Determination of Weld Loads and Throat Requirements Using Finite Element Analysis with Shell Element Models — A Comparison with Classical Analysis

Weld size requirements based on throat shear against electrode allowables were calculated with loads derived from FEA shell element results

BY M. A. WEAVER

ABSTRACT. Finite element analysis (FEA) has become a practical method of predicting stresses and deflection for loaded structures. FEA accurately identifies the load path, which can be difficult using classical analysis with complex structures. FEA shell element models are effective for predicting loads in weldments fabricated from plate, sheet, structural shapes and tube. The formulation used for a finite element shell model is that of full penetration welds at every joint. Although the loads carried through joints are calculated by FEA, they are not readily presentable. This article presents a method to derive the loads at weld joints from the stress results of FEA shell element models. Additionally, using the calculated weld loads, weld throat stresses or size requirements are calculated using classical methods.

Introduction

Most common basic FEA packages are suitable for this analysis. COSMOS/M was used for the examples here. With its parametric command files, design variations are easily evaluated. With any FEA package, accurate load estimation depends on the quality of the model built by the analyst.

As presented, this method is standard classical weld stress analysis, except that the forces on the weld joint are determined using FEA. The forces through the weld are divided by the weld throat area and compared to the shear allowable of the electrode material.

The benefits of utilizing this method are as follows:

- Accurate determination of weld loads including distribution of weld loads along the joint. The weld joint loads are resolved at each FEA node of the joint in the model. This is useful for prediction of both static failure and fatigue failure.
- Rapid determination of weld throat requirements or stress levels from a solved FEA model. The process of extracting weld loads and determining throat requirements or stress levels can be highly automated.
- Shear loads induced by mismatch of lateral deflection due to restraint/Poisson effects are included in the calculated loads. These loads are often ignored with classical analysis.
- An estimate of the ductile reserve of the joint with respect to the hydrostatic load state is available. This has been proposed as a cause of non-ductile failure of weld joints (Ref. 1). Although not performed in the implementation presented, information useful for this evaluation is obtained. Investigation is ongoing in this area.

There is room for improvement in failure prediction of fillet and partial penetration welds and research is ongoing at many sites. Using FEA, the loads at a weld joint can easily be resolved into directions associated with the weld joint. From this, stress states at the root and toe of the weld due to applied loads can be predicted. With this information, fracture initiation may be better modeled and predicted. This would seem a fruitful area for research. With more accurate prediction and classification of failure resistance, the fabrication cost for a given structural reliability can be reduced.

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KEY WORDS

Finite Element Analysis
Fatigue/Fracture
Loaded Structures
Static Strength
Throat Requirements
Weld design
Throat Shear

Implementation

For fillet and partial penetration groove welds, the criteria used for sizing welds is to divide the load transmitted (traction) through the weld by the minimum throat area and compare that value with the electrode shear allowable. (See Appendix for a description of this criteria and the associated safety factors.)

The applicability of this method for single-sided welds where the weld root sees tension is subject to special considerations and limitations that are discussed.

A welded T-joint and a lap-joint are analyzed for demonstration. First, the weld for a T-joint of a fabricated steel bracket is analyzed. The results will be compared to a classical analysis of the same joint. Finally, the weld of a lap joint for an aluminum fall arrest lug is sized.

The method is presented in four steps:

1) From the Finite Element Analysis, list to a file the stress tensor at each node of a weld joint in one terminated part for both the top and bottom stresses.

2) Extract the stress tractions through the weld at each weld joint node for both element faces (top and bottom) by multiplying the joint normal unit vector into the shell element top and bottom stress tensors.

3) From the tractions and the part thickness, solve for the normal load (lb/in.), bending load (in.-lb/in.) and joint shear (lb/in.) at each node.

4) From the formulas appropriate for the weld joint (double-sided fillet, double-sided partial penetration groove, or single-sided welds — fillet or partial penetration with limitations) and the

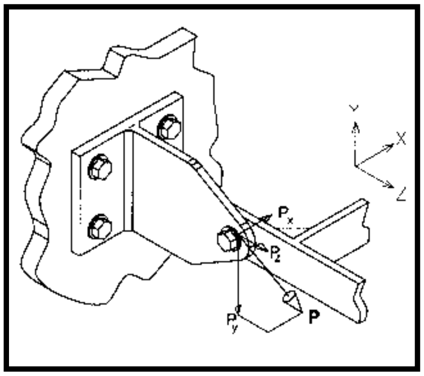


Fig. 1 — Depiction of bracket loads.

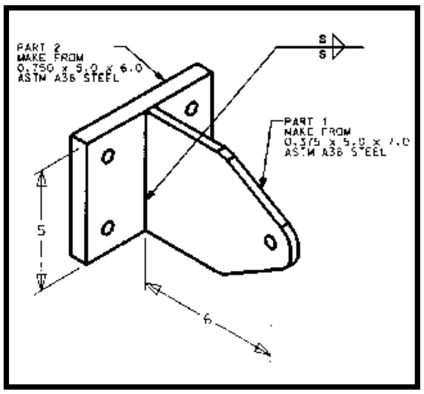


Fig. 2 — Fabrication detail of T-bracket.

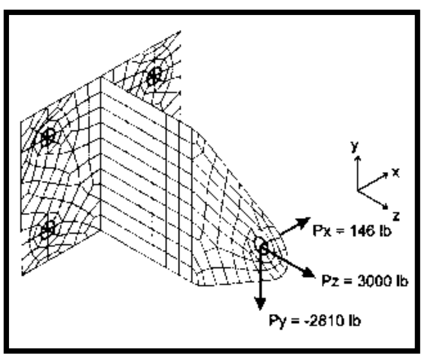


Fig. 3 — Finite element model of T-bracket.

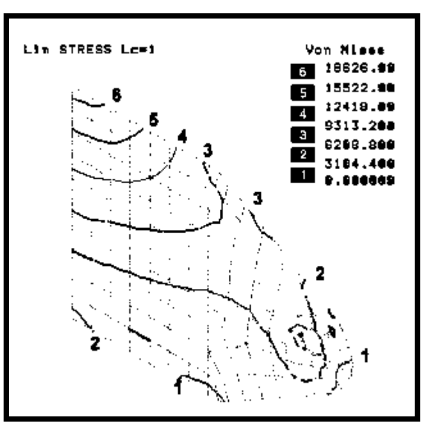


Fig. 4 — Von Mises stress results plotted on part one of bracket only.

throat size, calculate the weld stress. Conversely, from the desired stress level, solve for the required throat size.

Weld Size Requirement for a Steel T-Joint Bracket

Figure 1 depicts a welded steel bracket loaded vertically and horizontally. Figure 2 shows a fabrication detail of the bracket where the size of the double-sided fillet weld is S. This T-joint is subject to bending in both the strong and weak directions, tension and shear.

This bracket is made from ASTM A36 steel and welded with matching E60XX electrode. The required safety factor against ultimate failure is 3.0, so the allowable weld throat "shear" stress used to size the joint was 13.2 ksi [$^1/_{3.0} \cdot$ (60 ksi)(0.3)(2.2)], see Appendix. The objective of this analysis is to determine the weld size, S, that results in a maximum throat stress of 13.2 ksi.

The loads in the weld are easily determined using classical analysis for this bracket. The weld size requirements will be calculated first, using the loads from finite element analysis and then will be compared to the results obtained using classical analysis.

With finite element analysis results, care must be taken when identifying the stresses (loads) at weld joints or other discontinuities. Figure 3 depicts a finite element model of the T-joint under investigation. Figure 4 shows the finite element stress results in part 1 (the stem of the "t" shown in Fig. 2) of the joint. Figure 5 shows stress results for the assembly. Comparison of Figs. 4 and 5 shows that the displayed stress in part 1 near the weld joint are different in the two plots from the same analysis. The elements for part 1 were put on a separate "set" or "layer" and the nodal stresses plotted in Fig. 4 are based only on the stresses in part 1. This is the most accurate representation of the stress state of part 1. The stresses at the joint of parts 1 and 2 shown in Fig. 5 are based on the calculated average of the stresses in both parts at the joint. The stresses shown in Fig. 5 are unrealistically low in part 1 and unrealistically high in part 2 at the joint because of this.

Nodal stress values are calculated as the average stress of all of the *active* elements in contact with each node. At discontinuities such as weld joints, the plotted stress is the average of the stress in each side of the discontinuity. To identify the stresses (and loads) in a part at a discontinuity (weld joint), the stresses must be calculated for one side of the discontinuity by activating results for the area of interest only, as is shown by the comparison of Figs. 4 and 5.

The four steps are described and applied as follows:

Step 1: List to a file the stress tensor at each node of a weld joint in one terminated part for both the top and bottom stresses.

Activate the elements for one terminated part of the of the weld joint and the nodes of the joint only as shown in Fig. 7. For lap and T-joints, there is only one terminated part — Fig. 6. For corner and butt joints, both parts terminate and either part may be selected.

Some weld joints, such as a flare-V-groove between two adjacent rectangular steel tubes, have no terminated part. One solution is to chamfer or round the tube corners in the finite element model and model the weld itself as shell elements connecting the tube walls similar to the actual weld. These weld elements then become the terminated part.

List to text files the stresses in the *top* and the *bottom* of terminated part at the active nodes — Fig. 8A, B. Top and bottom are terms used to distinguish the element sides; they have no significance with respect to up or down. The top face of an element is the face where the node sequence is counterclockwise. Figure 8D is a list of top stresses at the nodes of the weld joint with the elements for both parts 1 and 2 active — it is incorrect for extracting weld loads and corresponds to the stress plot of Fig. 5.

In step 2, a coordinate system aligned with the weld joint in the terminated part is introduced. Depending on the method of implementation, it may be beneficial to list the top and bottom stresses in a coordinate system aligned with the weld joint. Coordinate system 3, shown in Fig. 7, was used for this example. In addition, the stress tensor mathematics as presented in this step, are often not taught in undergraduate engineering classes; rather, the concepts are taught using Mohr's circle. Lemaitre, *et al.* (Ref. 2), offers a good reference for stress tensor mathematics, as well as failure theory.

Step 2: Extract the stress tractions resulting from loads transmitted through the weld joint at each weld joint node for both element faces.

To determine the loads transmitted through the weld joint, as opposed to loads that run alongside the weld, the "weld joint normal" of a selected terminated part is identified — Fig. 6.

For this purpose, the weld joint normal is defined as the direction perpen-

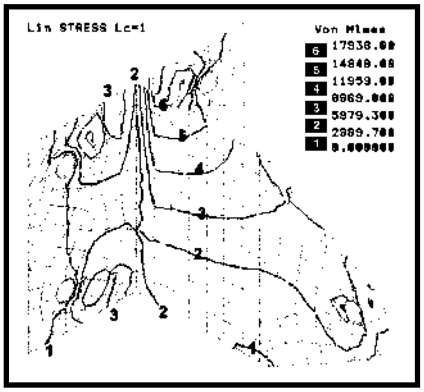


Fig. 5 — Von Mises stress results plotted for the entire bracket.

WELD JOINT STRESS TENSOR LISTS AND ANALYSIS RESULTS

A) STRESSES ON THE "TOPS" OF THE SHELL ELEMENTS OF PART 2 AT THE WELD JOINT:

* Selection List 1 Load case 51 Top Face Layer 1 Cs = 3

Node	SIG_X	SIG_Y	SIG_Z	TAU_XY	TAU_XZ	TAU_YZ
340	3.753e-010	4.468e+003	1.956e+004	3.848e+002	-3.902e+002	-2.530e+003
348	1.321e-009	3.808e-003	1.647e+004	3.493e+002	1.105e+002	-2.029e+003
356	6.072e-009	3.715e-003	1.491e+004	1.948e+002	2.821e+002	-1.832e+003
:	:	:	:	:	:	:

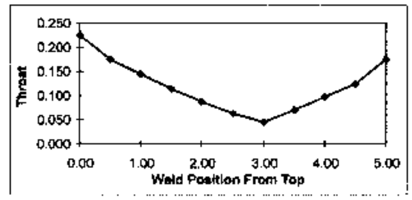
B) STRESSES ON THE "BOTTOMS" OF THE SHELL ELEMENTS OF PART 2 AT THE WELD JOINT:

* Selection List 1 Load case 51 Bottom Face Layer 1 Cs = 3

Node	SIG_X	SIG_Y	SIG_Z	TAU_XY	TAU_XZ	TAU_YZ
340	3.753e-010	2.531e+003	7.884e+003	3.848e+002	-3.902e+002	-1.210e+003
348	1.321e-009	1.132e+003	3.602e+003	3.493e+002	1.105e+002	-1.186e+003
356	6.072e-009	3.181e+001	4.527e+002	1.948e+002	2.821e+002	-1.470e+003
:	:	:	:	:	:	:

C) RESULTS OF WELD THROAT REQUIREMENT CALCULATIONS:

tb_0750.xls
Tue Mar 18 14:11:28 1997
Joint Normal (X, Y, Z): (0,0,1)
Thickness: 0.375
Welded Both Sides, Fillet
Allowable Stress: 13200
Min Weld Throat, t: 0.224 at node 340
Min Fillet Size, S: 0.317 at node 340
Weld Load Output:



El/Nd	Normal_load (lb/in)	Bending_Load (in-lb/in)	Shear_load (lb/in)	Min Throat (in)
340	5145.75	136.828	716.354	0.224
348	3763.5	150.797	604.235	0.175
356	2880.51	169.421	628.098	0.145
:	:	:	:	:

D) INCORRECT STRESSES IN THE NODES OF THE JOINT – AVERAGE STRESS OF PARTS 1 & 2:

* Selection List 6 Load case 51 Top Face Layer 1 Cs = 3

Node	SIG_X	SIG_Y	SIG_Z	TAU_XY	TAU_XZ	TAU_YZ
340	6.869e+003	2.137e+003	6.520e+003	8.434e+001	-8.252e+001	-4.544e+002
348	7.089e+003	2.055e+003	5.490e+003	1.225e+002	1.178e+002	-2.394e+002
356	5.910e+003	2.002e+003	4.970e-003	3.922e+001	1.988e+002	-8.162e+001
:	:	:	:	:	:	:

Fig. 8 — Tabulated FEA and weld calculation results.

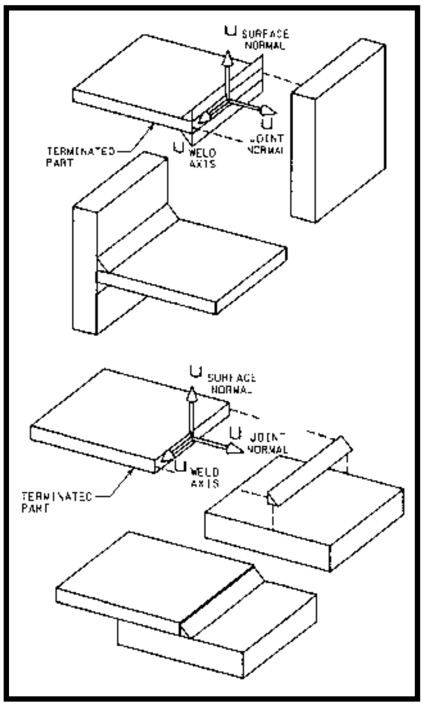


Fig. 6 — Weld joint coordinate system of the terminated part.

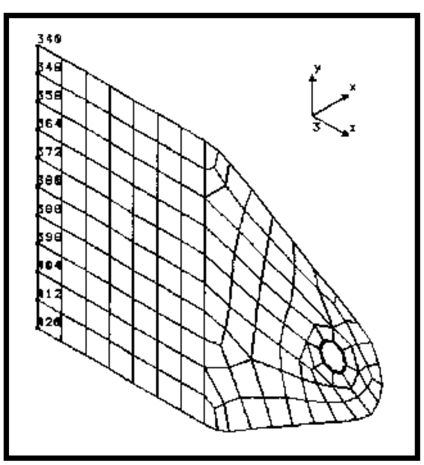


Fig. 7 — Element and node activation for listing part stresses at weld joint.

dicular to the plane formed by the axis of the weld and the normal (perpendicular) direction of the surface of the terminated part at the node of evaluation — Fig. 6. In mathematical terms,

$\mathbf{u_s}$ ≡ surface normal unit vector
$\mathbf{u_w}$ ≡ weld axis unit vector
$\mathbf{u_j}$ ≡ weld joint normal unit vector
$\mathbf{u_j} = \mathbf{u_s} \times \mathbf{u_w}$.

The stress traction vector, **T**, acting on the plane defined by the weld joint normal vector, $\mathbf{u_j}$, results from loads transmitted through the weld joint. It is extracted by multiplying the weld joint normal, $\mathbf{u_j}$, into the stress tensor, σ.

$$\mathbf{T} = [\sigma]\mathbf{u_j}$$

In expanded notation, the expression is

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \begin{Bmatrix} u_{j_x} \\ u_{j_y} \\ u_{j_z} \end{Bmatrix}$$

One way to resolve the traction into weld joint coordinate system, (s, w, j) is

$$\begin{Bmatrix} T_s \\ T_w \\ T_j \end{Bmatrix} = \begin{Bmatrix} \mathbf{T} \bullet \mathbf{u_s} \\ \mathbf{T} \bullet \mathbf{u_w} \\ \mathbf{T} \bullet \mathbf{u_j} \end{Bmatrix}$$

where T_s represents the shear acting perpendicular to the terminated part, T_W represents the weld joint longitudinal shear, and T_j represents the tension or compression in the terminated part through the weld joint.

For a lap joint, T_j also represents the transverse shear. If the joint is loaded in plane, ($T_s = 0$) and there is a transverse component to the load ($T_j \neq 0$), AWS D1.1, *Structural Welding Code — Steel* (Ref. 3) has alternate increased weld load allowables based on transverse/longitudinal load orientation. This transverse/longitudinal orientation is available with these results. Caution should be exercised, however, because although joints with transverse in-plane loading have greater strength, they have less ductility and energy absorption than longitudinally-loaded joints. Refer to AWS D1.1 Fig. C26 Commentary (Ref. 3).

For the T-bracket, the stresses are listed in coordinate system 3, which has the z-axis aligned with the weld joint normal. The preceding analysis simplifies as

$$\mathbf{u_j} = \mathbf{u_z}$$

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix} = \begin{Bmatrix} \sigma_{xz} \\ \sigma_{yz} \\ \sigma_{zz} \end{Bmatrix}$$

For node 340 of the T-joint (refer to Fig. 8), the top and bottom stress tractions through the weld joint are

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix}_{\frac{TOP}{340}} = \begin{bmatrix} 0 & 384.8 & -390.2 \\ 384.8 & 4,468 & -2,530 \\ -390.2 & -2,530 & 19,560 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}$$

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix}_{\frac{TOP}{340}} = \begin{Bmatrix} -390.2 \\ -2,530 \\ 19,560 \end{Bmatrix}$$

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix}_{\frac{BOT}{340}} = \begin{bmatrix} 0 & 384.8 & -390.2 \\ 384.8 & 2,531 & -1,210 \\ -390.2 & -1,210 & 7,884 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}$$

$$\begin{Bmatrix} T_x \\ T_y \\ T_z \end{Bmatrix}_{\frac{BOT}{340}} = \begin{Bmatrix} -390.2 \\ -1,210 \\ 7,884 \end{Bmatrix}$$

The extraction of stress tractions resulting from loads transmitted through the weld joint is complete.

Step 3: From the tractions and the part thickness, solve for the normal load (lb/in.), bending load (in.-lb/in.), and joint shear (lb/in.).

The equations used to determine part top and bottom stress due to bending, normal and shear loads are easily reversed to determine bending, normal and shear loads from the stresses. For node 340, the calculation is presented in Fig. 9.

This calculation determines the load per inch of weld joint. Columns 2–4 in Fig. 8C show the results of these calculations for the T-joint of the steel bracket. For comparison with classical analysis, the values for joint normal load, P and joint shear load, V are divided by 2 to obtain load per inch of weld, since there are two welds in the joint.

Step 4: From the formulas appropriate for the weld joint and the desired stress level, solve for the required throat size.

Three weld configurations are considered: 1) double-sided fillet weld, 2) double-sided partial penetration groove weld and 3) single-sided welds — fillet or partial penetration groove welds. The expressions for weld throat stress are different for each of these three and cover most cases.

The analysis will be presented first by developing the expression for weld throat stress given the weld loads, the joint geometry and the weld size. Next, the solution for the weld throat size given the allowable stress will be described. Finally, the weld size requirements for the steel bracket T-joint will be evaluated.

Weld Section Properties

Figure 10 presents the expressions used for weld area and section modulus about the weld axis for the three categories considered.

Double-Sided Fillet Weld

The section modulus for the double-sided fillet weld is unique in this presentation because it is calculated assuming the centroid of the of the weld throat on each side is at the part outer edge instead at the physical centroid of the throat — Fig. 10. This is drawn from the classical method of treating the weld as a line to develop properties (Ref. 4).

When developing the properties for a weld group using classical analysis, the method of treating a weld as a line does not differ much from calculating the properties using the actual weld centroid because compared to the overall geometry, the distance from the weld centroid to the part wall is small. Treating the weld as a line results in a much simpler calculation With a double-sided fillet weld of a plate in a T-joint, however, the difference between the two methods is significant.

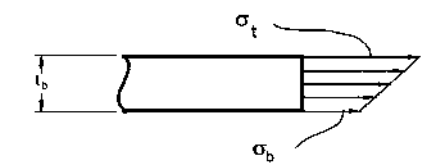
The resulting calculated stresses from bending loads in double-sided fillet welds treated as lines is more conservative. There is a dearth of references on this subject — most published investigations of fillet weld strength involve lap joints loaded in plane (Ref. 5). In the absence of illumination, the safer path was chosen.

Double-Sided Partial Penetration Groove Weld

The section modulus for a double-sided partial penetration groove weld is calculated using the geometrical section of the weld throat. The formulation shown is for the simple case of a weld with the weld size on both sides of the joint being equal and no fillet weld reinforcement.

Single-Sided Welds

No differentiation is made between fillet and partial penetration groove welds for analyzing single-sided welds. The section modulus for a single weld is



Resolution of Weld Loads, Node 340:

$t_b = \frac{3}{8} \cdot \text{in.}$ Base Material Thickness

$\sigma_t = 19,560$ psi Normal Stress at Top of Joint

$\sigma_b = 7884$ psi Normal Stress at Bottom of Joint

$\tau_{zx\_avg} = -390.2$ psi Average Shear Stress in Joint

$$\tau_{yz\_avg} = \frac{-2530 \text{ psi} - 1210 \text{ psi}}{2}$$

$$\tau_{avg} = \sqrt{\tau_{zx\_avg}^2 + \tau_{yz\_avg}^2} \qquad \tau_{avg} = 1910 \text{ psi}$$

Joint Normal Load:

$$P = \frac{\sigma_t + \sigma_b}{2} \cdot t_b \qquad P = 5146 \frac{\text{lbf}}{\text{in.}}$$

Joint Bending Load:

$$M = \left| \frac{\sigma_t - \sigma_b}{2} \right| \cdot \frac{t_b^2}{6} \qquad M = 136.8 \frac{\text{in. lbf}}{\text{in.}}$$

Joint Shear Load:

$$V = \tau_{avg} \, t_b \qquad V = 716.4 \frac{\text{lbf}}{\text{in.}}$$

Fig. 9 — Load calculation for one node.

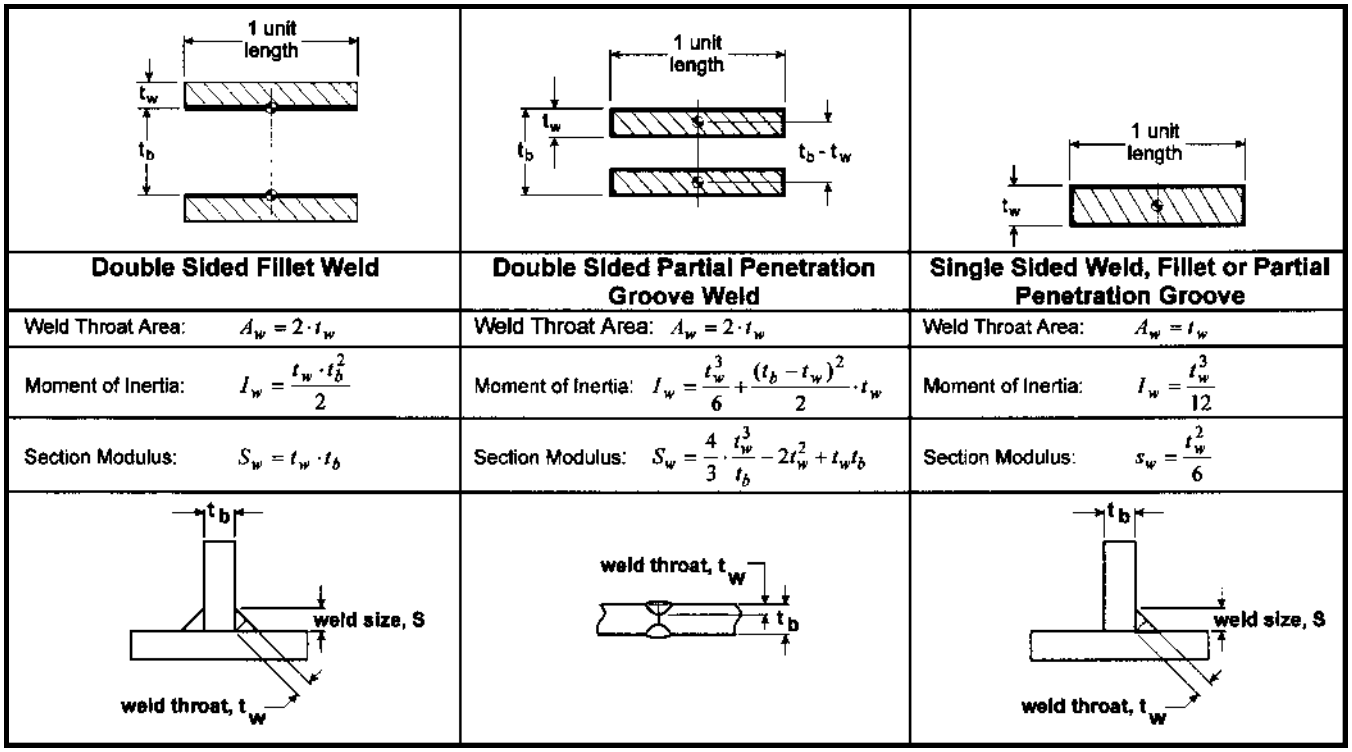


Fig. 10 — Weld section properties.

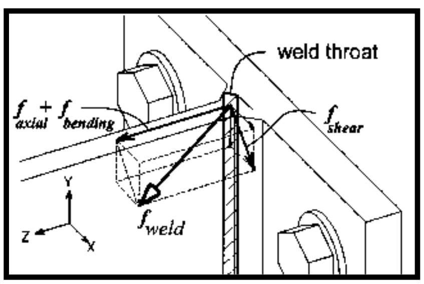


Fig. 11 — Components of weld throat stress traction.

calculated using the geometrical section of the weld throat.

Weld Throat Stress

From the weld load components determined in step three and the weld section properties for a given weld size, the weld throat stress components can be determined as follows:

Stress due to normal load:

$$f_{\text{normal}} = \frac{P}{A_w}$$

Stress due to bending:

$$f_{\text{bending}} = \frac{M}{S_w}$$

Stress due to shear:

$$f_{\text{shear}} = \frac{V}{A_w}$$

Total stress magnitude:

$$f_{\text{weld}} = \sqrt{\left(\left|f_{\text{bending}}\right| + \left|f_{\text{normal}}\right|\right)^2 + \left(f_{\text{shear}}\right)^2}$$

Refer to Fig. 11. Note in the above equation that the bending and normal stresses are combined so that their magnitudes are additive — this will always be the case on one side of the joint.

For evaluation of the weld size, the total traction magnitude is compared to the electrode shear allowable, F_a.

The calculation for the total weld throat traction just presented is of practical use for determining stress levels of existing designs. For new design, a method of calculating throat size requirements is presented.

Determination of Weld Size

Given the weld loads determined in step 3, the joint type and geometry and the allowable shear stress, there will exist a throat size where the calculated magnitude of the weld throat stress traction will equal the allowable shear stress. For double-sided fillet welds treated as lines, A_w and S_w are linear with respect to t_w, and this can be solved explicitly for the required throat size:

For the double-sided fillet weld on the steel bracket at node 340, the formulation is as follows:

$$t_{w_{\text{MIN}}} = \frac{1}{F_a} \cdot \sqrt{\left(\frac{M}{t_b} + \frac{P}{2}\right)^2 + \left(\frac{V}{2}\right)^2}$$

$$t_{w_{\text{MIN}}} = \frac{\sqrt{\left(\frac{137 \frac{\text{in. - lb}}{\text{in.}}}{0.375 \text{ in.}} + \frac{5146 \frac{\text{lb}}{\text{in.}}}{2}\right)^2 + \left(\frac{716.4 \frac{\text{lbf}}{\text{in.}}}{2}\right)^2}}{13,200 \text{ psi}}$$

$$t_{w_{\text{MIN}}} = 0.224 \text{ in.}$$

For an equal leg fillet weld, the weld size, S, is equal to the square root of 2 times the throat,

$$\begin{aligned} S &= \sqrt{2} \cdot t_w \\ &= \sqrt{2} \cdot (0.224 \text{ in.}) \\ &= 0.317 \text{ in. or } 0.32 \text{ in.} \end{aligned}$$

This is the value for S that should be used for the joint callout in Fig. 2.

Figure 8C displays the results of the above calculation for every node in the joint. Figure 12 shows a plot of the weld throat stress as a function of the weld throat size.

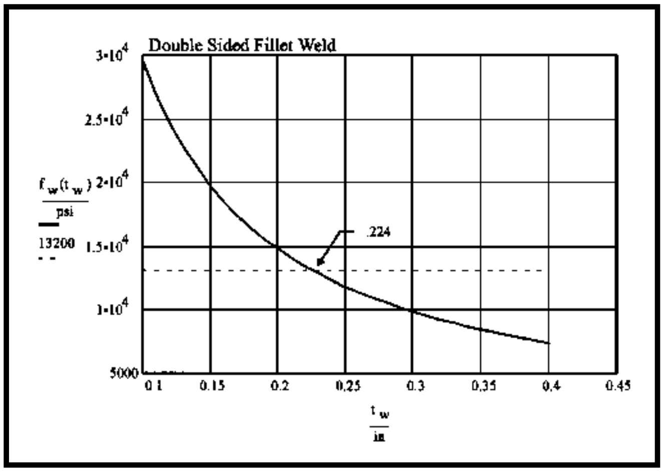


Fig. 12 — Plot of weld throat stress vs. weld throat size for souble-sided fillet weld at node 340.

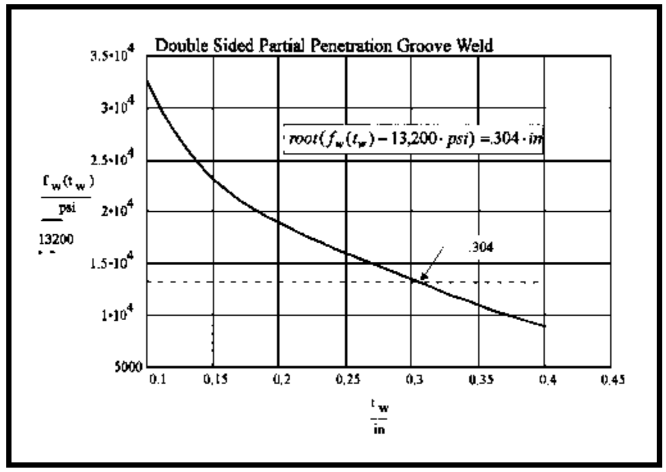


Fig. 13: — Plot of weld throat stress vs. weld throat size for double-sided partial penetration groove weld at node 340.

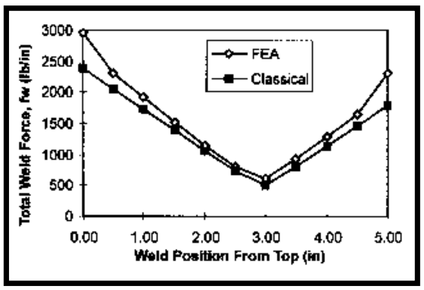


Fig. 14 — Comparison of weld loads along joint from FEA and classical calculations.

An explicit expression for a double-sided partial penetration groove weld requires solution of a sixth-order polynomial, while a single-sided weld results in a fourth-order polynomial that must be solved. Rather than pursue these, it was more expedient to implement an iterative search in the computer program. The weld throat size, t_w, is adjusted until the calculated throat traction equals the allowable shear stress for the electrode. This method is employed for both double-sided partial penetration groove welds and single-sided welds. Figure 13 shows a plot of the weld throat stress as a function of the weld throat size at node 340 of the T-joint, if it were a double-sided, partial penetration groove weld. The resulting throat size for a maximum throat traction of 13,200 psi is 0.304 in.

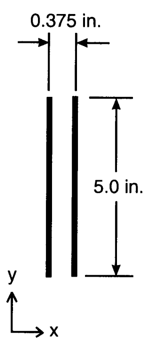
This concludes the calculation of the weld throat size of the steel bracket T-joint based on the results of finite element analysis. For comparison, the same joint is now analyzed using classical methods.

Determination of T-Joint Weld Size Using Classical Analysis

The T-joint double-sided fillet weld will be evaluated using the method of treating a weld as a line, as described by Blodgett, *et al.* (Refs. 3–5).

Refer to Figs. 2 and 3 for the joint geometry and loads. The classical calculation is as follows:

Section Properties:



$$A_w = 2 \cdot d = 2 \cdot (5\text{ in.}) = 10\text{ in.}$$

$$S_{wx} = \frac{d^2}{3} = \frac{(5\text{ in.})^2}{3} = 8.33\text{ in.}^2$$

$$S_{wy} = b \cdot d = (0.375\text{ in.})\,(5\text{ in.}) = 1.88\text{ in.}^2$$

Applied Loads:

Normal Load, P:

P = 3000 lb

Shear Load, V:

$$V = \sqrt{(146\text{ lb})^2 + (-2810\text{ lb})^2} = 2814\text{ lb}$$

Bending Load About x, M_x:

M_x = (2810 lb) (5 in.)

= 14,050 in.-lb

Bending Load About y, M_y:

M_y = (146 lb) (5 in.)

= 730 in.-lb

Weld Loads:

Normal Load, f_{normal}:

$$f_{normal} = \frac{P}{A_w} = \frac{3000\text{ lb}}{10\text{ in.}} = 300\text{ lb/in.}$$

Shear Load, f_{shear}:

$$f_{shear} = \frac{V}{A_w} = \frac{2814\text{ lb}}{10\text{ in.}} = 281\text{ lb/in.}$$

Bending Load About x, f_{bx}:

$$f_{bx} = \frac{M_x}{S_{wx}} = \frac{14{,}050\text{ in.}-\text{lb}}{8.33\text{ in.}^2} = 1690\text{ lb/in.}$$

Bending Load About y, f_{by}:

$$f_{by} = \frac{M_y}{S_{wy}} = \frac{730\text{ in.}-\text{lb}}{1.88\text{ in.}^2} = 388\text{ lb/in.}$$

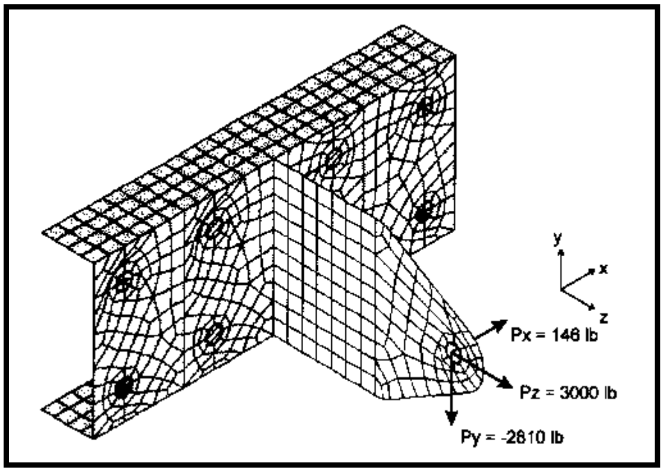


Fig. 15 — T-joint welded to matching channel.

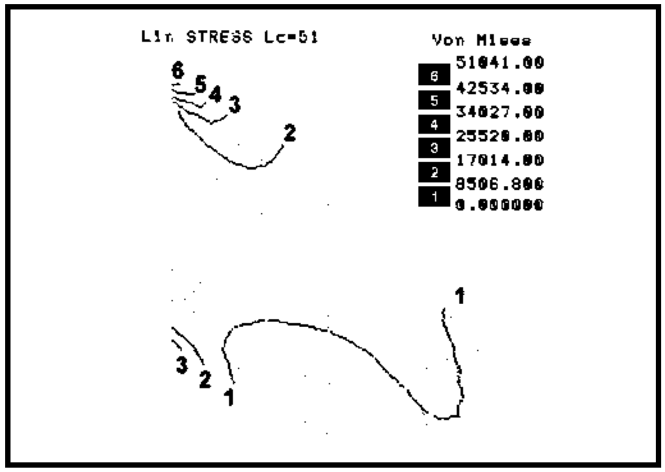


Fig. 16 — Von Mises stresses in part 1 welded to channel.

Total Weld Load, f_w:

$$f_w = \sqrt{\left(f_{normal} + f_{bx} + f_{by}\right)^2 + \left(f_{shear}\right)^2}$$

$$= \sqrt{\left(300\frac{\text{lb}}{\text{in.}} + 1690\frac{\text{lb}}{\text{in.}} + 388\frac{\text{lb}}{\text{in.}}\right)^2 + \left(281\frac{\text{lb}}{\text{in.}}\right)^2}$$

$$= 2390 \text{ lb/in.}$$

Required Weld Throat Size, t_w:

$$t_w = \frac{f_w}{F_a}$$

$$= \frac{2390 \text{ lb}}{13{,}200 \text{ psi}}$$

$$= 0.188 \text{ in.}$$

The required weld throat size as calculated using classical analysis is 20% smaller that the value calculated using the loads from the FEA. Figure 14 compares the weld loads calculated using FEA and classical analysis. The results are reasonably close. Some causes of the difference are:

1) *Poisson Effect* — Part 2 of Fig. 2 (0.75-in. thick) restrains part 1 (0.375-in. thick) from the lateral contraction/expansion associated with the Poisson Ratio, due to normal loads at the weld joint. This induces a shear load that is carried through the weld. The loads obtained from FEA account for this for f_{normal}, while it is not accounted for in the beam formulas used with classical analysis. (With the current implementation, the Poisson effect due to bending about the weld-weak axis is ignored, because the shear stresses are opposite and they cancel each other in the shear load calculation.)

2) Uneven distribution of the load path due to the bolts and the non-linear effects of out-of-plane forces on part 2.

3) End effects.

The FEA accounts for these effects, while the classical analysis used does not. The difference between these methods for this joint design is not great and this steel T-bracket is a good candidate for classical evaluation.

The finite element analysis method of determining weld loads becomes useful when estimating weld loads using classical analysis is difficult.

For a quick, simple example, Fig. 15 shows the same 0.375-in. thick part 1 bracket welded to a matching 5 x 9 lb/ft channel. By inspection, most of the applied normal and bending load will be transferred from the part 1 bracket to the channel near the channel flanges.

Figures 16 and 17 confirm this. This design is not suitable for the classical beam formulas. More advanced classical analysis similar to that presented for rectangular tubular structures (Ref. 3) or conservative assumptions would be appropriate.

Design of Single-Sided Welds

Design of single-sided welds where the root of the weld is subject to tension requires careful study of joint restraint, loading geometry and has limitations.

Figure 18 depicts a pipe welded in a T-joint loaded in bending. This is an acceptable single-sided joint with the root in tension. Figure 19 is a diagram of the joint, loading and restraint through the top section, where the single-sided weld is subject to tension. The weld in this section is not subject to severe bending, because the section of the pipe adjacent to the weld is restrained from rotating. The loading on this weld joint is similar to the weld loading on a double lap joint.

In contrast, the steel T-joint bracket under investigation — Figs. 1–5 — is not recommended for a single-sided joint without careful consideration of the applied loads and the resulting resistance to failure. The three loading directions will be considered separately.

If Px can put the root of the joint in tension and is unrestrained, no amount of deformation will take the weld out of bending and stop continued deformation. This condition has the lowest resistance against failure.

When Px puts the root of the weld in compression, the weld will not have degraded resistance based on calculated weld stresses.

The application of a tensile Pz load again puts the weld in bending with the root in tension. The bending load will be equal to the load times the distance between the centerline of the part and the weld centroid. Therefore, fillet welds will see more severe induced bending than a partial penetration groove weld. Of note with this loading is that the joint will see bending deformation only until the applied load is in line with the weld centroid.

The application of Py puts the joint in bending about its strong axis. One end of the joint will experience tension and the other will see compression. The moment from the load offset at the tensile end will induce the part to rotate so that the weld root opens, while the load offset at the compression end will induce the part to rotate so that the weld root closes. This creates a warping, twisting load in the part. A shorter, stubbier part will provide more restraint against opening the weld root at the tensile end than will a long thin part. Again, special investigation of

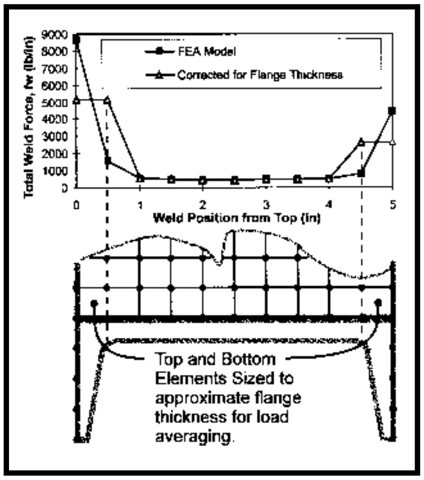


Fig. 17 — Weld loads in T-joint with channel.

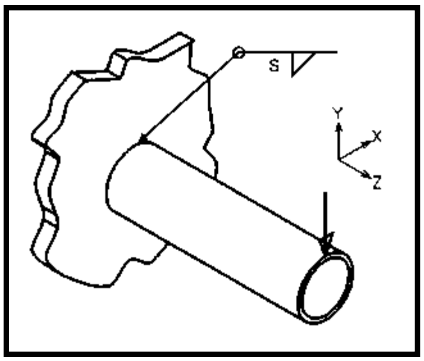


Fig. 18 — Pipe T-joint welded on one side, loaded in bending.

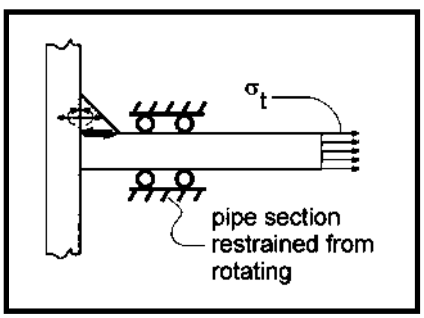


Fig. 19 — Section through top of pipe T-joint, loaded in tension.

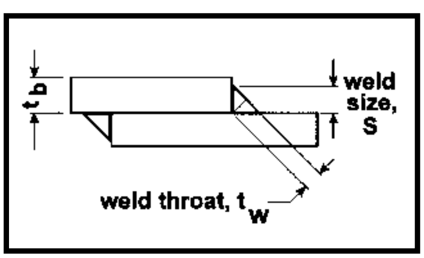


Fig. 20 — Welds of double fillet-welded lap joint are evaluated individually.

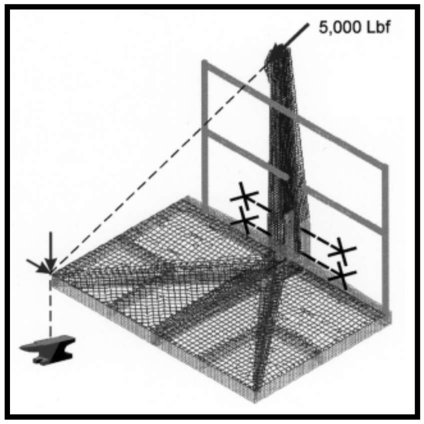


Fig. 21 — Finite element model of fall arrest platform.

the joint against the desired resistance to failure is required.

Configurations with one-sided fillet welds where the root is in unconstrained tension are good candidates for redesign.

The single-sided formulation is used for double fillet welded lap joints as shown in Fig. 20. Even though this is a double weld joint, each weld is evaluated individually

Weld Size Requirement for a Lap Joint of a Fall Arrest Lug

Figure 21 is a depiction of a fall arrest platform. This platform is designed to withstand the most severe type of fall arrest system — that of a simple lanyard allowing a maximum free-fall of six feet. OSHA (Ref. 8) stipulates by the simplest method that the structure for such a fall arrest system must withstand a lanyard load of 5000 pounds without failure.

This structure is fabricated from 5086-H112 Aluminum with 5356 electrode. The published minimum tensile strength of 5086-H112 is 31,500 psi and the published minimum shear strength for 5356 electrode is 17 ksi (Ref. 9).

There were 54 welds evaluated for 13 load cases. Ten load cases were used to evaluate fall arrest loads at various locations and three load cases were used to evaluate the floor and structure for the fatigue loading of day-to-day usage. This analysis was highly automated and numerous platform material sizing and geometry variations could be evaluated overnight with batch processing.

Weld #01 of the fillet welds in the lap joint between the fall arrest lug (part 1) and the support post side (part 4) is analyzed for demonstration — Fig. 22, Detail A. This is the inside weld between the lug (part 1) and the post side (part 4).

The geometry of this joint has some features that increase the load in this weld. Specifically, because the post is fabricated of plates with overhang of part 4 with respect to part 2, the x direction load combined with the overhang induce a bending moment in the weak direction of the single sided weld — Fig. 23. The distribution of the load transmitted through weld #01 (V14 and M14) along the joint is difficult to calculate using classical analysis. Conservative assumptions would be required, resulting in larger welds and thicker material requirements.

Special care is required when creating a finite element model of lap joints with either shell or solid elements. It must be ensured that only the nodes of the weld joint in the two parts are merged (joined). The nodes on the faying surfaces that are not part of the weld joint must be removed from the selection set or layer before merging is performed — Fig. 24.

For weld 1, the terminated piece is part 4, the post side (Fig. 22). Coordinate system 15 was used to evaluate the loads in weld 1 — Fig. 25. The elements of part 4 and the nodes of weld 1 are shown in Fig. 26. The results are plotted in Fig. 27.

Finite element analysis provided a reasonable estimation of loads for this analysis that would have been difficult to estimate using classical methods. Also, FEA was of value determining the configuration of the lug to avoid hot spots at the top and bottom.

Intermittent Welds

On the first cut when modeling structures with intermittent welds, it is expedient to merge (connect) all of the nodes along the weld joint. The results of the weld analysis will predict a required weld size for a continuous weld. This gives the designer the distribution of the load along the joint for refinement of weld deposit requirements. If the joint is uniformly loaded and designed against static failure, it may be reasonable to use this result to size the intermittent weld by providing the same throat area as the predicted continuous weld.

On the other hand, if the loads exhibit non-uniform distribution or the structure is to be cyclically loaded, it is recommended that further models be built with the nodes merged at only the locations of welded connection.

Applicability and Limitations

This form of design evaluation is based on elastic behavior only. Depending on the expected failure mode and the

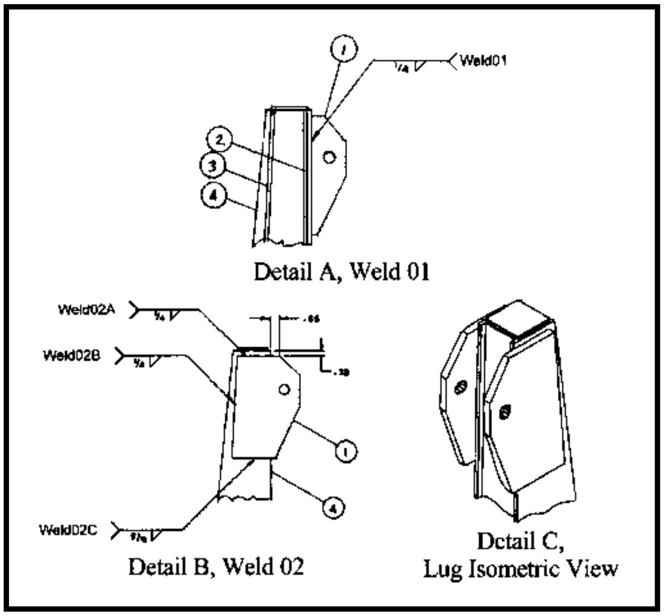


Fig. 22 — Details of the fall arrest anchor and post.

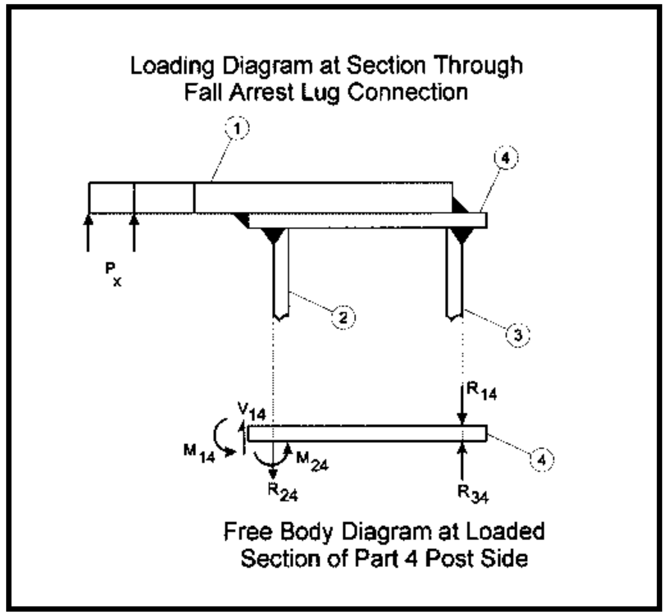


Fig. 23 — Loading aiagram of the fall arrest post side.

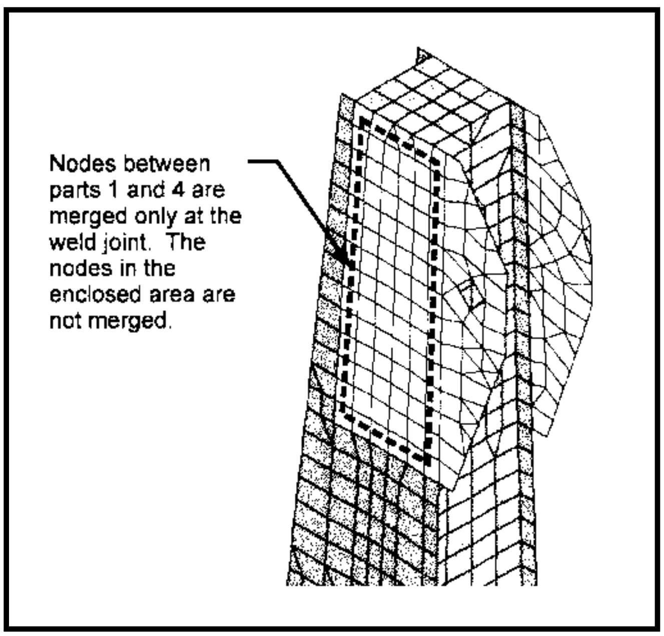


Fig. 24 — Finite element model of lap joint.

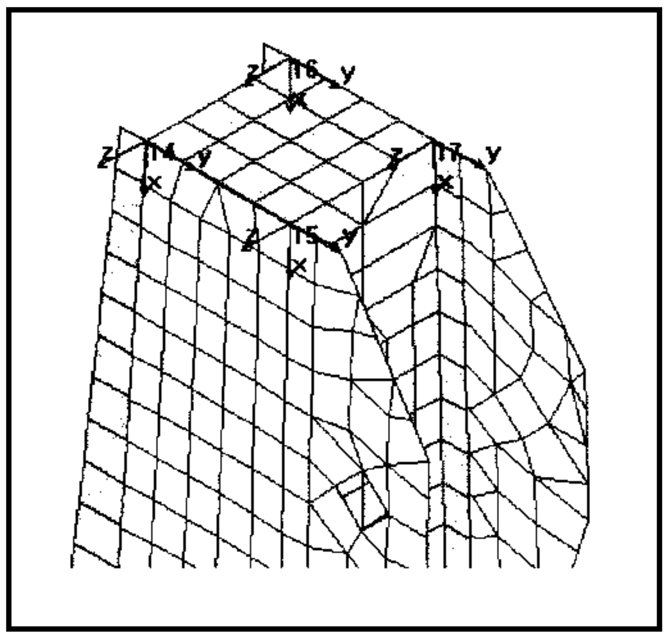


Fig. 25 — Coordinate systems used for post weld joints.

definition of failure, elastic analysis is either a reasonable model or is conservative (in terms of rupture strength). Elastic stress ranges are a very meaningful predictor of resistance to fatigue. For static, ductile failure resistance, the definition of failure determines the applicability of elastic analysis. For design where meaningful change in geometry would cause loss of function (as for most mechanical equipment), elastic analysis is entirely appropriate and accurately predicts the onset of yield. For applications where loss of function occurs when load-bearing capacity is lost, but large plastic deformation can be tolerated and may be desired — as in seismic design or automotive frames — elastic analysis with a safety factor against ultimate strength will generate conservative strength results and is not likely to provide an accurate prediction of the behavior of the structure regarding the design intent. Under this latter case, non-linear plastic analysis or the use of tabulated plastic factored resistances provide a better prediction of behavior.

The Choice of Shell Elements

An alternative to using shell elements for generic analysis of weldments with FEA is the use of solid elements.

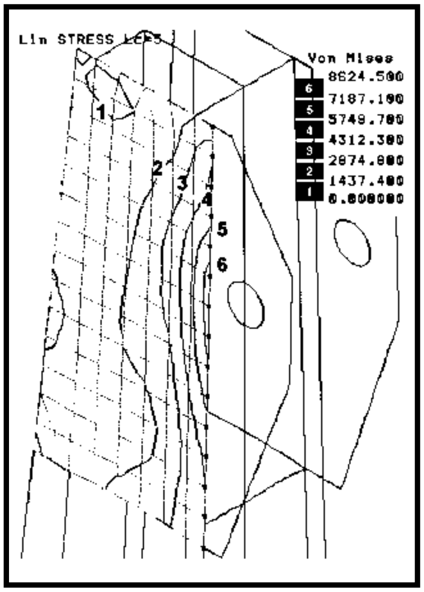


Fig. 26 — Von Mises stresses in part 4 post side plate with nodes of weld 01 displayed.

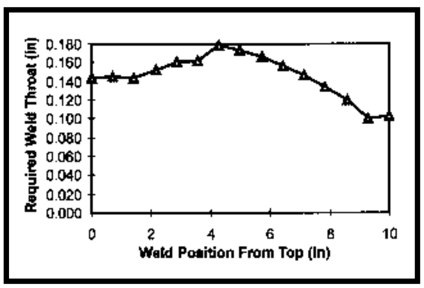


Fig. 27 — Calculated throat requirement for weld 01.

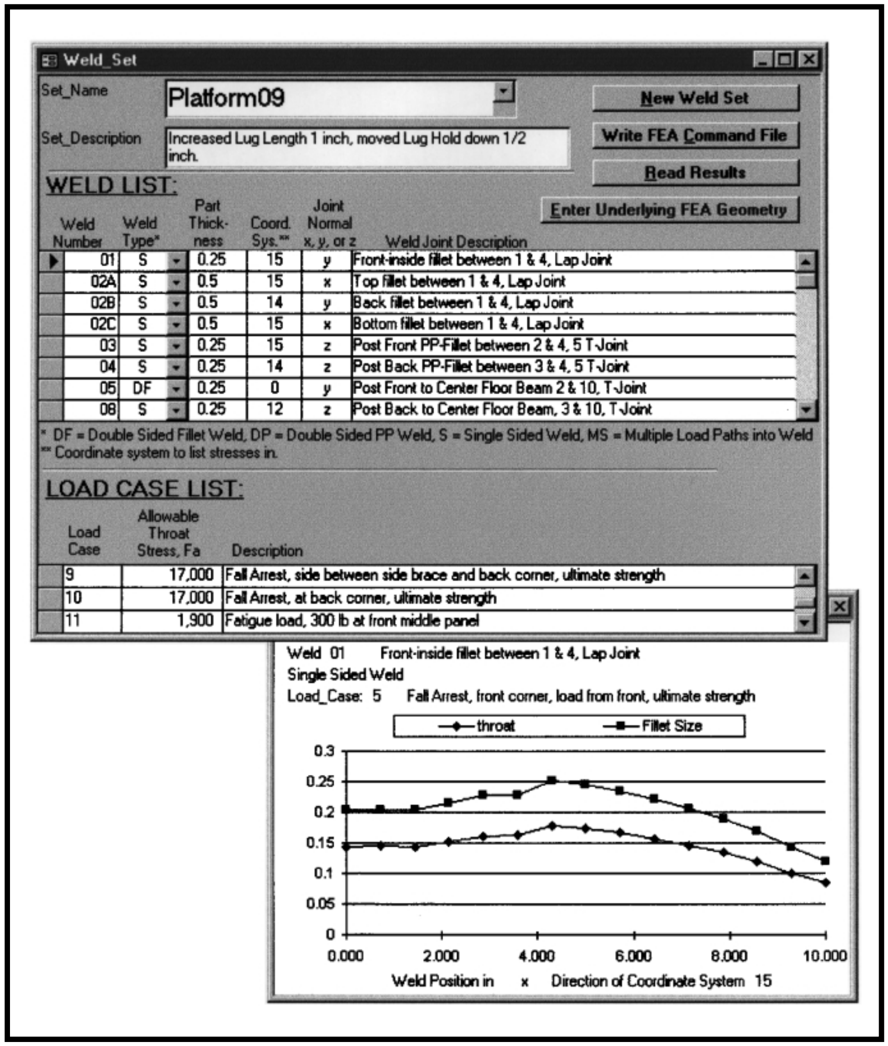


Fig. 28 — FEWELD database.

Reasons for Not Modeling Welds with Solid Elements

1) The published strength data for static and fatigue failure is in terms of nominal throat stress. This information is not easily presented or extracted from a solid element model.

2) The size of the weld would have to be known *a priori*. The benefit of using shell elements as presented is that the required weld size can be calculated from the results of the FEA analysis.

3) The effort required to build solid models of welds and the computational resources needed to solve such models make their use uneconomic for most designs within most organizations.

Situations Where a Solid Model of the Weld is Appropriate

1) Solid modeling can provide useful predictions of notch stresses for fatigue evaluation if the weld profile and penetration can be modeled to accurately.

2) For structures where the stiffness difference between the actual weld geometry and a shell element representation of the joint would be meaningful.

3) For situations where plastic behavior of the weld itself is of interest.

The Present System

Presently, this analysis is performed external to the finite element analysis software. A database of welds is created that contains the necessary information: part thickness, weld type, allowable throat stress and definition of the shell elements and nodes by surfaces and weld end points to be evaluated for weld loads — Fig. 28. A database such as this organizes the work to automate many of the tasks; however, improvements in productivity can be obtained from improvements in the modeling environment. More of the manual effort of building the database can be automated.

Future Development

With the information that the finite element analysis results readily provide, that is, the orientation and magnitude of the traction at the root and face of the weld, improved failure prediction may be possible compared to the method of comparing the weld shear allowable to the magnitude of the traction divided by the throat area. This would result in more efficient designs — less material used for a given reliability.

Solicitation

The author is interested in comments on this method and recommendations for improvement. He can be reached through email at mw@weavereng.com or at Weaver Engineering, 1219 Westlake Avenue N, Suite 210, Seattle, WA 98109. Related information is available on the internet at www.weavereng.com.

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Appendix

Stress Criteria for Fillet Welds with AWS D1.1

The following is the method and rationale of applying the requirements of AWS D1.1 (Ref. 3) for weld size determination.

The shear stress allowable for static loading in the Structural Welding Code, AWS D1.1, is 0.3 times the electrode tensile strength for fillet welds and partial penetration groove welds not in bearing, except fillet welds of lap joints loaded in plane with a transverse load component have an increased allowable per 2.14 of AWS D1.1-96. See also Lesik (Ref. 10). The increased allowable is new with the 1996 code. There are no directly published shear strengths for steel electrodes in AWS D1.1 or AWS electrode specifications; however, the commentary for section 2 (section 8 for pre-1996 versions of AWS D1.1) does reveal that the allowable stress is based on a safety factor ranging from 2.2 for in-plane longitudinal shear to 4.6 for in-plane transverse loads based on test results (Ref 5). These tests were performed on lap joints loaded in-plane. Based on this datum, the minimum ultimate shear strength for steel electrode used for analysis is taken as 0.66 (= 0.3 x 2.2) times the electrode minimum tensile strength. Because out-of-plane loading was not evaluated in the testing referenced by the AWS D1.1 and very few testing results of out-of-plane loading have been published, the lower safety factor of 2.2 is used to estimate joint strength by the author for all joints loaded out of plane. For E60XX electrode, this results in an ultimate shear strength of 39.6 ksi. For tubular structures welded with 60 or 70 ksi electrode, the strength is taken as 2.67 times the allowable stress, per 2.40.1.3.

This is useful when designing for compliance with codes and specifications requiring other safety factors for static loading. For example, ANSI/ALI B153.1-90, *American National Standard for Automotive Lifts — Safety Requirements* requires a safety factor of 3.0 against ultimate failure for ductile material while deferring to *"ANSI/AWS D1.1-90 Sections 1 through 7, Section 8 where applicable, …", "… and the Commentary on Structural Welding Code — Steel, (Part of ANSI/AWS D1.1)"* for welding techniques and *weld joint design*. The resulting allowable weld throat shear stress used for design with this code is 13.2 ksi (= $^1/_{3.0} \cdot$ 39.6 ks) for E60XX electrode.

Of note is the evaluation of only the stresses due to loads carried through the weld joint. Stresses along the axis of the weld from loads not passing through the weld are not used (see note 3 in Table 2.3 of AWS D1.1-96). With respect to static loading resistance, these axial stresses will participate in the onset of yield, increasing or decreasing the load at which yield initiates depending on the load geometry. A justification for this approach can be made for fillet and partial penetration welds, where the weld cross section is less than the base metal cross section for axial loads and the weld sizes are not great. As far as the weld is concerned, these axial stresses are seen as applied axial strains and a small amount of yielding will relieve the stresses associated with them, while the base metal remains in an elastic state. This is true, because the weld will be constrained to strain in the axial direction by the same amount as the base material adjacent to the weld. If the weld cross section is significant compared to the base metal cross-section for axial load, this assumption will be attenuated and further investigation is suggested. Also, in the case of plastic design where the base material is expected to see large deformation, the combined effects of axial and through weld elongation must be considered in the resistance of the joint. A high, tensile hydrostatic stress state (associated with large welds combined with severe cross-section or load path discontinuities, such as mismatched base metal sizes) will cause a crack to propagate across the joint before its theoretical ductile limit is reached. It is good to remember that fillet and partial penetration welds are brought into this world with the equivalent of a crack at the root.

The method used to size fillet welds against ductile failure is based on the practical approach of comparing the magnitude of the stress resulting from loads passing through the weld joint to the electrode and base metal shear strengths. From the standpoint of the mechanics discipline of physics, this approach is close for a joint in pure longitudinal shear only. In general, for other loading geometries, this approach results in a more conservative (earlier failure) prediction than other ductile failure theories. However, factors such as the high-stress concentration at the weld root, residual stresses and distortion induced by the welding process, and weld defects call for a conservative approach.

Per AWS D1.1-96 for dynamically-loaded structures (fatigue), the allowables for stress range in the fillet weld are also in terms of shear on the weld throat (Category F, Table 2.4 and Figs. 2.9 and 2.10). The values for redundant structures correspond to the underlying study referenced in the commentary (Refs. 11, 12), where the recommendations are drawn for a 95% survival rate at a 95% confidence level from the underlying test data. These studies are oriented directly at bridge construction. The total stress state in a fillet weld — not just the traction through the throat — will contribute to fatigue failure; however, the traction through the throat is subject to the stress concentration at the root, while stresses along the weld axis are not. Because the root is essentially a crack, the weld is born into stage 2 fatigue with respect to loads through the weld while the weld is closer to stage 1 fatigue for loads along the weld axis. Additionally, there are separate allowables for stresses in the base metal adjacent to weld joints that are near the same range as the allowables for the weld throat shear (Categories B through E, Table 2.4 of AWS D1.1-96). These account for the load path discontinuity at the welds and notch effect.