the web, as shown in Figure A-1. The size of the root cracks were varied to investigate how this would affect the equivalent thickness of a flat plate. Fully embedded 3D cracks were required in order to model offset embedded cracks as shown in Figure A-2. This required a considerable amount of additional computational cost and effort. Surface cracks in the web weld toe were modeled with varied web thickness. Surface cracks were also modeled along the weld reinforcement as shown in Figure A-3.

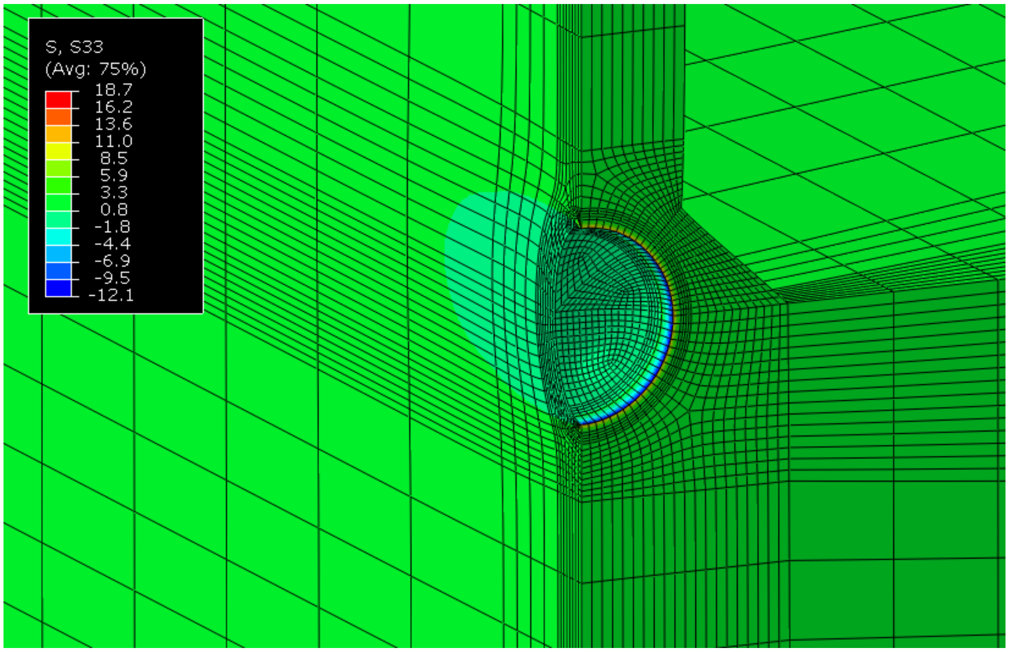

Figure A-1. Embedded Crack in Root of T Weld

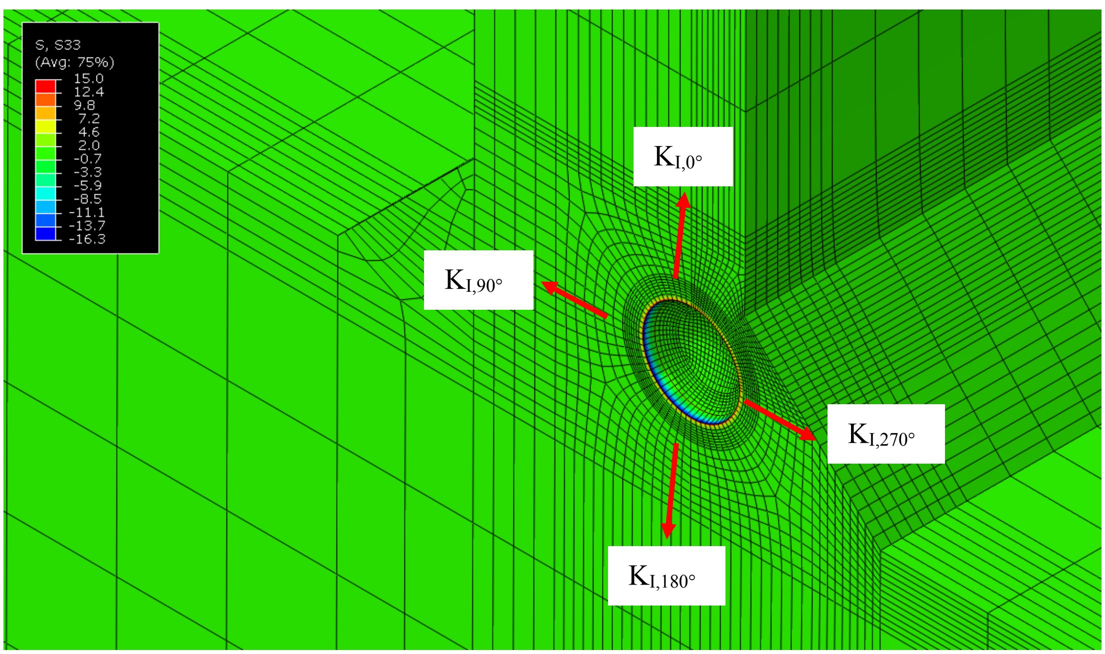

Figure A-2. Embedded Crack at ¼ Point of T Weld

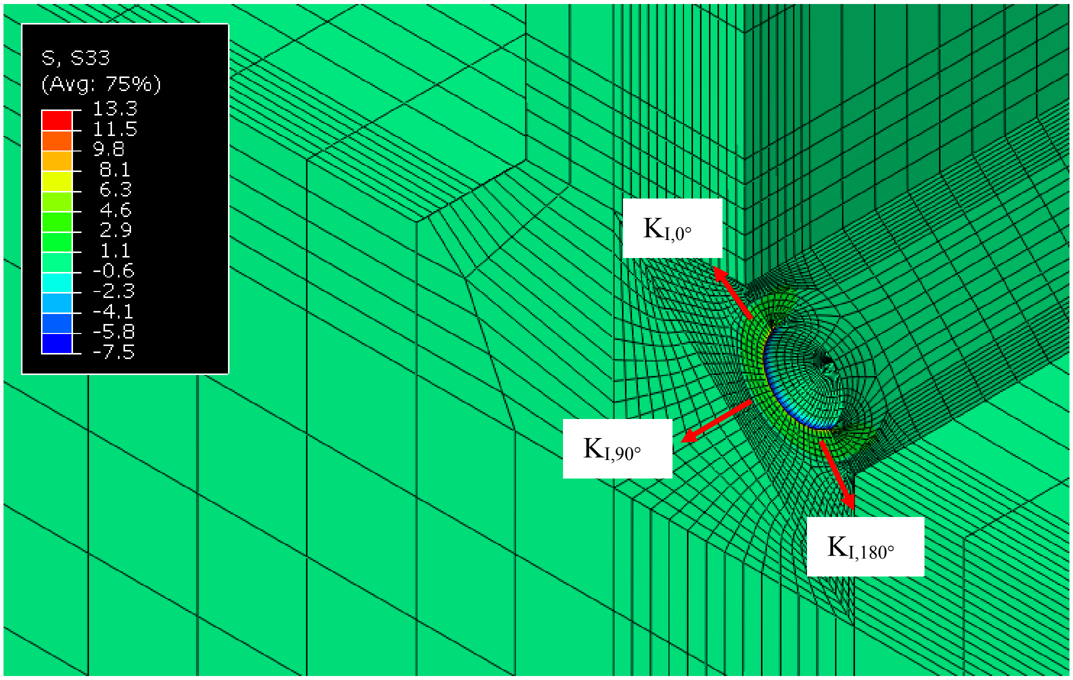

Figure A-3. Surface Crack in T Weld Reinforcement

The SignalFFS software utilizes the notation shown in Figure A-4 for the K_I values as one sweeps around an embedded crack. Similar notation is used for a surface crack, except that the crack only extends from 0°-180°. This notation was adopted for the ABAQUS results with 0° extending along the axis of the web for embedded cracks, as shown in Figure A-2, or along the free surface, as shown in Figure A-3. The ABAQUS K_I values are compared to the classical flat plate solutions for various "equivalent flat plate thicknesses" in Table A-1.

To represent cracks in the root of the CJP weld as embedded cracks in a flat plate, a portion of the reinforcement contributes towards the "equivalent flat plate thickness". As the crack becomes closer to the free surface (i.e., the remaining ligament is decreased), the percentage of the reinforcement that contributes to the "equivalent flat plate thickness" was found to decrease. This occurs since the thickness of the remaining ligament drives the K_I values much greater than the total thickness of the plate. This can be seen for the model with the offset embedded crack located ~1/4 of the thickness of the web and reinforcement. For surface cracks, it is unconservative to include weld reinforcement in an "equivalent flat plate thickness". For surface cracks, the controlling location of the K_I values occurred along the free surface (i.e., $K_{I,0°}$ and $K_{I,180°}$) rather than in the remaining ligament (i.e., $K_{I,90°}$ and $K_{I,270°}$). It was found that the flat plate solutions using just the web thickness for both the surface cracks at the web toe and those along the reinforcement correlated well to the results from ABAQUS.

Therefore, based on the results of the "equivalent flat plate thickness" for surface cracks and the dependency on the thickness of the remaining ligament for embedded cracks, the Research Team believes that the thickness of the web only should be used to determine the critical flaw size of the T and corner welds loaded parallel to the weld and flange. Thus, the critical flaw sizes which have already been calculated for equal thickness CJP butt welds can be conservatively applied for T and corner welds loaded parallel to the weld and flange. There is an advantage of using this approach as it will greatly simplify the different rejection criteria required to be used in the shop.

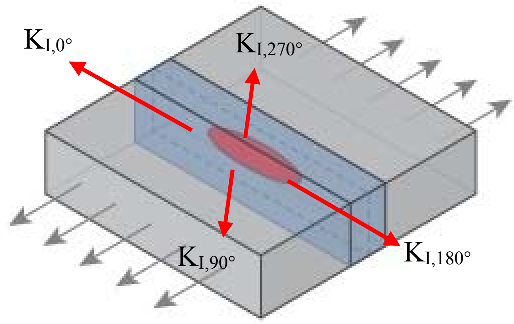

Figure A-4. SignalFFS K_I Value Notation

Table A-1. K_I Results for T Welds Loaded Parallel to Weld and Flange

Thickness		Crack Size		Crack Location	Equivalent Thickness	Classical Flat Plate				ABAQUS Results				
Web	Flange	Height	Length			$K_{I,0°}$	$K_{I,90°}$	$K_{I,180°}$	$K_{I,270°}$	$K_{I,0°}$	$K_{I,90°}$	$K_{I,180°}$	$K_{I,270°}$	$K_{I,max}$
0.5"	2"	0.1"	0.1"	Root	Web Only	0.253	0.253	0.253	0.253	0.253	0.253	0.253	0.253	0.253
					Web + 80% Reinforcement	0.253	0.253	0.253	0.253					
					Web + 100% Reinforcement	0.253	0.253	0.253	0.253					
0.5"	2"	0.3"	0.3"	Root	Web Only	0.453	0.459	0.453	0.459	0.440	0.439	0.438	0.439	0.440
					Web + 80% Reinforcement	0.441	0.440	0.441	0.440					
					Web + 100% Reinforcement	0.440	0.439	0.440	0.439					
0.5"	2"	0.5"	0.5"	Root	Web Only	0.895	NA	0.895	NA	0.586	0.585	0.575	0.585	0.592
					Web + 50% Reinforcement	0.594	0.608	0.594	0.608					
					Web + 70% Reinforcement	0.585	0.592	0.585	0.592					
					Web + 80% Reinforcement	0.582	0.587	0.582	0.587					
					Web + 100% Reinforcement	0.578	0.580	0.578	0.580					
0.5"	2"	0.2"	0.2"	~1/4 Point Thickness	Web Only	0.417	0.374	0.417	NA	0.362	0.359	0.360	0.364	0.367
					Web + 33% Reinforcement	0.362	0.360	0.362	0.367					
					Web + 50% Reinforcement	0.360	0.359	0.360	0.361					
					Web + 80% Reinforcement	0.359	0.358	0.359	0.359					
					Web + 100% Reinforcement	0.358	0.358	0.358	0.358					
0.5"	2"	0.1"	0.2"	Surface (Top Toe of Reinforcement)	Web Only	0.417	0.374	0.417	NA	0.412	0.365	0.371	NA	0.412
					Web + 50% Reinforcement	0.412	0.373	0.412	NA					
					Web + 80% Reinforcement	0.411	0.372	0.411	NA					
					Web + 100% Reinforcement	0.411	0.372	0.411	NA					
1"	2"	0.1"	0.2"	Surface (Top Toe of Reinforcement)	Web Only	0.411	0.372	0.411	NA	0.411	0.364	0.370	NA	0.412
					Web + 50% Reinforcement	0.410	0.372	0.410	NA					
					Web + 80% Reinforcement	0.410	0.372	0.410	NA					
					Web + 100% Reinforcement	0.409	0.372	0.409	NA					
0.5"	2"	0.1"	0.2"	Surface (Middle of Reinforcement)	Web Only	0.417	0.374	0.417	NA	0.417	0.367	0.417	NA	0.417
					Web + 50% Reinforcement	0.412	0.373	0.412	NA					
					Web + 80% Reinforcement	0.411	0.372	0.411	NA					
					Web + 100% Reinforcement	0.411	0.372	0.411	NA					

A.2 T and Corner Joints Loaded Perpendicular to Weld

T and corner joints loaded perpendicular to the weld and flange were evaluated for critical flaw sizes considering fatigue loading and fracture. Since the stress in these members is perpendicular to the weld, stress concentrations occur due to the geometry. Two-dimensional finite element analysis was performed to evaluate the stress concentration for various T and cruciform geometries. It should be noted that this 2-D analysis was only performed to determine the SCF and not to explicitly evaluate the flaws.

The T weld geometry in these models had a loaded plate located on only one side of the supporting plate. An example of the deformed shape of this geometry is shown in Figure A-5. The thickness of the loaded plate and supporting plate were varied from 0.5" to 4". Stress concentration occurs at the toes of the T weld. For simplification, the toe at the loaded plate will be referred to as the "top toe" and the toe at the supporting plate will be referred to as the "bottom toe". To evaluate the stress concentration factors, the stress was plotted along a path through the thickness of the loaded plate along the top and bottom toes as shown in Figure A-6.

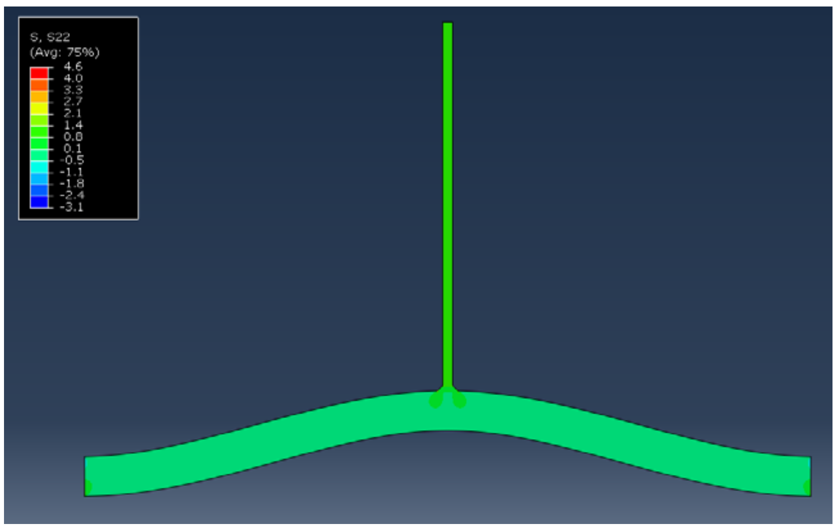

Figure A-5. T Weld Loaded Perpendicular Deformed Shape

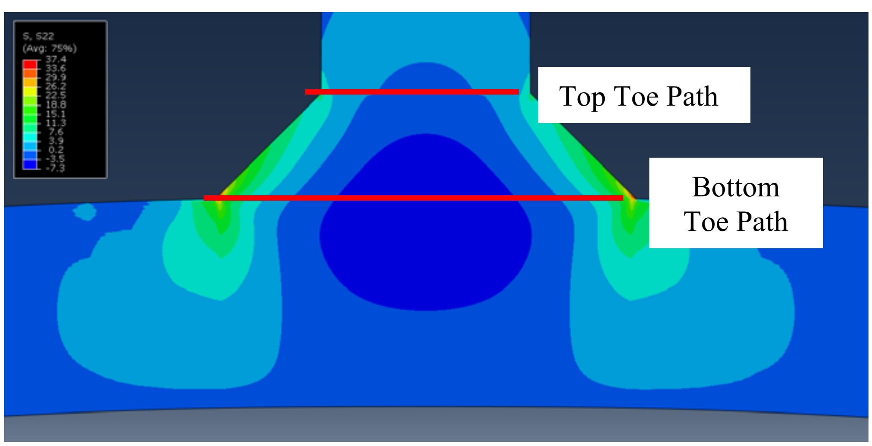

Figure A-6. T Weld Loaded Perpendicular Stress Measurement Paths

The axial stresses along these paths are plotted in Figure A-7 for each T weld geometry. The maximum stress occurs at the toes of the weld and varies greatly based on the stiffness of the supporting plate. Since the same unsupported length was used in the supporting plate regardless of plate thickness, the 0.5” to 0.5” T joint has the least stiff supporting plate, which resulted in the greatest stress concentration at the weld toe. Although the maximum stress varied greatly depending on the stiffness of the supporting plate, all of the T welds had tensile stresses less than the applied unit tension stress (i.e., <1 ksi) in the middle portion of the weld. The point where the stresses changed from concentrated tensile stresses on the edge of the plate to decreased tensile stresses in the center of the plate was also quite consistent for all of the models. Figure A-7 shows that the stresses in the middle 68% of the weld thickness experience decreased tensile stresses compared to the applied unit tension stress or, in some cases, compressive stress.

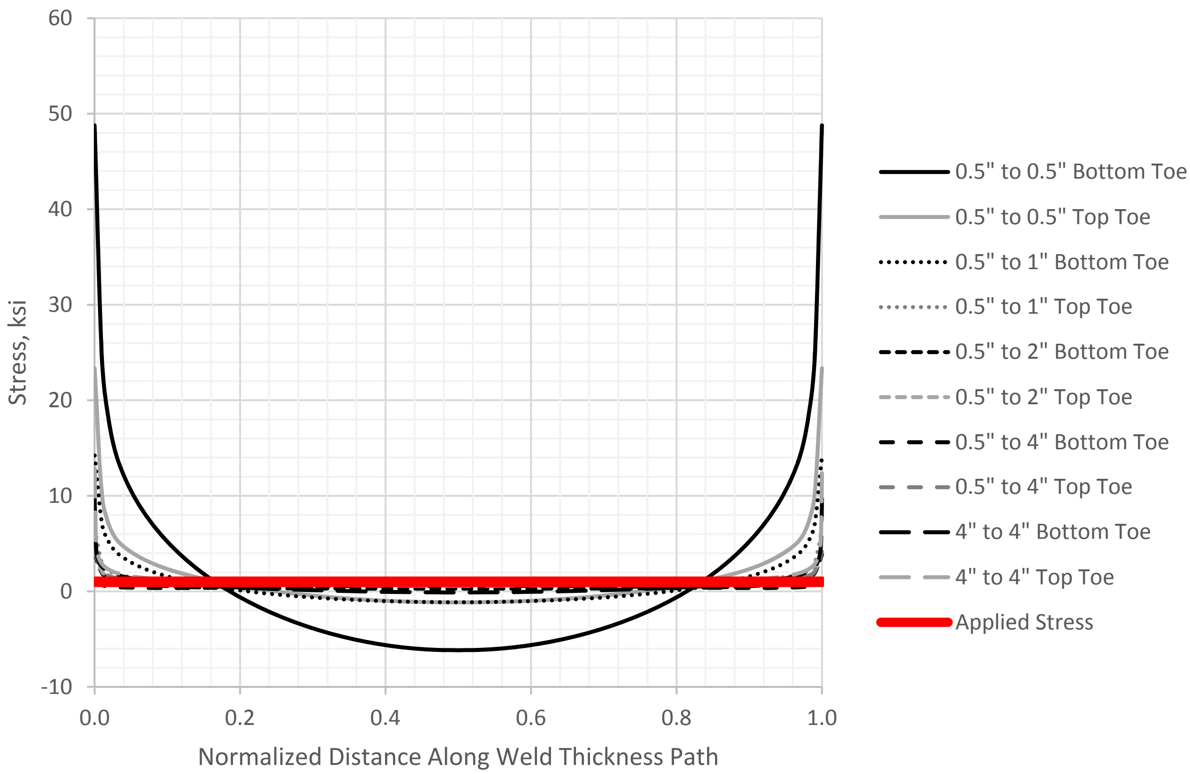

Figure A-7. Results for T Welds Loaded Perpendicular to Weld

Similar analysis was performed for cruciform welds loaded perpendicular to the weld and flange. This analysis was performed for the two geometries that bounded the results of the T weld analysis (i.e., 0.5” to 0.5” and 0.5” to 4” cruciform welds). It was found that the stress concentration at the weld toes is reduced by approximately an order of magnitude in cruciform welds when compared to T welds due to the lack of bending in the supporting plate. The stress concentration is also limited to only the top toe location as the stress at the bottom toe is less than the applied stress throughout the weld thickness. The same general trend at the top toe where the tensile stress is increased near the surface and decreased in the middle of the weld was found for cruciform welds. The region of the middle of the plate that experiences decreased tension is approximately 76% of the weld thickness.

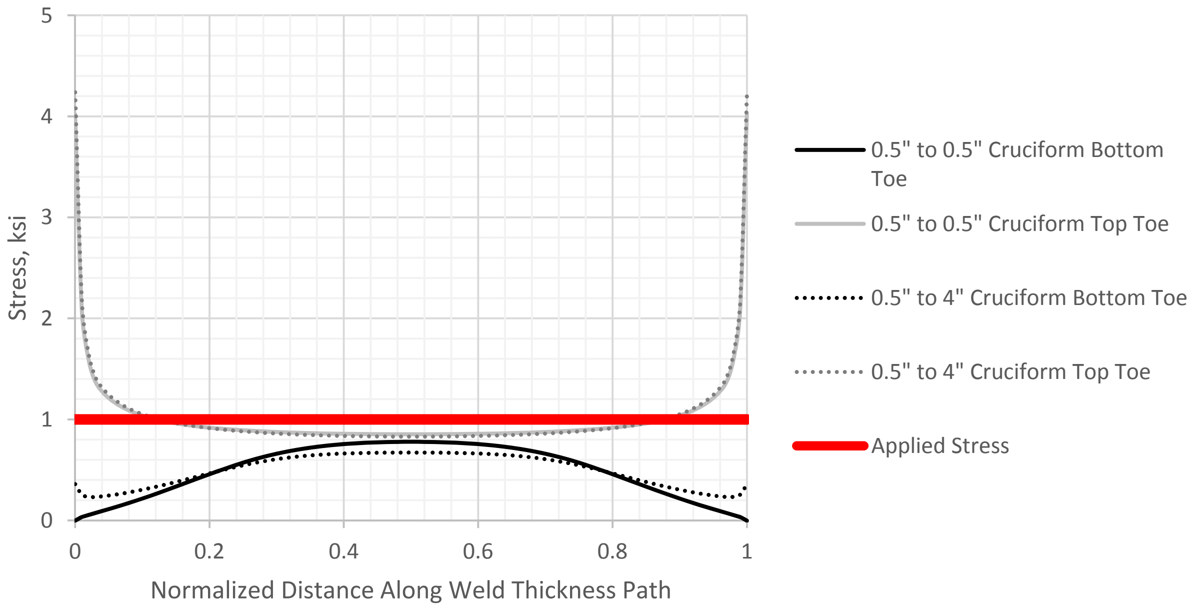

Figure A-8. Results for Cruciform Welds Loaded Perpendicular to Weld

Since the middle two-thirds of the T and cruciform welds loaded perpendicular to the weld and flange experience decreased tension compared to the applied stress. The Research Team proposes that the results for embedded flaws in equal thickness CJP butt welds be used for these welds since these results would be equivalent to assuming no stress concentration. At the surface of the welds, especially at the weld toes, there is a large stress concentration. This will result in decreased critical flaw sizes compared with equal thickness CJP butt welds.

BS 7910 includes expressions to account for the stress concentration at the toes of cruciform connections when calculating K_I for surface cracks. This is performed through a modification factor (M_k) which is multiplied by the classical flat plate K_I solution to estimate K_I with the stress concentration. This modification factor was compared to a computationally developed modification factor by dividing the K_I values from 2D finite element models in ABAQUS with toe cracks in cruciform connections by the classical flat plate K_I value. The BS 7910 solution was found to be conservative, but good correlation was found for most geometries and toe crack lengths. The modification factor from the simplified BS 7910 expression was within 12% of the value calculated from the finite element models in all cases.

While the BS 7910 modification could be used to calculate a critical crack size for surface cracks in cruciform joints, it depends on the thickness of both the through plate and loaded plates. It is also not valid for non-cruciform T welds since the stress concentration depends on the stiffness of the supporting plates in this case. This is similar to the complexity involved in determining the stress concentration at the welded connection to a bolted base plate (e.g., high mast light towers [1]–[3]). There is not currently an expression in BS 7910 for toe cracks in non-cruciform T welds. Further, as shown previously these welds experience very high stress concentrations at the weld toes which will greatly diminish the critical crack sizes. Due to these reasons and as described previously, the Research Team recommends that more stringent acceptance criteria be in place for detected surface and near surface flaws in T and corner welds (cruciform and non-cruciform) loaded perpendicular to the weld and flange.

In addition to the analysis of the stress profile through the welds, additional investigation was performed to compare the results from previous studies which had developed K_I solutions for partial joint penetration (PJP) in cruciform connections to the FE analysis results to determine which were better suited for the evaluation. Frank [4] developed an equation for the fatigue strength of fillet welded cruciform joints which have a PJP root flaw. In addition, BS 7910 includes another expression for the same condition. Both of these expressions were compared to the finite element results from two-dimensional models of various cruciform connection geometries. It was found that both expressions were within 6% of the results from the finite element models. It was decided to use the BS 7910 expression to determine critical crack sizes of PJP conditions in cruciform joints since it provided slightly better correlation to the ABAQUS results and is part of a modern FFS acceptance criteria. However, it is interesting to note that the Frank and Fisher approach, developed over 35 years ago yielded very accurate estimates.

The fatigue and fracture conditions for various cruciform connections were investigated for the critical size of PJP using an Option 1 approach and combining the “Extended Embedded Flaws in Plates” reference stress solution from Annex P and the “Weld Root Flaws in Cruciform Joints” K_I solution from Annex M of BS 7910. The resulting critical flaw size was found to typically exceed the geometry limits on the crack height to weld width ratio (2a/W) imposed in the BS 7910 solution. The solution is limited to 2a/W ratios between 0.1 and 0.7, but the critical flaw size was often too small (i.e., 2a/W < 0.1) for thick web plates, high grades of steel, low fracture toughness, or high stress ranges. The results of the critical flaw sizes for the combined fatigue and fracture analysis are shown in Table A-2, with the results which were outside the geometry limit denoted as “NA”.

Table A-2. Critical Flaw Sizes for PJP in Cruciform Connections

Fracture Toughness		Kc=50 ksi√in				Kc=75 ksi√in					
Yield Strength		Grade 36 - 50		Grade 70 - 100		Grade 36 - 50		Grade 70 - 100		Grade 36 - 100	
Fatigue Stress		≤ 4 ksi	≤ 5 ksi	≤ 4 ksi	≤ 5 ksi	≤ 4 ksi	≤ 5 ksi	≤ 4 ksi	≤ 5 ksi	≤ 7.5 ksi	≤ 8 ksi
Web Plate Thickness	**Weld Size**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**	**Flaw Height**
0.5"	0.25"	11/64"	11/64"	NA	NA	11/32"	15/64"	7/64"	7/64"	7/64"	3/32"
1"	0.375"	11/64"	11/64"	NA	NA	11/32"	7/32"	NA	NA	NA	NA
1"	0.5"	NA[1]	NA	NA	NA	25/64"	1/4"	NA	NA	NA	NA
1.5"	0.5"	NA	NA	NA	NA	11/32"	NA	NA	NA	NA	NA
2"	0.625"	NA	NA	NA	NA	11/32"	NA	NA	NA	NA	NA

Notes:

1. Not Applicable – does not meet the geometry limits in BS 7910 solution

Unlike the embedded flaws in the equal thickness CJP butt welds which were assumed to have an elliptical shape and, thus, had a limiting flaw length as well as height, the PJP was assumed to extend the full length along the weld axis in the BS 7910 solutions and, thus, only had a limiting flaw height. As can be seen, most combinations of web plate thickness, weld size, grade of steel, stress range, and fracture toughness resulted in critical flaw sizes which were outside the limits of the BS 7910 solutions. For those that did result in an acceptable result, the critical flaw sizes are much larger for PJP in a cruciform connection than embedded flaws in an equal thickness CJP butt weld. This is likely due to the combination of the increased thickness from the weld reinforcement and reduced stress in the center of the plate due to the stress concentration at cruciform joints. It should be noted that the critical flaw sizes for embedded flaws in an equal thickness CJP butt weld were developed by assuming the embedded flaw was located at the ¼ point of the plate thickness while the PJP solutions in BS 7910 assume that the flaw is centered on the root of the weld.

The use of the critical flaw sizes from the equal thickness CJP welds seem to be conservative for PJP flaws in cruciform connections. Therefore, the equal thickness butt weld criteria could be applied to embedded flaws, such as lack of penetration, in cruciform connections. Inspection of these joints using ultrasonic methods may also be more difficult due to the limited access and the additional complexity in the geometry. During the literature review, it was determined that radiographic testing cannot be used as a supplemental inspection method. Therefore, the likelihood of undersizing or missing PJP flaws in cruciform joints may be greater than embedded flaws in equal thickness CJP butt welds, and additional conservatism in the critical flaw sizing may help to limit the acceptance of flaws greater than the true critical flaw size.

A.3 List of References

[1] S. Roy, Y. C. Park, R. Sause, J. W. Fisher, and E. J. Kaufmann, "NCHRP Web-Only Document 176: Cost-Effective Connection Details for Highway Sign, Luminaire, and Traffic Signal Structures," Washington, DC, 2011.

[2] M. K. Warpinski, R. J. Connor, and I. C. Hodgson, "Influence of Flexibility on the Fatigue Performance of the Base Plate Connection in High-Mast Lighting Towers," *J. Struct. Eng.*, vol. 136, no. 3, pp. 324–329, Mar. 2010.

[3] J. H. Hall and R. J. Connor, "Influence of Base Plate Flexibility on the Fatigue Performance of Welded Socket Connections," *J. Struct. Eng.*, vol. 134, no. 6, pp. 911–918, Jun. 2008.

[4] K. H. Frank and J. W. Fisher, "Fatigue Strength of Fillet Welded Cruciform Joints," *Journal of the Structural Division*, vol. 105, no. 9. pp. 1727–1740, 1979.