

Design Assessment of Ship Interface Template Set (SITS) Channel System for Mounting of Submarine Rescue System (SRS) Final Report

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EWI

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Signature

Date

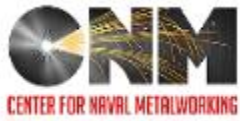
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1.0 Executive Summary / Abstract

This primary aim of this project was to determine the possibility of a reduction in welding time for installing the LARS base and/or SITS structure and also to determine if changing channel material from EH-36 to a reduced grade (such as AH-36) was acceptable. The means of determine the project aims were drop tower testing, finite element modeling, and calculations of welding time and other production welding activities.

Drop tower testing of welded channels to the deck plate showed cracking in the welds but not separation or cracking into the channel or deck. The demonstrated robustness of the channel to deck system with non-design impact loading provided reassurance that the channel to deck system should hold up in most sea conditions.

Modeling efforts were performed to determine if a change to the welds on the LARS base could be implemented. Stiff boundary conditions used in the models showed that there was enough loading on the welds that redesigns of LARS Base area welds were not attempted.

While a general reduction to weld time by changing to smaller welds overall was not found, a specific change to welds shorter than 6-in. long in areas forward of the LARS base was found to provide savings in weld time of about 3 hours under reasonable assumptions of activity time and conditions. This change can be justified by comparing to the previous justification for the weld sizing of welds in this area.

While one of the original aims involved a potential material substitution (from EH-36 to AH-36) to account for material acquisition issues, it was later determined that the original material acquisition issue was a non-critical path element, so material substitution became a non-issue.

2.0 Background / Problem Statement

The system for mounting the Ship Interface Template Set (SITS) to the deck of a Vessel of Opportunity (VOO) has been designed for the Submarine Rescue System (SRS) using channel sections welded to the deck and bolted on their webs to the structure above. Implementations have demonstrated that several difficulties are presented by the current design requirements that limit speed of assembly. These include the choice of rarer ABS Grade EH-36 steel for the channels, a multi-pass requirement for weld size, welding positions that cannot easily be achieved with the structure in place, and tight relative position requirements for the individual welded channels. Implementations have had to take extra time to get waivers on welding material and use lap plates not in the design to accommodate the position requirements.

Current SITS Welding Requirements:

- Material and weld size/length requirements appear to be onerous based on ABS Rules and experience with similar requirements in many other situations.
- EH-36 material is welded to VOO decks that are typically ABS Grade A (or at most, ABS Grade DH-36). Changing channels to ABS Grades AH-36 or DH-36 would facilitate many improvements.

- Weld sizes of 3/8-in. are vastly in excess of ABS Rules that typically require the weld to be 1/16-in. less than the thickness of the material being joined. Reducing weld size to comply with ABS rules would speed the process of equipping VOO to sail away to DISSUB site.
- In addition, the 3/8-in. weld size can cause a significant heat-affected zone (HAZ) in the EH-36 channels and VOO deck materials.
- Weld length requirements of “weld all around” are excessive and difficult to accomplish in all areas due to tight clearances under the flanges of SITS beams.
 - o An earlier weld reduction document allowed the present extent of welding; many evolutions have taken place without negative performance of the SRS. Anticipated response to Liaison Action Request (LAR) is that additional welding might be required.
 - There seems to be scant justification for this.

This project has provided a thorough review of the situation and provide an independent engineering assessment of the needs of the service to enable reasonable requirements for the welding and the channel sections can be proposed.

3.0 Objective(s)

The project team will review the designs of the SITS to a VOO deck interface to determine materials and weld sizes so that substantial time can be saved while assuring that structures have proper strength and toughness to provide the level of safety and reliability needed for the Submarine Rescue Command community.

4.0 Technical Approach (by task)

Task 1 Create Initial Models Based on Review of Existing Design Requirements

Determining the loads in the LARS base to be analyzed in detail using the finite element method was the main activity for this task. A preliminary analysis which approximates maximum Von Mises stress, or Von Mises stress resultant, was used. This preliminary analysis calculates primary and secondary shear stresses. The stresses were then used to calculate the Von Mises failure criteria. The results of this task were used for Task 3.0 efforts.

Task 2 Determine Basic Material Properties and Structural Impact Tests

Mechanical testing was performed to provide information for comparison with the models presented as components of this project. Three types of testing were performed: mechanical, as well as chemical, tests performed by the material supplier, standard mechanical tests on the supplied material at EWI, and drop weight tests on model channel to deck welded structures.

Task 3 Evaluate Connection Performance with Different Use Scenarios

Using the load calculation from Task 1.0, two styles of finite element models were developed: models that simulate the 'structural' channels (which were obtained from a steel mill in the final shape) and models that simulate the 'formed' channels (which were formed into a channel shape from flat plate). These two model types were used to represent the 5 common types of channel sections that are used for installations on a VOO. Additionally, observations from a previous trial rescue mission indicated locations where complete welds were unable to be made, these were simulated as well as lap and cap plates.

Task 4 Perform Model Calculations to Determine Optimum Materials and Weld Designs

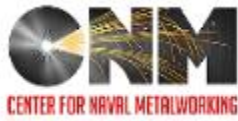
After the main models were developed, the finite element models were queried in order to evaluate the acceptance criteria that was provided by the NAVSEA Technical Warrant Holder. The method consists of producing a series of stress plots at various locations within the model for evaluation. Many images were produced to attain the desired results needed for evaluation – a total of approximately 1000 images were developed.

Task 5 KG Effects of Taller Channels

The ability to raise the SRS on higher channels was reviewed considering the constraints of trying to avoid asking for additional ship stability while providing improved welding access.

Task 6 Estimates of Welding Time Savings

Two types of welding time savings were considered for the welding of channel to deck: arc on-time alone and a combination of arc-on-time, cleaning time, preparation time at the weld site, and moving time between sites. While the combination does not include all the components of time to weld the channel to the deck, it does provide a wider view that the more common measure of arc on-time. Examples of things not included are general preparation time for the welders, coordination among multiple welders and marking of the desired weld locations.



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EWI calculated arc on-time and additional time for cleaning, moving between weld locations and preparing for welding at the location. An approximate percentage of lap plates needed was chosen as 60%. Once total time was calculated, the total was divided by 10 to account for 10 welders sharing the welding effort approximately equally.

Calculations of variations on the welding plan were performed for cases recommended for reduction in amount of welding.

5.0 Technical Activities Performed

This project consisted of the following technical tasks:

- Task 1 – Create Initial Models Based on Review of Existing Design Requirements
- Task 2 – Determine Basic Material Properties and Structural Impact Tests
- Task 3 – Evaluate Connection Performance with Different Use Scenarios
- Task 4 – Perform Model Calculations to Determine Optimum Materials and Weld Designs
- Task 5 – KG Effects of Taller Channels
- Task 6 – Estimates of Welding Time Savings

6.0 Results and Discussions

6.1 Task 1: Create Initial Models Based on Review of Existing Design Requirements

6.1.1 Determining LARS Nodes for Finite Element Analysis

TTT Engineering LLC was tasked with determining which of the LARS nodes should be analyzed in detail using the finite element method. A preliminary analysis which approximates maximum Von Mises stress, or Von Mises stress resultant, was used⁽¹⁾. This preliminary analysis calculates primary and secondary shear stresses. The stresses were then used to calculate the Von Mises failure criteria.

This section of the report provides details of the method. Table 1 presents the recommended nodes, applied loads, maximum Von Mises stress resultants and an estimate of the Maximum Von Mises stress for further investigation.

Table 1. Estimated Maximum Von Mises Stress Calculations Results

Channel Type	Node and Load Case	Longitudinal Force (lbs.)	Transverse Force (lbs.)	Vertical Force (lbs.)	Von Mises Stress Resultant (lbs./in.)	Approximate Maximum Von Mises Stress* (lbs./in ²)
1	44 G1	3,504	68,488	-2,564	5,408	32,000
2	66 A3	-50,706	102,380	-67,150	1,676	10,000
3	64 G3	72,680	714	-13,177	3,642	22,000
4	65 A3	20,139	51,492	-52,751	2,320	14,000
5	32 A2	670	-67,488	25,635	6,179	37,000

* Assumes a ¼" fillet weld

¹ Budynas, Richard G., and J. Keith Nesbett. 2020. *Shigley's Mechanical Engineering Design*. New York: McGraw-Hill.

6.1.1.1. LARS Base Node Analysis Details

C-Channel and Load Orientation Analysis

Five different C-channels configurations were identified on the LCS-ICD drawing number 7411192 Sheet 7 (Rev C). The details of Type 1 through 4 can be found in drawing number 7412879 (Rev H), while the details for the Type 5 can be found in Drawing 7413008 (Rev A).

There are eighty-two nodes and eight different load cases presented in the LCS ICD. The ICD presents deck forces relative to the vessel of opportunity (VOO) in a three-dimensional cartesian coordinate system: Longitudinal (in the for/aft direction with forward being positive), Athwartship (with positive to the port side), and Vertical (perpendicular to the plane of the deck with positive being up).

Figure 1 shows the assigned node numbers and orientation of the C-channels on the VOO (taken from VOO ICD – DWG# 7411192, Sheet 7). There are three orientations of the C-channels; some c-channels orientated with the length in the for/aft direction some were orientated with the C-channel length orientated in the athwartship direction, while others are at approximately +/- 45-degrees with respect to the VOO. Therefore, an orientation scheme was implemented prior to executing the calculations.

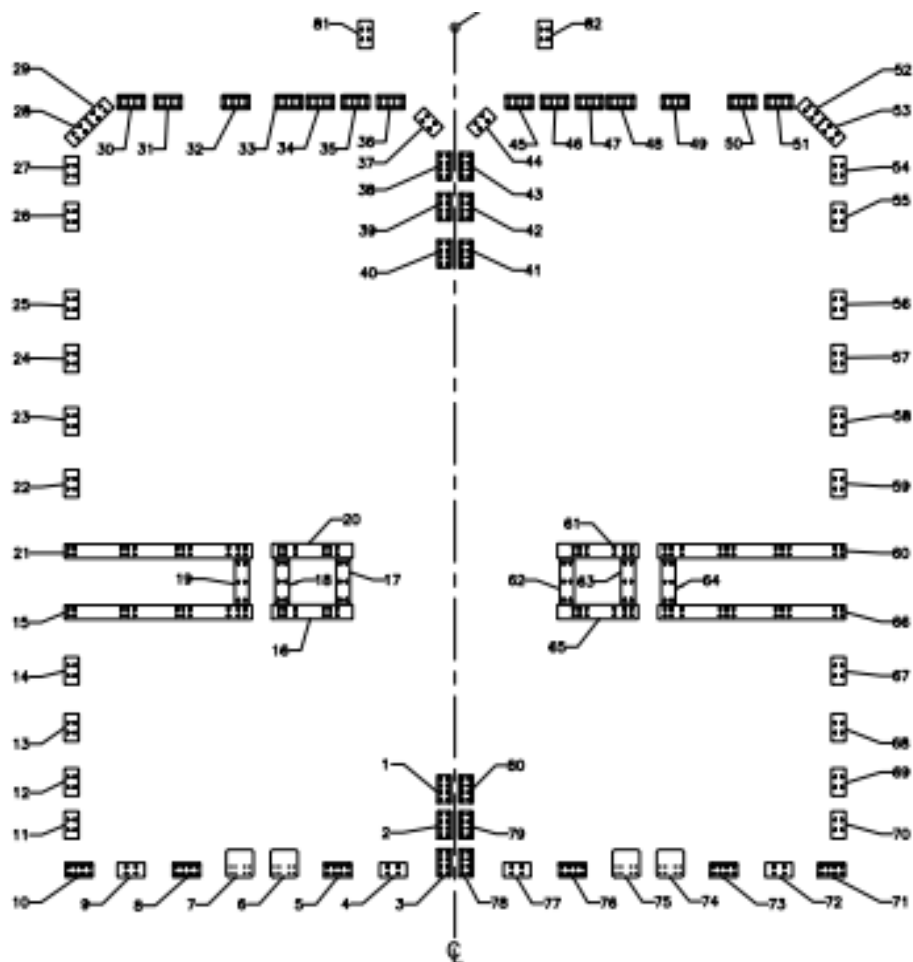


Figure 1. C-Channel Node Numbers, Location, and Orientation

Nodes were identified as: LL (the longitudinal deck load is in the long direction of the C-channel), LT (the longitudinal deck load is transverse to long direction of the C-channel), and Special (this requires coordinate transformations to align the loads from the VOO coordinate reference frame to the c-channel reference frame).

Figure 2 shows schematically a typical C-channel and load configuration for the analysis. The LL orientation did not require any changes to the loads per the LCS ICD prior to conducting the analysis. The LT orientation required the longitudinal and athwartship loads be swapped. While the Special orientation required a coordinate transformation.

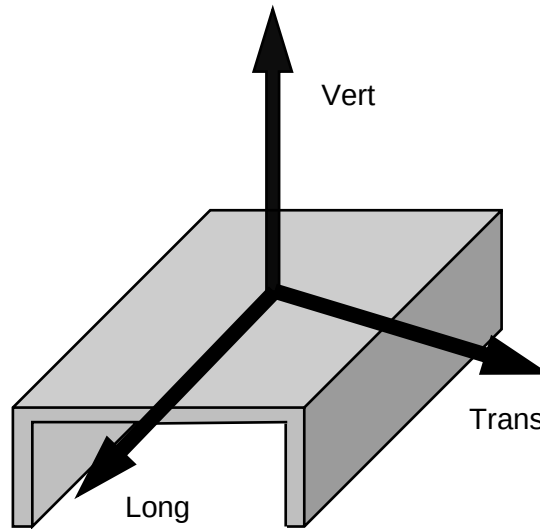


Figure 2. Typical C-Channel Analysis Configuration

Figure 3 shows schematically a traditional vector coordinate transformation.

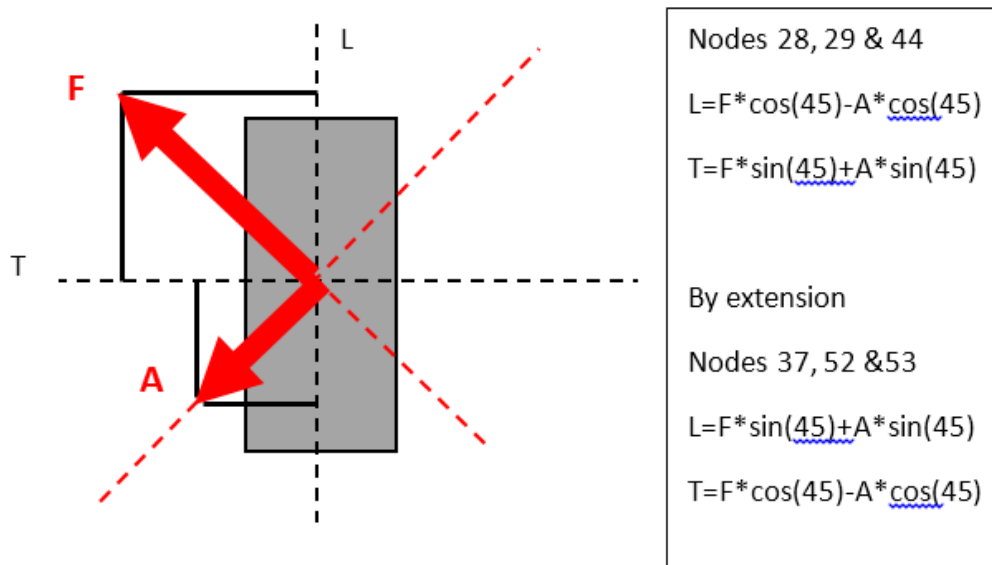


Figure 3. Special Orientation Coordinate Transformation Shear Stress Resultant Calculations

Once the forces were oriented on the C-channels in a consistent manner, the Von Mises stress resultants were calculated.

To obtain the Von Mises stress, one divides the resultant by the length of the weld throat (stress resultants have units of lb./in.). Resultants were selected because there is utility in being able to quickly determine the stress due to different fillet weld sizes or other weld geometries. This analysis technique relies on several key concepts from mechanics of materials:

- Calculated stresses are an average stress
- All of the stresses are shear stress and calculated at the throat of the weld
- Linear superposition of vertical stress
- Stress due to transverse and longitudinal forces generate both primary and secondary shear stress
- Loads are applied at the center of the channel

6.1.1.2 Effects of the Vertical, Transverse, and Longitudinal Forces

Figure 4 presents a typical c-channel subjected to a vertical force. During this type of loading the welds, symbolized as the black triangles, are subjected to a shear stress resultant calculated by

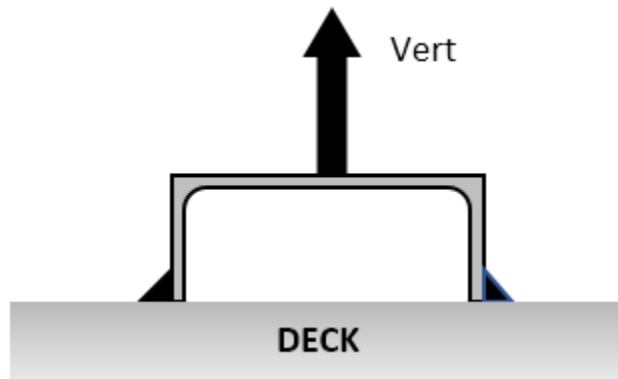


Figure 4. C-Channel Subjected to Vertical Force

Figure 4 presents a typical C-channel subjected to a vertical force. During this type of loading the welds, symbolized as the black triangles, are subjected to a shear stress resultant calculated by Equation 1.

$$\tau_{Vert} = \frac{Vert}{2 * l} \quad (1)$$

Where: Vert = the vertical force
 l = the length of the weld into the page

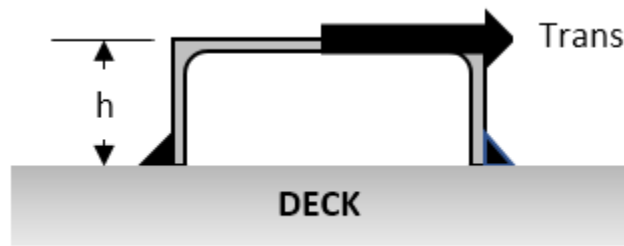


Figure 5. Typical C-Channel Subjected to a Transverse Load

Figure 5 presents the C-channel subjected to a transverse load. The transverse load case subjects the welds to two types of stress. Primary shear stress is uniformly distributed along both welds, in the transverse direction. The secondary shear stress, due to the overturning moment ($Trans \cdot h$), subjects the weld on the left to a uniform tensile stress in the vertical direction and the weld on the right to a uniform compressive stress in the vertical direction. Equation 2 and Equation 3 present the primary and secondary shear stress resultants equation respectively.

$$\tau_{Trans} = \frac{Trans}{2 \cdot l} \quad (2)$$

Where: Trans = the transverse force
 l = the length of the weld into the page

$$\tau_{Trans,Secondary} = \frac{Trans \cdot h}{w \cdot l} \quad (3)$$

Where: Trans = the transverse force
 h = the height of the C-channel
 l = the length of the weld into the page
 w = the width of the C-channel (7 inches)

Figure 6 presents the C-channel subjected to a longitudinal load. The longitudinal load case subjects the welds to two types of shear stress. Primary shear stress is uniformly distributed along both welds, in the longitudinal direction. The secondary shear stress, due to the overturning moment ($Long \cdot h$), subjects the welds to a linear stress distribution in vertical direction, tension on the left, compression on the right crossing zero at the mid length of the C-channel. One could consider this equivalent to a beam bending stress.

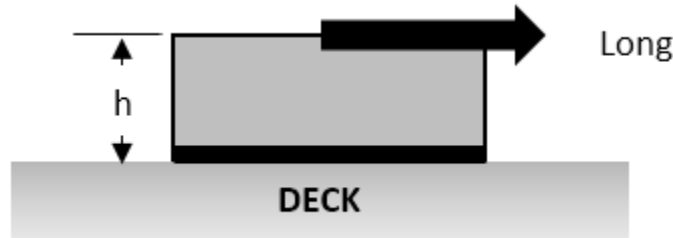


Figure 6. Typical C-Channel Subjected to a Longitudinal Load

Equation 4 and Equation 5 present the primary and secondary shear stress resultants equation respectively.

$$\tau_{Long} = \frac{Long}{2 \cdot l} \quad (4)$$

Where: Long = the longitudinal force
l = the length of the weld along the c-channel

$$\tau_{Long,Secondary} = \frac{3 \cdot Long \cdot h}{l^2} \quad (5)$$

Where: Long = the longitudinal force
h = the height of the C-Channel
l = the length of the weld along the C-Channel
w = the width of the C-Channel (7 inches)

The primary shear stresses are in each of the primary directions, longitudinal, transverse and vertical. Both of the secondary shear stresses are manifested in the vertical direction. The vertical stress varies depending on location along the weld and the weld being analyzed. However, we are only interested in the maximum vertical shear stress.

This maximum vertical stress occurs in one of the corners of the C-channel. One of the corners will experience a constructive interference pattern therefore, we can then simply add the absolute value of vertical shear stress and both of the secondary shear stress resultants, presented in Equation 6.

$$\tau_{Vert,Total} = |\tau_{Vert}| + |\tau_{Trans,Secondary}| + |\tau_{Long,Secondary}| \quad (6)$$

6.1.1.3 Von Mises Yield Criteria

The generalized, 3D, Von Mises yield criteria is presented in Equation 7 using a traditional x, y, z notation.

$$\sigma_{Von} = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2}{2} + \frac{(\sigma_{yy}-\sigma_{zz})^2}{2} + \frac{(\sigma_{zz}-\sigma_{xx})^2}{2} + 3(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)} \quad (7)$$

Implementing our engineering assumption, all stresses are shear stresses, Equation 7 can be simplified by setting all of the normal stress terms to zero. Substituting the stress resultants presented in Equations 2, 4, and 6 yields Equation 8. The overbar denotes the maximum Von Mises Stress Resultant.

$$\overline{\sigma}_{Von} = \sqrt{3(\tau_{Long}^2 + \tau_{Trans}^2 + \tau_{Vert,Total}^2)} \quad (8)$$

The shear stress resultants and maximum Von Mises stress resultants were calculated for each node and load case with a spreadsheet. The spreadsheet was reviewed for each c-channel type to find the node and load case with the largest maximum Von Mises stress resultant. The node and load case with the largest maximum Von Mises stress resultant was recorded and tabularized in Table 1. The spreadsheet entitled “SubRescue Load Cases Rev2” was delivered to EWI as part of the project (Appendices A – L contain the full list of calculations performed). The maximum Von Mises stress can then be calculated by dividing the resultant by the length of the weld throat.

6.1.2 Common C-Channels Used with Welding Lengths for Finite Element Modeling

TTT Engineering LLC was tasked with determining which of the LARS nodes should be analyzed using the finite element method. The details of the selection process are presented in Section 6.1.1. The initial assumption was the C-channels could be welded on both sides of the entire length, which was considered the baseline case for all C-channel types.

Photographic evidence was reviewed to determine additional weld geometries for modeling efforts in Task 3.0. Weld lengths were estimated by printing the photographs and using a scale. The scale factor was estimated by measuring the length of the C-channel on the image and comparing that to the nominal length from the fabrication drawings.

Weld lengths were then estimated by measuring the length of the weld from the image and scaling the measured length. No attempt was made to adjust for parallax errors. Figure 7 presents the three weld geometries for the Type 1 and 5 C-channel.

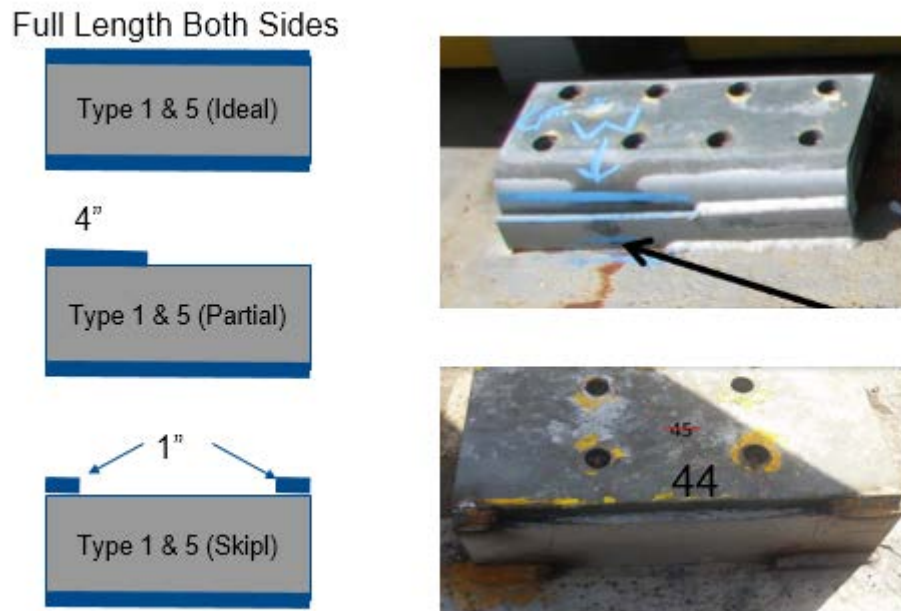


Figure 7. Types 1 and 5 C-Channel Weld Length Estimates

Figure 8 presents the two weld geometries for the Type 2 C-channel.



Figure 8. Type 2 C-Channel Weld Length Estimates

Figure 9 presents the two weld geometries for the Type 3 C-channel, the estimated weld lengths are 1/4 inch, the dimensions presented in Figure 9 are the spacing length.

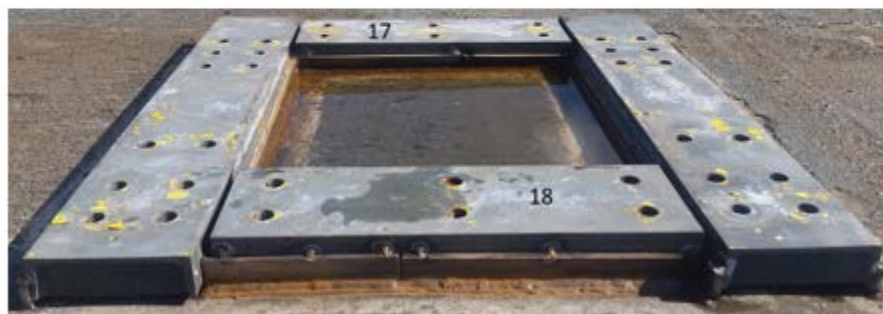
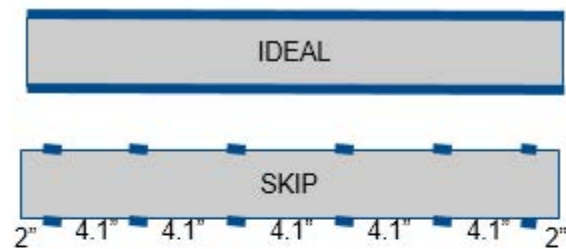


Figure 9. Type 3 C-Channel Weld Length Estimates

Figure 10 presents the two weld geometries for the Type 4 C-channel.

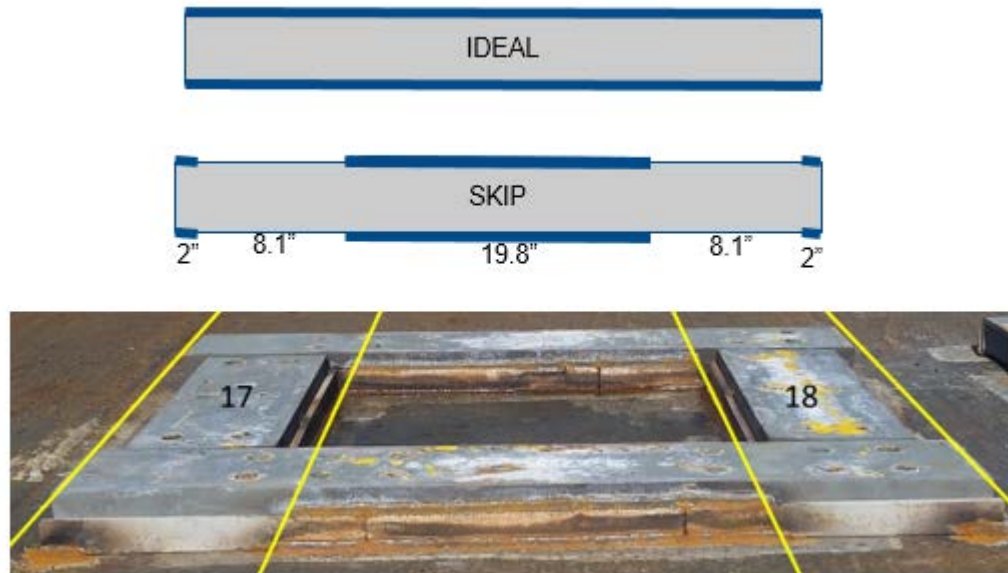


Figure 10. Type 4 C-Channel Weld Length Estimates

Additional models were developed in Task 3.0 using lap plates and end caps as shown in Figure 11 (per Drawing 7413006):

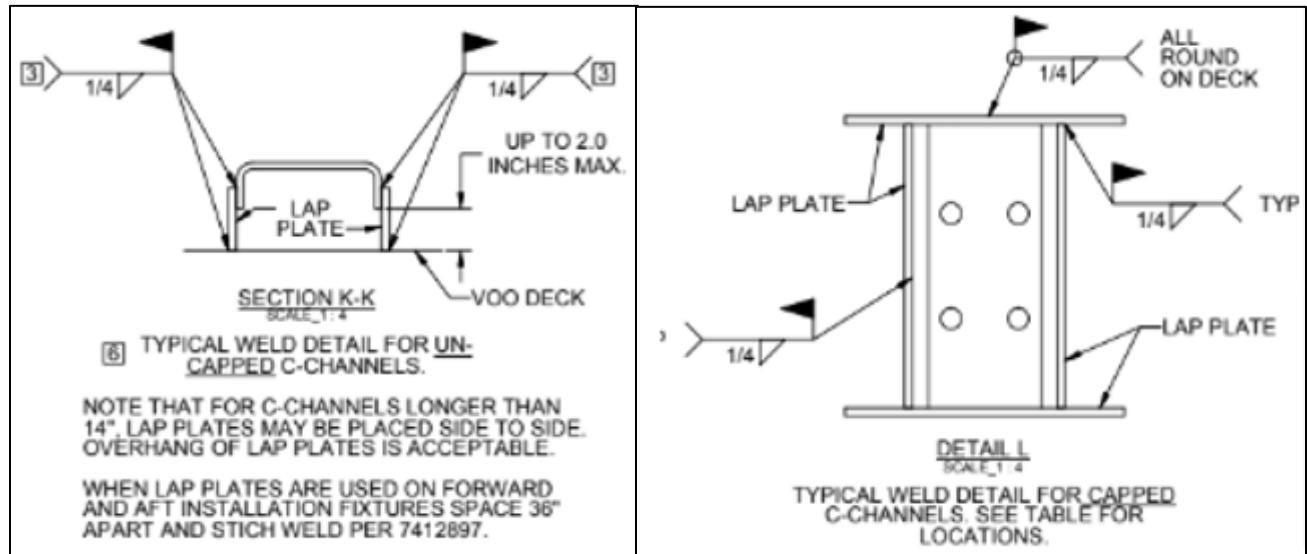


Figure 11. Drawing 7413006 Showing Lap Plates and End Caps

6.2 Task 2: Determine Basic Material Properties and Structural Impact Tests

6.2.1 Mechanical Testing and Chemistry Reported Results from Material Supplier

6.2.1.1 ABS Grade EH-36 5/16-in. Formed Channel and ABS Grade EH-36 3/8-in. Lap Plate

BENMAR Fabrication (or BENMAR) provided material for the 5/16-in. thick EH-36 formed channels. This material had been provided to BENMAR by American Alloy Steel as 3/8-in. thick plate. BENMAR machined the material to 5/16-in. thick and formed the channel, as well as cutting pieces of the 3/8-in. thickness material for the lap plates. The test report for the plate include chemistry as shown in Table 2.

**Table 2. Chemistry of 5/16-in. Formed Channel and 3/8-in. Lap Plate
(reported by American Alloy Steel)**

C	Mn	P	S	Si	Total Al	Sol. Al	Cu	Ni	Cr
.15	1.33	.008	.002	.23	.028	.026	.21	.14	.08
Mo	Cb	V	Ti	B	N	Co	Fe		IIW CE
.06	.017	.006	.008	.0001	.0068	.0025	Balance		.43

The plate had tensile test results reported by American Alloy Steel on the 3/8-inch thick plate and is shown in Table 3.

**Table 3. Tensile Test Results of 5/16-in. Formed Channel and 3/8-in. Lap Plate
(reported by American Alloy Steel)**

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 8 inches (%)	Reduction of Area (%)	Direction
58	77	22	N/A	Transverse

The plate had Charpy v-notch tests reported for -50°F with the long direction in the transverse direction and the specimen size was 7.5 mm, as shown in Table 4.

**Table 4. Charpy V-Notch Test Results of 5/16-in. Formed Channel and 3/8-in. Lap Plate
(reported by American Alloy Steel)**

Test 1 Energy (ft-lbs.)	Test 2 Energy (ft-lbs.)	Test 3 Energy (ft-lbs.)	Average Energy (ft-lbs.)
53	34	35	41

The 3/8-in thick plate material passed an ultrasonic examination that was required per ABS Rules for Materials and Welding 2018, Part 2 (Section 17.11).

6.2.1.2 ABS Grade EH-36 1/2-in. Formed Channel

BENMAR provided material for the 1/2-inch EH-36 thick formed channels. This material had been provided to BENMAR by American Alloy Steel as 1/2-in thick plate. The test report for the plate include chemistry as shown in Table 5.

Table 5. Chemistry of 1/2-in. Formed Channel (reported by American Alloy Steel)

C	Mn	P	S	Si	Total Al	Sol. Al	Cu	Ni	Cr
.12	1.42	.010	<.001	.32	.026	.025	.19	.10	.07
Mo	Cb	V	Ti	B	N	Co	Fe		IIW CE
.06	.027	.006	.002	.0002	.0062	.0020	Balance		.40

The plate had tensile test results reported by American Alloy Steel on 1/2 in thick plate, as shown in Table 6.

Table 6. Tensile Test Results of 1/2-in. Formed Channel (reported by American Alloy Steel)

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 8 inches (%)	Reduction of Area (%)	Direction
61	79	39	N/A	Transverse

The plate had Charpy tests reported for -50°F with the long direction in the transverse direction and the specimen size 10 mm, as shown in Table 7.

**Table 7. Charpy V-Notch Test Results of 1/2-in. Formed Channel
(reported by American Alloy Steel)**

Test 1 Energy (ft-lbs.)	Test 2 Energy (ft-lbs.)	Test 3 Energy (ft-lbs.)	Average Energy (ft-lbs.)
97	81	100	93

The 1/2-in. thick plate material passed an ultrasonic examination that was required per ABS Rules for Materials and Welding 2018, Part 2 (Section 17.11).

6.2.1.3 C7×12.7-in AH-36 Structural Channel

BENMAR provided material for the C7×12.7-in. AH-36 structural channels. This material had been provided to BENMAR by CMC Steel Alabama as structural channel. The test report for the plate include chemistry as shown in Table 8.

**Table 8. Chemistry of C7×12.7-in. AH-36 Structural Channel
(reported by CMC Steel Alabama)**

C	Mn	P	S	Si	Total Al	Sol. Al	Cu	Ni	Cr
.13	0.73	.013	.025	.16	-	-	.30	.11	.14
Mo	Cb	V	Ti	B	N	Sn	Fe		IIW CE
.031	.009	.006	.001	.0003	.0093	.0013	Balance		.31

The plate had tensile test results reported by CMC Steel Alabama on structural channel, as shown in Table 9.

**Table 9. Tensile Test Results of C7×12.7-in. AH-36 Structural Channel
(reported by CMC Steel Alabama)**

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 8 inches (%)	Reduction of Area (%)	Direction
53.1	71.4	25	N/A	
53.1	73.2	28	N/A	

The structural channel had Charpy tests reported for +32°F with the long direction and the specimen size 7.5 mm, as shown in Table 10.

**Table 10. Charpy V-Notch Test Results of C7×12.7-in. AH-36 Structural Channel
(reported by CMC Steel Alabama)**

Test 1 Energy (ft-lbs.)	Test 2 Energy (ft-lbs.)	Test 3 Energy (ft-lbs.)	Average Energy (ft-lbs.)
35	21	26	29

6.2.2 EWI Standard Mechanical Tests

6.2.2.1 ABS Grade A Plate

EWI performed mechanical tests on materials, using both tensile tests and Charpy impact tests. The tensile tests were performed at two rates 0.05 in./sec. and 1 in./sec. to check for differing behavior as a function of loading speed.

The Charpy tests were performed at -18°F and -40°F.

The Grade A plate material used as model deck plate was tensile tested with results shown in Table 11.

Table 11. Tensile Test Results of 1/4-in. Grade A Plate

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 2 inches (%)	Reduction of Area (%)	Strain Rate (in./second)
48.5	70.6	35.7	64.7	0.05
46.8	71.3	35	64.3	0.05
50.1	72.6	31.8	63.5	1
49.6	72.4	32	63.8	1

The average yield-to-tensile ratio for the Grade A plate was 0.67 at the 0.05 in./sec. rate and 0.69 at the 1 in./sec. rate.

The Grade A plate material was Charpy impact tested using half size specimens, with the results shown in Table 12.

Table 12. Charpy V-Notch Test Results of 1/4-in. Grade A Plate

Temperature (°F)	Absorbed Energy (ft-lbs.)	Lateral Expansion (mm)	Shear (%)
-18	13	0.9	39
-18	12	0.83	39
-18	13	0.82	39
-18	12	0.83	39
-18	13	0.81	40
-40	4	0.32	21
-40	12	0.76	21
-40	3	0.3	21
-40	7	0.53	21
-40	10	0.63	21

The average absorbed energy at -18°F was 12.6 ft-lbs., equivalent to 25.2 ft-lbs. on full-size specimens using an area conversion.

The average absorbed energy at -40°F was 7.2 ft-lbs., equivalent to 14.4 ft-lbs. on a full-size specimen using an area conversion.

The results exceed the required minima for strength of Grade A plate and provide a baseline for the Charpy impact properties, which are not required for Grade A material.

6.2.2.2 ABS Grade AH-36 Structural Channel

The Grade AH-36 structural channel material was tensile tested with results shown in Table 13.

Table 13. Tensile Test Results of Grade AH-36 Channel

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 2 inches (%)	Reduction of Area (%)	Strain Rate (in./second)
54.0	74.6	34.8	62.6	0.05
53.4	74.4	33.7	61.6	0.05
55.7	75.1	32.6	63.2	1
54.9	75.0	32.6	63.1	1

The Grade AH-36 structural channel material was Charpy impact tested using three-quarter size specimens, with results shown in Table 14.

Table 14. Charpy V-Notch Test Results of Grade AH-36 Channel

Temperature (°F)	Absorbed Energy (ft-lbs.)	Lateral Expansion (mm)	Shear (%)
-18	4	.29	10
-18	4	.22	12
-18	9	.39	12
-18	4	.21	12
-18	4	.24	12
-40	2	.10	12
-40	2	.15	10
-40	3	.18	11
-40	2	.08	11
-40	3	.12	11

The average absorbed energy at -18°F was 5 ft-lbs., equivalent to 6.8 ft-lbs. on full-size specimens using an area conversion.

The average absorbed energy at -40°F was 2.4 ft-lbs., equivalent to 3.2 ft-lbs. on a full-size specimen using an area conversion.

6.2.2.3 ABS Grade EH-36 5/16-in. Formed Channel

The Grade EH-36 5/16-in. thick formed channel material was tensile tested with results shown in Table 15.

Table 15. Tensile Test Results of 5/16-in. Grade EH-36 Formed Channel

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 2 inches (%)	Reduction of Area (%)	Strain Rate (in./second)
59.7	81.1	34.0	62.2	0.05
60.0	80.8	35.7	65.1	0.05
63.3	82.1	32.7	66.4	1
62.8	81.9	32.6	66.0	1

The EH-36 5/16-in. thick formed channel material was Charpy impact tested using three-quarter size specimens, with results shown in Table 16.

Table 16. Charpy V-Notch Test Results of 5/16-in. Grade EH-36 Formed Channel

Temperature (°F)	Absorbed Energy (ft-lbs.)	Lateral Expansion (mm)	Shear (%)
-18	65	1.89	58
-18	55	1.67	58
-18	91	2.35	77
-18	65	1.92	62
-18	69	2.02	62
-40	46	1.64	54
-40	41	1.35	54
-40	52	1.59	54
-40	52	1.61	54
-40	43	1.39	54

The average absorbed energy at -18°F was 69 ft-lbs., equivalent to 93.2 ft-lbs. on full-size specimens using an area conversion.

The average absorbed energy at -40°F was 46.8 ft-lbs., equivalent to 63.2 ft-lbs. on a full-size specimen using an area conversion.

6.2.2.4 ABS Grade EH-36 1/2-in. Formed Channel

The Grade EH-36 1/2-in. thick formed channel material was tensile tested with results shown in Table 17.

Table 17. Tensile Test Results of 1/2-in. Grade EH-36 Formed Channel

Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 2 inches (%)	Reduction of Area (%)	Strain Rate (in./second)
66.9	80.5	39.7	67.1	0.05
60.6	80.4	37.4	67.2	0.05
61.7	81.3	34	64.8	1
61.3	81.4	34.3	65.2	1

The Grade EH-36 1/2-in. plate material was Charpy impact tested using full size specimens, with results shown in Table 18.

Table 18. Charpy V-Notch Test Results of 1/2-in. Grade EH-36 Formed Channel

Temperature (°F)	Absorbed Energy (ft-lbs.)	Lateral Expansion (mm)	Shear (%)
-18	100	1.96	53
-18	83	1.81	53
-18	96	1.95	53
-18	140	2.44	58
-18	112	2.11	58
-40	72	1.55	40
-40	84	1.74	40
-40	99	1.93	45
-40	78	1.67	40
-40	72	1.55	40

The average absorbed energy at -18°F was 106.2 ft-lbs.

The average absorbed energy at -40°F was 81 ft-lbs.

6.2.3 Drop Weight Testing

Drop weight testing was performed to provide small-scale testing that modelled situations more severe than were expected for the service conditions on the channel to deck welded joints. The loading by impact on the LARS, for instance, would occur remotely to the channels of the SITS would be distributed around the base rather than concentrated on any one node.

6.2.3.1 Test Design

EWI desired to test representative specimens with drop weight impact loading to demonstrate the resistance of the welded joints to the deck under an exaggerated condition of nearby rapid loading. Normal loading of the system will have very little impact component and that impact will primarily be applied well away from the SITS to deck interface, such as cable slap on the crane component. Impact applied far from a welded section will have less direct effect on that section because deflection of the intervening structure will smooth the transfer of the loading.

Five types of specimens were fabricated, as shown in Table 19. All the specimens had a square 10-in. by 10-in. backplate of 1/4-in. thick Grade A steel to represent the deck plate.

All the specimens used a 6-in. long channel with the flange tips toward the backplane. Three of the specimen types used fillet welds to join the tip of the flanges to the backplate. Two of the specimen types used intermediate 3/8-in. thick lap plates of the same material as the 5/16-in. formed channels.

The lap plates were welded on both the thin long edges on the side toward the channel and on the side toward the backplate with 1/4-in. leg fillet welds. The lap plates overlapped the channel flange by 1-in., causing the tip of the channel flange to be 2-in. from the back plate surface.

Table 19. Components of the Five Types of Drop Weight Specimens

Channel	Dimensions (inch)	Lap plates	Lap plates Dimensions (inch)	Baseplate	Baseplate Dimensions (inch)
AH-36 Structural Channel	C7×12.25×6	None	None	Grade A	10×10×1/4
EH-36 Formed Channel	5/16 (formed) ×6	None	None	Grade A	10×10×1/4
EH-36 Formed Channel	1/2 (formed) ×6	None	None	Grade A	10×10×1/4
EH-36 Formed Channel	1/2 (formed) ×6	EH-36	6×3×3/8	Grade A	10×10×1/4
EH-36 Formed Channel	1/2 (formed) ×6	EH-36	6×3×3/8	Grade A	10×10×1/4

Two loading directions were chosen, one parallel to the channel axis and here called longitudinal and one perpendicular to the flange surface of the channel and here called transverse. The loading was designed to be applied through contact with the exterior surface of the channel. In the case of the transverse loading of channels with lap plates, the contact point was on the lap plates adjacent to the fillet weld to the channel.

The drop weight was chosen as 400 lbs. with a drop height of 120-in. The contacting tup of the drop weight system was tipped with a half cylinder (4-in. long and 3/4-in. diameter) of hardened steel.

The tup was joined to the main part of the drop weight with two bolts. The drop weight is guided along two vertical rods and has an emergency stop tubular column around each bar to prevent the tup from traveling all the way to the baseplate support.

The backplate support was designed with a slide against the bottom fixture to allow adjustment of the position of the impact varying with the size of the channel and the presence or absence of lap plates. This adjustment was also used between longitudinal and transverse impacts, since the impact position in the center of the web end for longitudinal would be on a curved surface if the same distance from the baseplate was used for that orientation on the formed channels.

The impact position was centered on the end of the channel web for the longitudinal impacts and the impact position was centered on the length of the channel flange for the transverse impacts. The position of impact was chosen on the channel flange to avoid contacting the corner of the channel. The distances of the impact position from the backplate surface are given in Table 20.

The backplate support was fabricated from 1-in. thick steel, shown in Figure 12 and Figure 13. The hole pattern was designed to allow the backplate to be bolted to the support in the two desired orientations.



Figure 12. Backplate Support Showing Front Side Where the Backplate Will Be Bolted to the Face



Figure 13. Backplate Support Showing Gussets

The planned system is shown in Figure 14 at the moment of impact for a longitudinal structural channel specimen without lap plates. The vertical rods that form the track are shown as transparent in this figure. In the actual testing, the lower portion of these rods had exterior clamshell stops added to prevent the hammer from continuing to the lower fixture, if its energy were sufficient to break off the channel. These clamshell stops were set to be contacted if the hammer tip reached $\frac{1}{2}$ inch below the contact point on the channel.

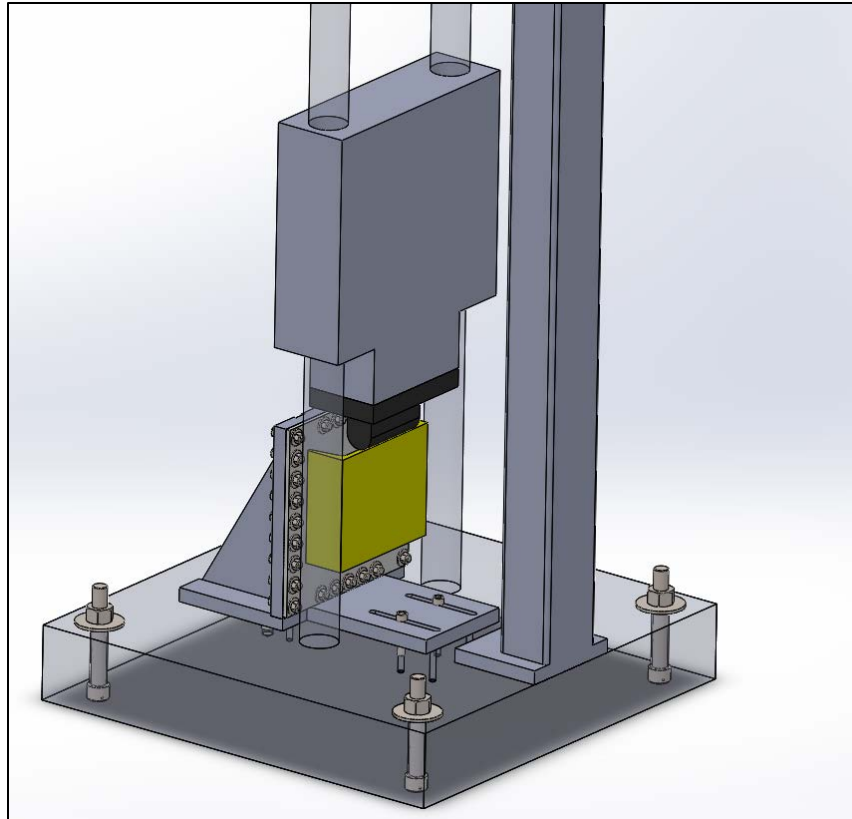


Figure 14. Example of Longitudinal Channel Specimen at Drop Weight Impact

6.2.3.2 Fabrication

EWI selected Ultracore 71 A85 filler wire (0.045-in. diameter) for making the fillet welds (this filler wire meets ABS Grade 3Y requirements). This grade of wire is designed to provide strength and impact toughness nearly equivalent to the EH-36.

The welds were made with parameters selected from the manufacturer's recommendations using the constant voltage power supply setting.

The weld size was determined on practice welds with cross-sections. The weld lengths were chosen to be nearly the full length of the specimen, but without end wraps. An example weld start end between channel and plate is shown in Figure 15. An example lap plates weld to the channel at the stop end is shown in Figure 16.



Figure 15. Example Fillet Weld Shown After Testing from the Start End



Figure 16. Example Fillet Weld From Lap Plates to Channel Shown at Stop End

Tack welds were made on the inside surfaces of the channel joining to the adjacent member. Similar tacks were made to join the lap plates on the inside surface to the back plate. These tack welds were about 1/2-in. from the ends. Lap plates were also tacked at the end of the lap plates to the channel. The tacks were not designed to provide additional resistance to the loading but did provide an indication of weld opening when the tacks were observed to have fractured.

6.2.3.3 Testing Method and Instrumentation

After the test specimens were fabricated, EWI laid strain gage strip rosettes at three locations on the channel web exterior. These were located at 1 inch from each end and at the center of length with the center of the gage along the center axis of the web and the strip longer direction perpendicular to the channel axis, as shown in Figure 17.

The strip rosettes chosen have 1/8-in. square gage patterns with the two outer ends 45-degrees off from the orientation of the central gage. The gages were laid with the long direction 45-degrees to the long axis of the channel, so the two outer end gages provided the transverse and longitudinal direction strains.



Figure 17. Welded Channel Showing Placement of Strain Gage Strip Rosettes

The wiring for the strain gages was directed away from the impact area to a high-speed strain recording system.

The purpose of the strain gages was to have numerical information on the stresses transferred into the channel from the impact. The stresses of most interest for failure risk are those on shear planes within the fillet welds. These stresses cannot be directly determined by strain gaging but can be estimated better if the stress history on the channel web is known.

EWI also set up a high-speed camera to record the behavior during the impact event. The primary interest was in the history of displacement of the impact point, so the camera aim was chosen to record this area on all specimens.

6.2.3.4 Estimate of Behavior

EWI used a simple estimate of the effect of impact to compare the loading situations on the drop weight tests. The approximation described in Section 16.4 in Roark's Formulas for Stress and Strain determines a factor that multiplies the static stress, assuming that the static stress distribution remains the same but changes in magnitude. In Equation 9, the multiplying factor F is

$$F=1+(1+2*(h/d))^{0.5} \quad (9)$$

Where: h = height of the drop
 d = maximum deformation

The multiplying factor method immediately gets the impact factor used for bridge decks where the impact factor is 2 for $h=0$.

The stresses of interest were calculated based on a line load causing stresses due to shear on the throat of the weld using the weld as line method of Omer Blodgett's Design of Welded Structures.

As described in Section 16.5 of Roark's Formulas for Stress and Strain, the formulas are not expected to be any more than rough estimates, since the approximation of the same stress distribution does not allow for temporary stress waves and the inertia of the members is not accounted for.

A uniform displacement d of 0.25 inch has been used for estimates in Table 20.

Table 20. Standard Estimate of Impact Stress for Impact Tests

Channel	Loading Direction	Lap plates	Distance from Surface of Baseplate (inch)	Static Stress (ksi)	Impact Factor	Impact Stress Estimate (ksi)
C7×12.7	Longitudinal	No	2.3	0.43	32	13.9
5/16	Longitudinal	No	2.3	0.43	32	13.9
1/2	Longitudinal	No	2.3	0.43	32	13.9
5/16	Longitudinal	Yes	4.3	0.81	32	26.0
1/2	Longitudinal	Yes	4.3	0.81	32	26.0
C7×12.7	Transverse	No	2.1	0.11	32	3.6
5/16	Transverse	No	2.1	0.11	32	3.6
1/2	Transverse	No	2.1	0.11	32	3.6
5/16	Transverse	Yes	4.1	0.22	32	7.1
1/2	Transverse	Yes	4.1	0.22	32	7.1

6.2.3.5 Results of Drop Weight Tests

EWI performed the drop weight testing on 20 specimens with full data recording. Table 21 lists the main specimen designs and the specimen numbers. Two additional specimens (TC5 and TC6) were tested without full data recording.

Table 21. Specimen Designs and Specimen Numbers

Base Plate	Channel	Channel Orientation	Lap plates	Test 1 Specimen Number	Test 2 Specimen Number
Grade A (1/4-in.)	Structural Channel AH-36	Longitudinal	None	TC3	TC4
Grade A (1/4-in.)	Structural Channel AH-36	Transverse	None	TC1	TC2
Grade A (1/4-in.)	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	TC7	TC8
Grade A (1/4-in.)	Formed Channel EH-36 (5/16-in.)	Transverse	None	TC21 (TC5)	TC22 (TC6)
Grade A (1/4-in.)	Formed Channel EH-36 (5/16-in.)	Longitudinal	EH-36 (3/8-in.)	TC15	TC16
Grade A (1/4-in.)	Formed Channel EH-36 (5/16-in.)	Transverse	EH-36 (3/8-in.)	TC13	TC14
Grade A (1/4-in.)	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	TC11	TC12
Grade A (1/4-in.)	Formed Channel EH-36 (1/2-in.)	Transverse	None	TC9	TC10
Grade A (1/4-in.)	Formed Channel EH-36 (1/2-in.)	Longitudinal	EH-36 (3/8-in.)	TC19	TC20
Grade A (1/4-in.)	Formed Channel EH-36 (1/2-in.)	Transverse	EH-36 (3/8-in.)	TC17	TC18

There were slight differences in the impact location between the specimen types and the individual specimens. These differences are described in Table 22.

All specimens were hit with the hammer centered on the center of the channel width for longitudinal specimens.

For transverse specimens, the impact point was centered on the length of the channel. Longitudinal specimens were usually hit from the end closed to the strain gage strip numbered 1 through 3 (there were four longitudinal specimens were hit in the reversed direction from the end closest to the gage strip 7 to 9).

Transverse specimens were usually hit from the side closest to the 3, 6, and 9 ends of the gage strips. Two specimens were hit in the reversed direction and one of these did not record all the data. A longitudinal specimen that had been hit in the normal orientation is shown in Figure 18.

Table 22. Loading Conditions and Restraints

Specimen Number	Channel	Channel Orientation	Lap plates	Orientation	Contact Point
TC3	Structural Channel AH-36	Longitudinal	None	Normal	On channel web end
TC4	Structural Channel AH-36	Longitudinal	None	Normal	On channel web end
TC1	Structural Channel AH-36	Transverse	None	Normal	On channel flange 1-1/2 in. from base plate
TC2	Structural Channel AH-36	Transverse	None	Normal	On channel flange 1-1/2 in. from base plate
TC7	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	Normal	On channel web end
TC8	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	Normal	On channel web end
TC21(TC5)	Formed Channel EH-36 (5/16-in.)	Transverse	None	Normal (Reversed)	On channel flange 1-1/2 in. from base plate
TC22(TC6)	Formed Channel EH-36 (5/16-in.)	Transverse	None	Normal (Normal)	On channel flange 1-1/2 in. from base plate
TC15	Formed Channel EH-36 (5/16-in.)	Longitudinal	EH-36 (3/8-in.)	Reversed	On channel web end
TC16	Formed Channel EH-36 (5/16-in.)	Longitudinal	EH-36 (3/8-in.)	Reversed	On channel web end
TC13	Formed Channel EH-36 (5/16-in.)	Transverse	EH-36 (3/8-in.)	Normal	On lap plates 2-7/8-in. from base plate
TC14	Formed Channel EH-36 (5/16-in.)	Transverse	EH-36 (3/8-in.)	Normal	On lap plates 2-7/8-in. from base plate
TC11	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	Normal	On channel web end
TC12	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	Normal	On channel web end
TC9	Formed Channel EH-36 (1/2-in.)	Transverse	None	Reversed	On channel flange 1-1/2 in. from base plate
TC10	Formed Channel EH-36 (1/2-in.)	Transverse	None	Normal	On channel flange 1-1/2 in. from base plate
TC19	Formed Channel EH-36 (1/2-in.)	Longitudinal	EH-36 (3/8-in.)	Reversed	On channel web end
TC20	Formed Channel EH-36 (1/2-in.)	Longitudinal	EH-36 (3/8-in.)	Reversed	On channel web end
TC17	Formed Channel EH-36 (1/2-in.)	Transverse	EH-36 (3/8-in.)	Normal	On lap plates 2-7/8-in. from base plate
TC18	Formed Channel EH-36 (1/2-in.)	Transverse	EH-36 (3/8-in.)	Normal	On lap plates 2-7/8-in. from base plate

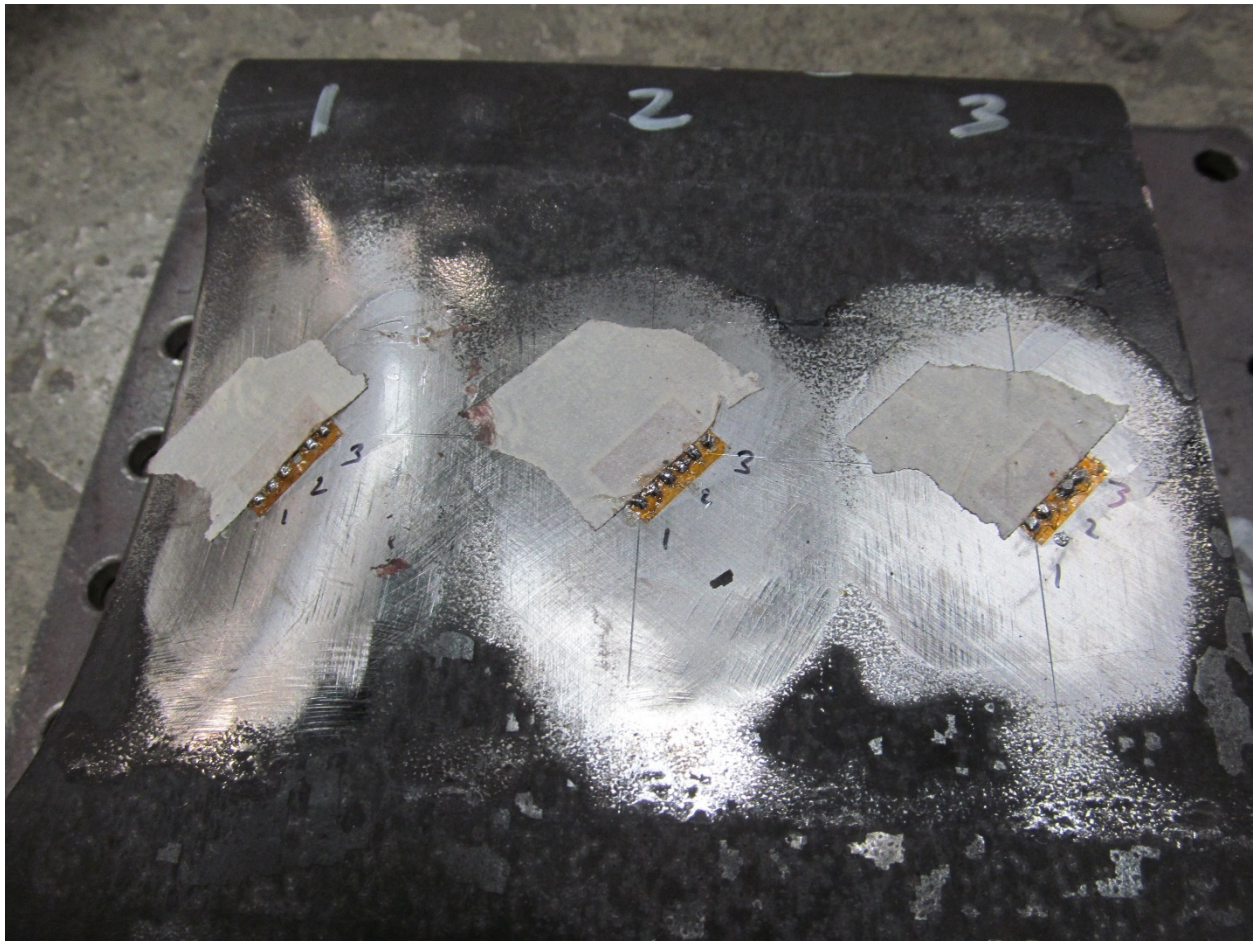


Figure 18. Strain Gage Strip Locations for Longitudinal Impact in the Normal Location

The final displacement was measured using the high-speed camera system aimed at the point of impact on most tests. In some cases, the displacement was limited by contact of the hammer with the clamshell stops. This information is listed in Table 23.

Table 23. Final Displacement and Displacement Limit

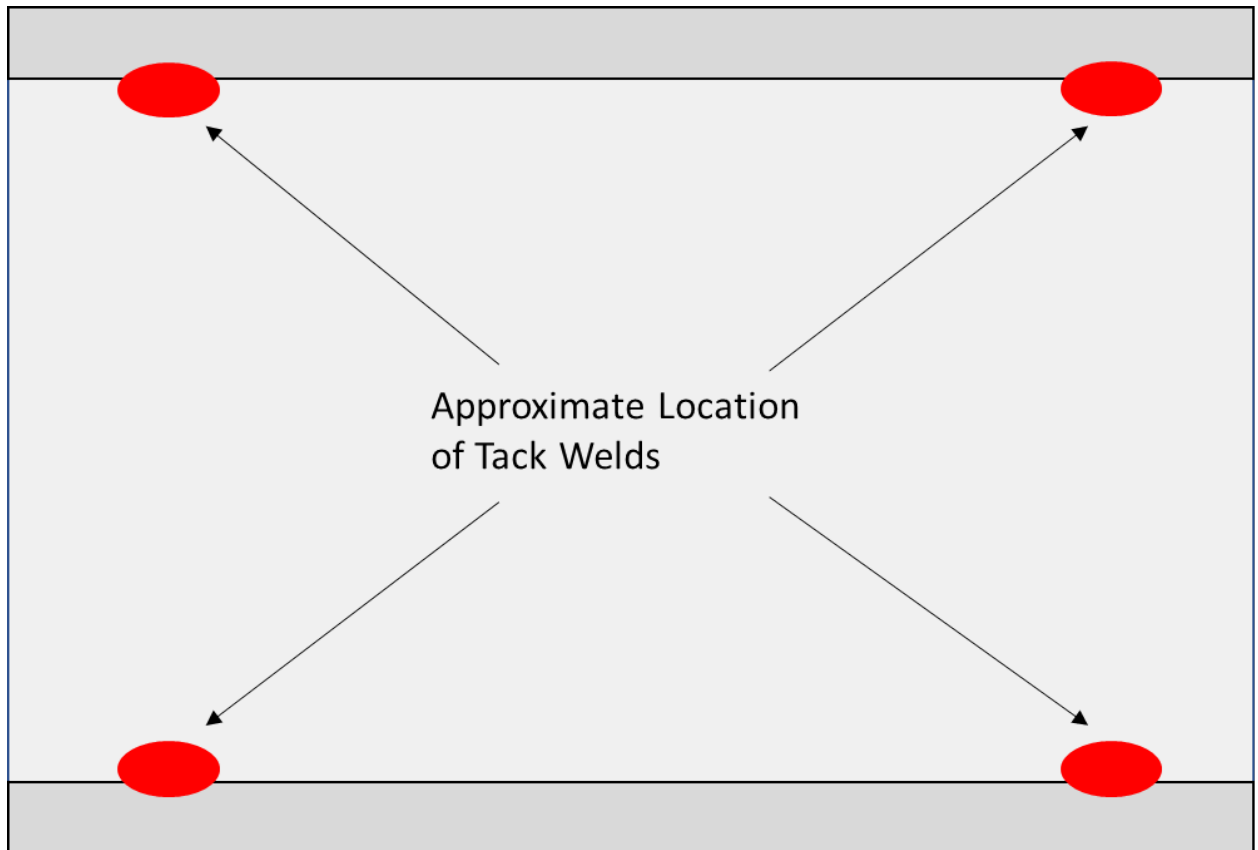
Specimen Number	Channel	Channel Orientation	Lap plates	Final Displacement	Displacement Limit
TC3	Structural Channel AH-36	Longitudinal	None	0.41	
TC4	Structural Channel AH-36	Longitudinal	None	0.41	
TC1	Structural Channel AH-36	Transverse	None	Not recorded	
TC2	Structural Channel AH-36	Transverse	None	1.23	
TC7	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	0.72	
TC8	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	Camera moved	
TC21(TC5)	Formed Channel EH-36 (5/16-in.)	Transverse	None	0.54	
TC22(TC6)	Formed Channel EH-36 (5/16-in.)	Transverse	None	1.06	
TC15	Formed Channel EH-36 (5/16-in.)	Longitudinal	EH-36 (3/8-in.)	0.57	
TC16	Formed Channel EH-36 (5/16-in.)	Longitudinal	EH-36 (3/8-in.)	0.41	Hammer Stop – tup broke
TC13	Formed Channel EH-36 (5/16-in.)	Transverse	EH-36 (3/8-in.)	1.28	Hammer Stop
TC14	Formed Channel EH-36 (5/16-in.)	Transverse	EH-36 (3/8-in.)	1.36	Hammer Stop
TC11	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	0.51	Hammer Stop – tup broke
TC12	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	0.53	
TC9	Formed Channel EH-36 (1/2-in.)	Transverse	None	1.13	
TC10	Formed Channel EH-36 (1/2-in.)	Transverse	None	0.68	Hammer Stop – tup broke
TC19	Formed Channel EH-36 (1/2-in.)	Longitudinal	EH-36 (3/8-in.)	0.44	
TC20	Formed Channel EH-36 (1/2-in.)	Longitudinal	EH-36 (3/8-in.)	0.17	
TC17	Formed Channel EH-36 (1/2-in.)	Transverse	EH-36 (3/8-in.)	1.43	Hammer Stop
TC18	Formed Channel EH-36 (1/2-in.)	Transverse	EH-36 (3/8-in.)	1.58	Hammer Stop

The specimens' condition of cracking after testing is shown in Table 24. Cracking was observed only on the welds joining to the backing plate on the ends toward the impact. Tacks were also observed to have cracked. The four tack locations for specimens without lap plates are shown in Figure 19. The twelve tack locations for specimens with lap plates include the four shown in Figure 19 between the lap plates and the deck, four in equivalent positions at the top of the lap plate joining to the channel and four at the ends of the channel at the tip of the flanges to the lap plates.

Table 24. Cracking of Main Welds and Tacks

Specimen Number	Channel	Channel Orientation	Lap plates	Crack Length	Cracked Tacks
TC3	Structural Channel AH-36	Longitudinal	None	-	-
TC4	Structural Channel AH-36	Longitudinal	None	1/4-@2	2
TC1	Structural Channel AH-36	Transverse	None	1/8 crater@1	3,4
TC2	Structural Channel AH-36	Transverse	None	1/8 crater@1 1/8 @4	3,4
TC7	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	1-1/8@1 3/16@2	1,2
TC8	Formed Channel EH-36 (5/16-in.)	Longitudinal	None	1/8crater@2	2
TC21(TC5)	Formed Channel EH-36 (5/16-in.)	Transverse	None	- (1/8 crater@1)	3,4 (3,4)
TC22(TC6)	Formed Channel EH-36 (5/16-in.)	Transverse	None	- (1/8@2 [1/8 from end])	3,4 (3,4)
TC15	Formed Channel EH-36 (5/16-in.)	Longitudinal	3/8 inch EH-36	3@1 2-1/4@2	1,2
TC16	Formed Channel EH-36 (5/16-in.)	Longitudinal	3/8 inch EH-36	1-1/8@1	1
TC13	Formed Channel EH-36 (5/16-in.)	Transverse	3/8 inch EH-36	1/8@5 1/8@6	4,5,6 (3 not joined)
TC14	Formed Channel EH-36 (5/16-in.)	Transverse	3/8 inch EH-36	3/16@5	3,4,5,6
TC11	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	1-3/16@1 1-3/16@2	1,2
TC12	Formed Channel EH-36 (1/2-in.)	Longitudinal	None	1/8@1 2-3/8@2	2
TC9	Formed Channel EH-36 (1/2-in.)	Transverse	None	1/8@1	3,4
TC10	Formed Channel EH-36 (1/2-in.)	Transverse	None	-	3,4
TC19	Formed Channel EH-36 (1/2-in.)	Longitudinal	3/8 inch EH-36	2-3/16@1 2-7/8@2	1,2
TC20	Formed Channel EH-36 (1/2-in.)	Longitudinal	3/8 inch EH-36	3/8@1 9/16@2	2

Specimen Number	Channel	Channel Orientation	Lap plates	Crack Length	Cracked Tacks
TC17	Formed Channel EH-36 (1/2-in.)	Transverse	3/8 inch EH-36	-	4,5,6
TC18	Formed Channel EH-36 (1/2-in.)	Transverse	3/8 inch EH-36	1/8@4 1/8@5 1/8@6	3,4,5,6



Not to Scale

Figure 19. Positions of Tack Welds Between Channel And Deck

All cracking on transverse testing was small, 3/16-in. long or less, when measured on the surface of the fillet welds. The transverse testing was effective at cracking the inside tacks, with only one successful tack to the main plate unbroken, at location 3 on TC17. An example of a short crack is shown in Figure 20.



Figure 20. Short Crack Localized on Weld End

Cracking was more variable on the longitudinal tests, ranging from no cracks observed to a total crack length of 5-1/4 in. on TC15; the two cracks from TC15 are shown in Figure 21 and Figure 22. On TC12 the largest difference in crack length between the two sides was observed. Only the tacks nearest the impact point joined to the main plate ever cracked. Cracking grew in severity of total length as the thickness of the channel increased for the cases without lap plates.

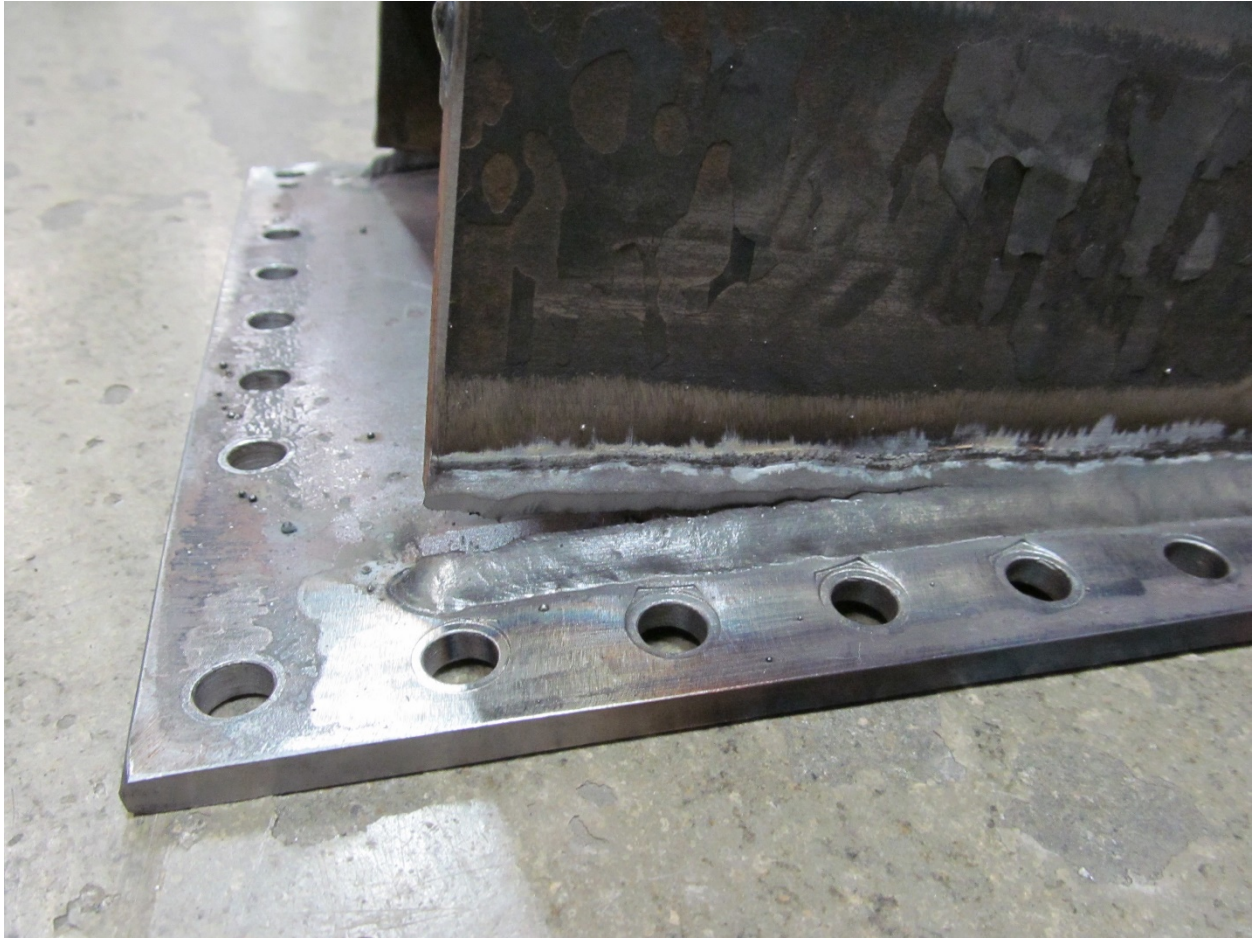


Figure 21. Crack at Position 1 on TC15



Figure 22. Crack at Position 2 on TC15

Discussion of results of drop weight testing

The materials sourced for the channels, lap plates, plate, and weld metal all are reasonable representations of channel to deck welding for the SRS. Strengths and elongation results exceed the required minima by large margins, as would be expected with modern steels.

The simple estimate of stresses before testing turned out to be inadequate for prediction because the small distance of the welds of interest and the stiff supports from the impact position. These simple estimates did not predict the yielding in the web observed in the strain gage results. These simple estimates also not predict sufficient stresses to cause the observed cracking in the weld areas.

Under high loads, the longitudinal channels had much less deflection than the transverse channels. Should plastic deformation occur in the SITS structure it would be expected that load would be transferred to the channels that are in the longitudinal orientation to the load rather than the transverse orientation.

6.2.3.6 Finite Element Analysis – Impact Testing

Finite element analysis is a computational method to numerically approximate the solution to differential equations. In the present case, the differential equations that govern elastic stress analysis are solved. The finite element program used for the analysis is COMSOL, which is an implicit package capable of multi-physics (all forms of differential equations, e.g. heat transfer, electrical, magnetic, etc.) simulation.

The finite element models used to create the channel sections were geometrically modified to simulate the configuration used in one of the drop weight tests (a description of the channels created for initial finite element modeling is found in Section 6.3 Task 3 Evaluate Connection Performance with Different Use Scenarios). The model consisted of a formed channel struck end-wise, i.e. along the x-axis in the previous modeling.

The details of simulating the contact mechanics of the weight striking the specimen are extremely non-linear because a complete model would simulate the contact area, the load distribution in the contact area and would also enforce the non-interpenetration condition. These are important properties to know if the details of the contact are required. In the present case, strain gauge data and impulse data (duration of impulse) were obtained experimentally and could be relied on if necessary. Hence, an impulse load was applied to the model, based on Roark's Formulas for Stress and Strain and the only variable that needs to be verified to produce a useful model is the duration of the pulse.

Figure 23 shows the model of the test specimen. The value of the load used was estimated using handbook formulas available from Roark and Young

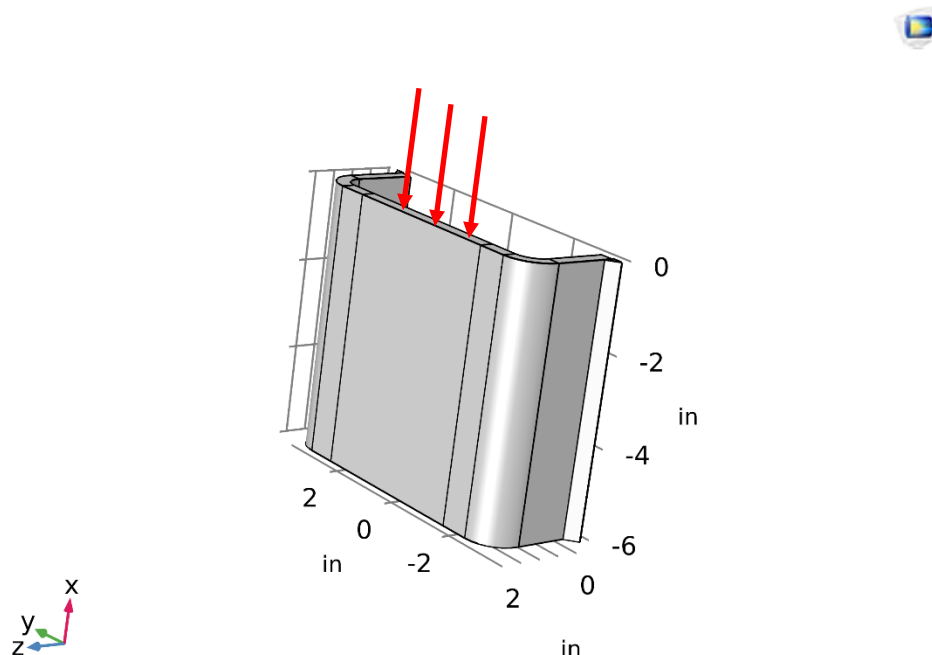


Figure 23. Finite Element Model of Test Specimen Showing Location of Impact

A squashing function was applied after the first half wave of the sine wave to ensure that no additional loading was applied to the model, i.e. that a single impulse was applied. The impulse that was applied to the model is shown in Figure 24.

Figure 25 illustrates a squashing function that was applied to force the sine wave impulse to zero after the first half wave was completed. Ideally, it goes from unit value to zero in a very small period of time. The length of time needed to force it to zero had to be calibrated to the impulse sine wave duration (note that the impulse is in microseconds).

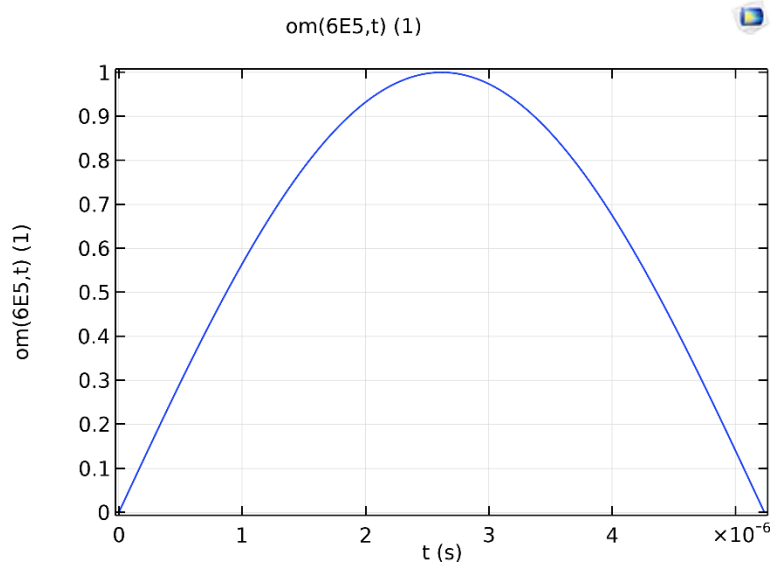


Figure 24. A Half Sine Wave Impulse Applied to the Model Using an Estimate of Duration

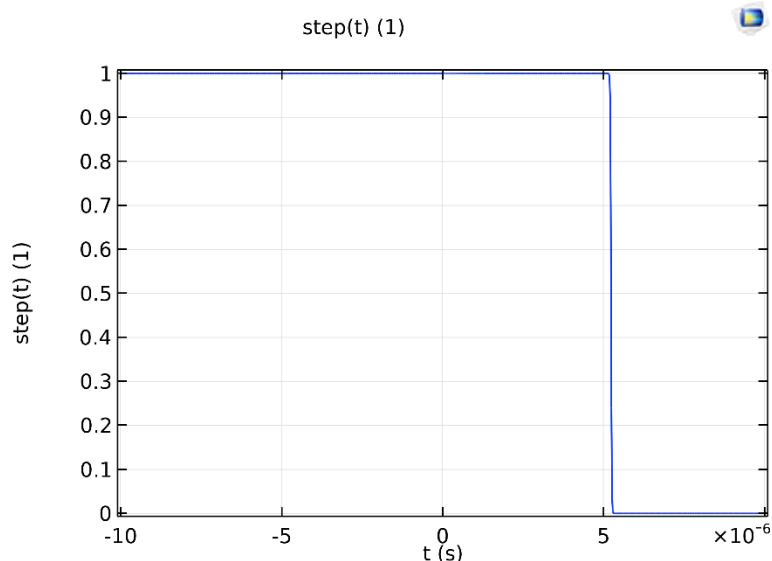


Figure 25. Example of the Squashing Function Used as Applied to the Model

Figure 26 shows an example of the impulse wave moving through the channel. The negative of the axial stress (σ_x in the model) is shown as it travels the distance of the specimen. Note the very short time frame (on the order of microseconds). As the wave travels, waves of opposite sign travel along behind it and are reflected inside the specimen. The stress on the welds can be obtained.

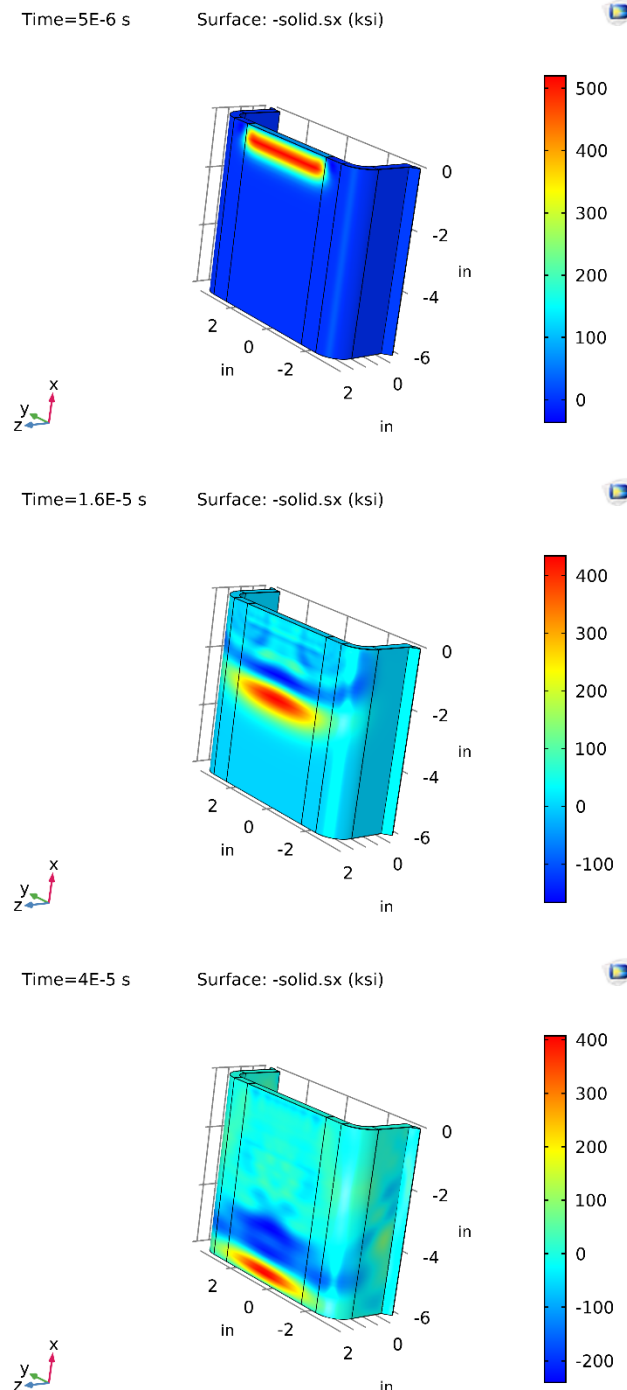


Figure 26. Example Results of the Impact Simulation

6.3 Task 3 Evaluate Connection Performance with Different Use Scenarios

6.3.1 Details of the Modeling Procedure

Two styles of finite element models were developed, i.e. one to simulate the 'structural' channels which were obtained from a steel rolling mill and one to simulate the 'formed' channels that were rolled from flat plate. Each of these styles was, in turn, used to model each of the 5 types of channel sections as described in Figure 7-10 (Figures 7-10 also show the areas of incomplete welding). For Figure 27, note the sharper edges and thickness change in the flanges (which is typical for structural channel). In Figure 28, note the corners are simply radiused (which is a result of the plate being formed to a channel shape).

Additionally, observations from a previous trial rescue mission indicated locations where complete welds were unable to be made, and these were simulated as well.

The dimensions for the use of lap plates, which are allowed up to 2-inches in height for leveling purposes, are shown back in Figure 11. Also shown in Figure 11 are the dimensions of cap plates, which are designated in certain areas for reinforcement.

Considering the various combinations of channel type, the use of lap and cap plates, and the areas of incomplete welding a total of 51 finite element models were developed to simulate all of these combinations; a description of each is given in Appendix M.

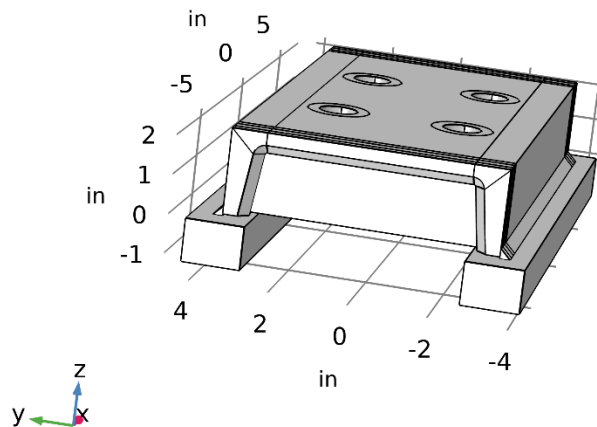


Figure 27. Type 1 Geometry Used in Finite Element Modeling of Structural Channel Sections

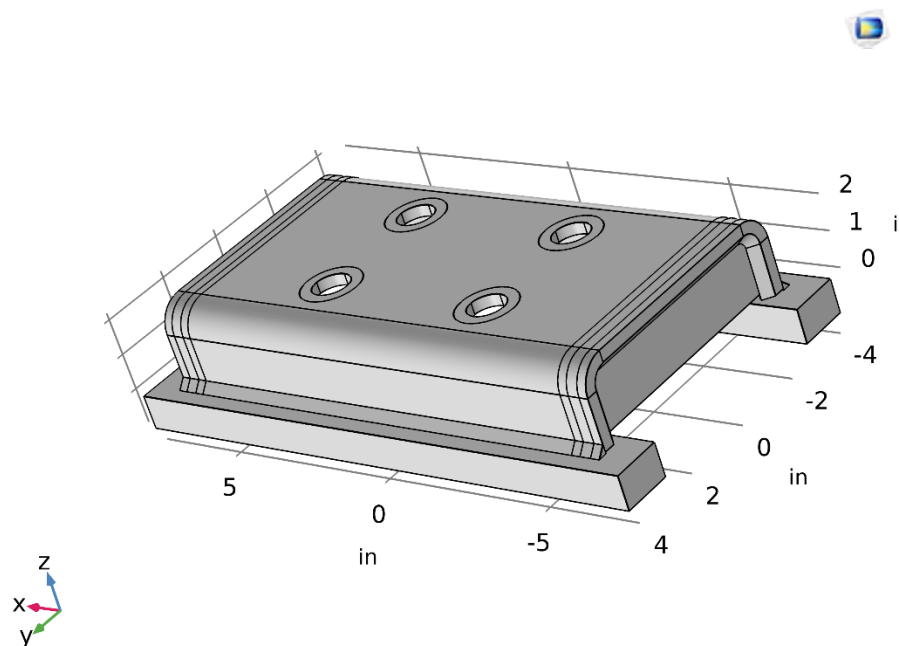


Figure 28. Type 1 Geometry Used in the Finite Element Modeling of Formed Channel Sections

6.3.2 Model Validation

Loads were applied to the model through the bottom of the bolt circles, as shown in Table 1. An illustration of the load application is shown in Figure 29. The models were validated by putting a unit load on the bolt circle (which is shown in the left image of Figure 29), then integrating the stress over the resultant area to determine whether the applied total load matched the computed integral of the stress over the area of the weld (shown in the right image of Figure 29). Once the applied and computed values matched within 5%, the mesh was deemed to be sufficiently refined and the model validated.

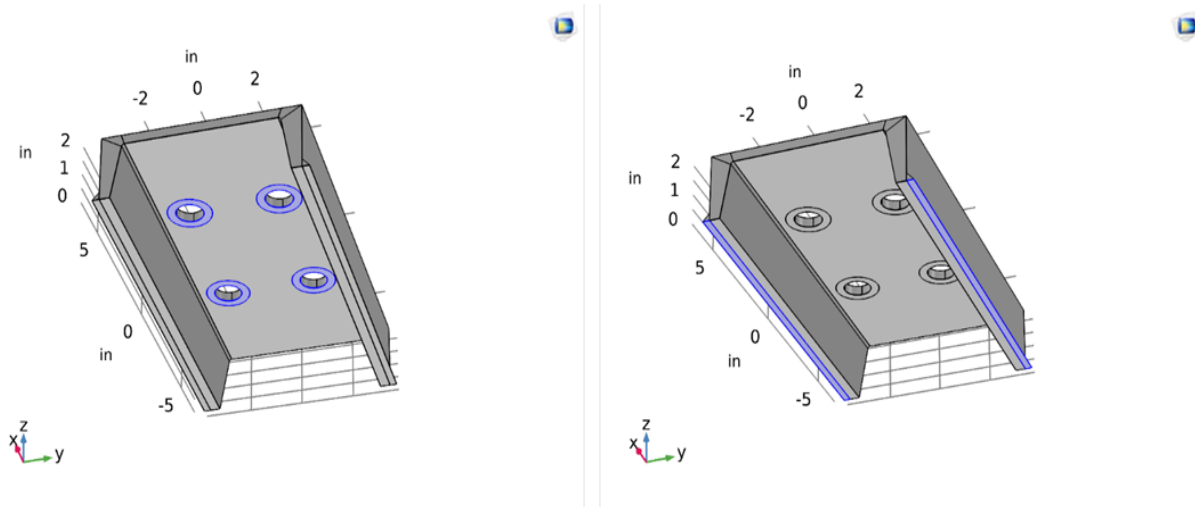


Figure 29. Loading Application for All Models

Note that all finite element simulations are an estimate and it is impossible to match the results exactly. The mesh refinement study included various types of tetrahedral, hexahedra, and prism elements. The results of the refinement study are shown in Table 25. The approximate density of the required mesh is shown in Figure 30 (This approximate mesh density was used for the remainder of the investigation).

Table 25. Results of Refinement Study

Mesh Type/Description	Model Predicted Load (lbs.)	Error
Coarse Tetrahedron Mesh	1821.6	82.16%
Fine Tetrahedron Mesh	1234.7	23.47%
Coarse Prism	1939.8	93.98%
Fine Prism	1052.6	5.26%
Fine Hexahedron	1018.1	1.81%

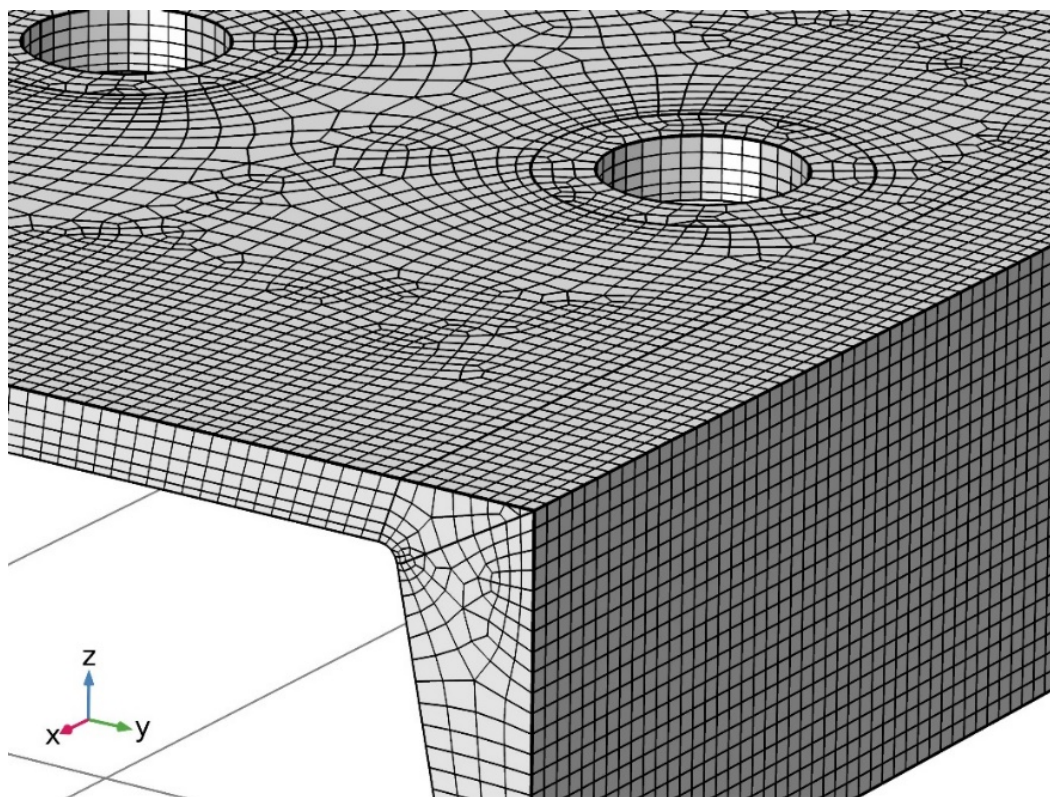


Figure 30. Up-Close Image of a Finite Element Mesh Which Produced Adequate Accuracy

6.3.3 Model Acceptance Criteria

The models used in the investigation are linear elastic. Therefore, post yielding behavior is not modeled, i.e. if the stress happens to exceed yield, the stress will simply increase linearly beyond yield. Because of this, certain areas within the weld will be predicted to have abnormally high stresses, specifically, the root and the face of the fillet weld. To illustrate this point, Figure 31 shows an early result of stress distribution prediction in the cross-section of a fillet weld. The left hand image shows the layout of a dual fillet weld and defines locations A-B-C-D. The right hand image shows the stress profile along a leg of the fillet (A-B and B-C) and across the throat (B-D).

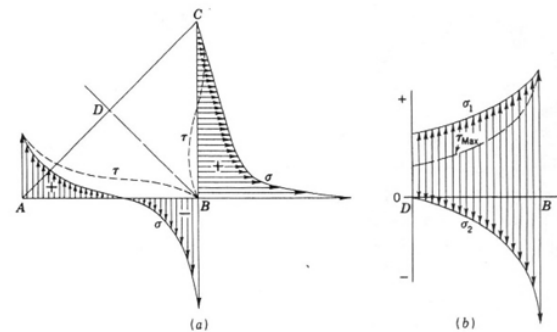
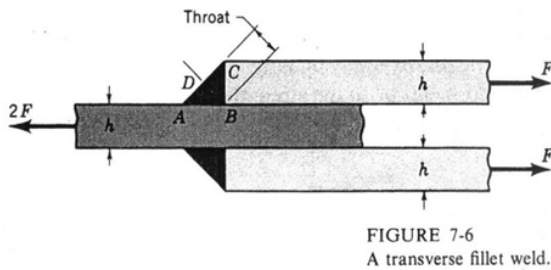


FIGURE 7-7
Stress distributions in fillet welds. (a) Stress distribution on the legs as reported by Norris; (b) distribution of principal stresses and maximum shear stress as reported by Salakian.

Figure 31. Stress Analysis of a Fillet Weld (as Reported by Shigley)

Acceptance criteria were furnished by the NAVSEA 05P Technical Warrant Holder for purposes of evaluating the welds. The criteria were requested because of the known over-prediction of stress in the weld profile, due to the linear nature of the model.

The acceptance criteria are shown in Figure 32. Box 1 and 2 of Figure 32 are used to determine the parameter F_a (which is used throughout the calculation); for purposes of this investigation, 36 ksi is used based on the material specification.

Box 3 is the shear allowable stress of the weld material on a 45-degree plane (the throat dimension B-D in Figure 31) and is computed to be 20.86 ksi for the remainder of this investigation.

Box 4 is the localized allowable stress computed to be 47.7 ksi, which is taken over a minimum dimension of 2-inches and on a 45-deg plane.

Box 5 is 18 ksi and Box 6, which pertains to fatigue, is to be computed by others.

Boxes 7, 8, and 9 are not directly related to weld evaluation but are rather part of a general acceptance criteria.

ACCEPTANCE CRITERIA FOR BASE MATERIAL AND WELDS ON THE LARS C-CHANNEL ATTACHMENT

Below is the table requested for the “reduced install time study”:

Stress Component	Allowable Stress/Load/Criteria
P-LARS	
1 General Stresses (base material and welds), if $\sigma_{\text{yield}}/\sigma_{\text{ult}} \leq .7$, unless otherwise stated below. (1), (2), (3), (4)	$\sigma_{\text{yield}}/1.33$ (Specified as F_a)
2 General Stresses (base material and welds), if $\sigma_{\text{yield}}/\sigma_{\text{ult}} > .7$, unless otherwise stated or modified below (1), (2), (3), (4)	$(\sigma_{\text{yield}} + \sigma_{\text{ult}})/3.25$ ($=F_a$)
3 Shear Allowable Stress	$\tau = 0.577 F_a$
4 Localized stresses – length not exceeding 2” or extend from the root of the weld.	σ_{yield}
5 Root of one sided weld in bending	$F_a/2$
6 Fatigue/Fracture	Indication does not reach critical crack size based on full number of anticipated cycles. (5)
Allowable Bearing Stress	$1.6 \sigma_{\text{yield}}$
Web Crippling	Steel Construction Manual - AISC
Buckling	Min Predicted Buckling $> 1.5 F_{cr}$

Notes:

- (1) Stresses in welds shall be determined across a 3” length. Averaging over the entire weld shall not be used to evaluate the weld. Hand calculations may be used, applied loads are based on extracting forces from the FEA model.
- (2) Assumes the welds have been VT and MT inspected.
- (3) Minimum properties shall be used in analysis.
- (4) Yield strength of weld shall be that of the base material due to dilution.
- (5) Defect size shall be based on NASA-5009 for the exposed face of the weld. For the root of the weld, the length shall be the width of the weld and the depth of the defect size shall be double of that specified in NASA-5009.

Figure 32. Acceptance Criteria for Model Evaluation

6.4 Task 4 Perform Model Calculations to Determine Optimum Materials and Weld Designs

6.4.1 Finite Element Analysis – Results

A method was developed to query the finite element models, as described below, in order to evaluate each of the acceptance criteria described above. The method consists of producing a series of stress plots at various locations within the model for evaluation. It typically takes 20 images to produce the desired results needed for evaluation—hence, a total of approximately 1000 images were developed. The images are distributed under separate cover for easier evaluation.

The images can be found on the CNM share point website (managed by ATI) at this link: <https://projects.navalmetalworking.org/non-mantech-projects/sub-rescue-fea/misc/sand-box/jims-sandbox/results-files>

(Note: to access these images, access is required from ATI. If access is required, the reader will need to contact Sean McDowell at sean.mcdowell@ati.org).

A common coordinate system is introduced which each model adhered to. The x-axis is longitudinal on the channel section, with the negative x-direction closest to the viewer in 3D images. The y-axis is horizontal shear across the channel, and the vertical direction is along the z-axis (see Figure 33). The weld that is on the left hand side in in Figure 33 (positive y-axis) is designated as “1” and the weld on the right hand side is designated as “2.” Each of the images, either 2D or 3D, shows the global coordinates in order to know where in the model the data were taken from. The images produced for each model are shown in Table 26.

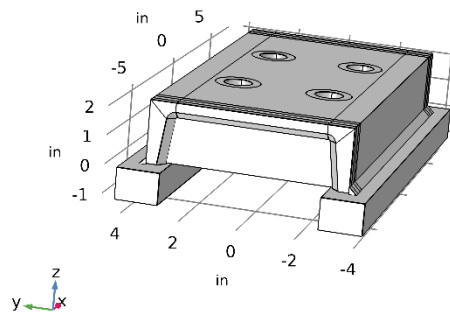


Figure 33. Common Coordinate System Applied for Presenting Results from All Models

A feature of most finite element modelling software is that the meshes of two bodies (or components) in contact with one another will automatically become part of the same body and the mesh will be automatically made continuous between the bodies. In the case of welding, if this is allowed to hold true during modelling, the stresses produced will be abnormally low, because the model will distribute the load across the base material as well as the weld. For this reason, each model in the area of the weld, was formulated to have a 0.050-in. gap so that the weld would be loaded correctly. The 0.050-in. gap (or arc length) was selected because with gap distances less than 0.050-in., the stresses in the root are shown to be high, which is shown in Figure 34 (the high stresses in the root were previously addressed back in Section 6.2.3).

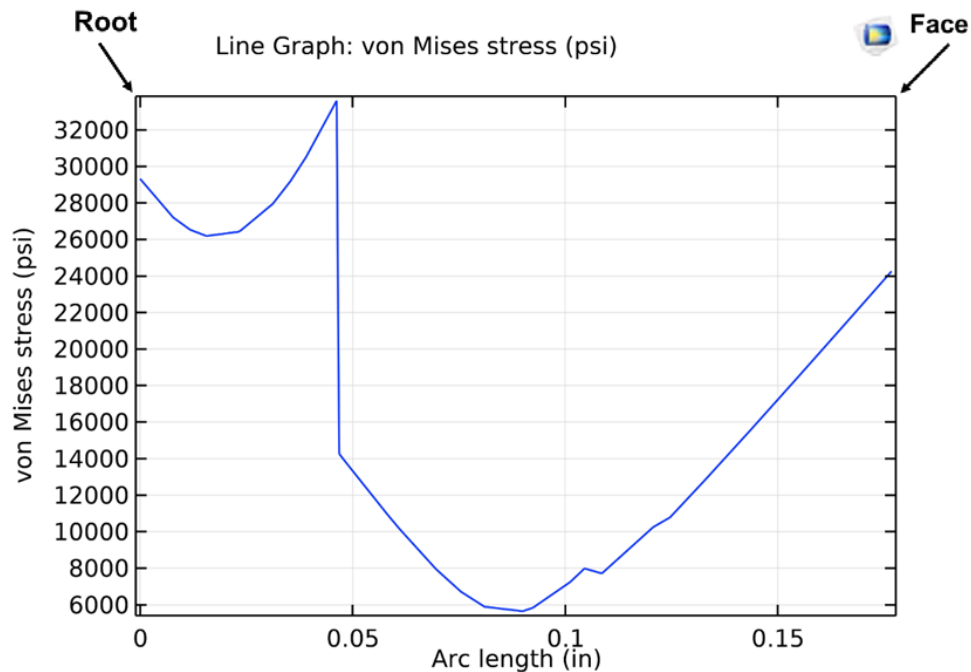


Figure 34. Von Mises Stresses from Root to Face in a Fillet Weld

As shown in Figure 35, the base area (in blue) simulates the deck located below the channel and has a 0.050-inch gap between it and the channel section. The weld (the grey triangular shape) is meshed and tied correctly to both the deck and the channel such that all loading is applied through the weld.

Table 26. Description of Images Produced for Each Created Model

Model Number	Image Number	Description
The first 2 digits of the image file are the model number (these images can be found in the link shown in Section 6.4.1).	01, 02	“Geom” 3D plots of the overall geometry
	03, 04, 05	“Mises” 3D plots of the von Mises stress
	06	“Mises1” 2D plots of the von Mises stress along the LHS weld as viewed in Figure 18. This is a 45-deg plane across the throat of the weld. This is not required for evaluation of the acceptance criteria.
	07	“Mises 2” 2D plots of the von Mises stress along the RHS weld as viewed in Figure 18. This is a 45-deg plane across the throat of the weld. This is not required for the evaluation of the acceptance criteria.
	08	“Norm 1” 2D plot of the stress projected normal to the 45-deg (throat) plane, used for bending evaluation of Box 5 in Figure 17. LHS weld of Figure 18.
	09	“Shear 1” 2D plot of the shear stress on the 45-deg (throat) plane, used for shear stress evaluation of Box 3 in Figure 17. LHS of Figure 18.
	10	“Norm 2” 2D plot of the stress projected normal to the 45-deg (throat) plane, used for bending evaluation of Box 5 in Figure 17. RHS weld of Figure 18.
	11	“Shear 2” 2D plot of the shear stress on the 45-deg (throat) plane, used for shear stress evaluation of Box 3 in Figure 17. RHS of Figure 18.
	12, 13, 14,15, 16, 17	“Princ1” and “Princ2” are 1D plots of max and min principal stresses (Sig-1, Sig-3) along the 45-deg plane, the horizontal leg and the vertical leg. Abscissa shows location in the model in the x-direction. “1” is the LHS weld as viewed in Figure 17 and “2” is the RHS weld as viewed in Figure 17. This is for evaluating Box 6 of the criteria.
	18	“PrincPeak” is max principal stress (Sig-1) on a short section of the weld in an area of high stress, on a 45-deg plane. The abscissa shows the location along the x-axis in Figure 17. This is used to evaluate Box 4 in the criteria.

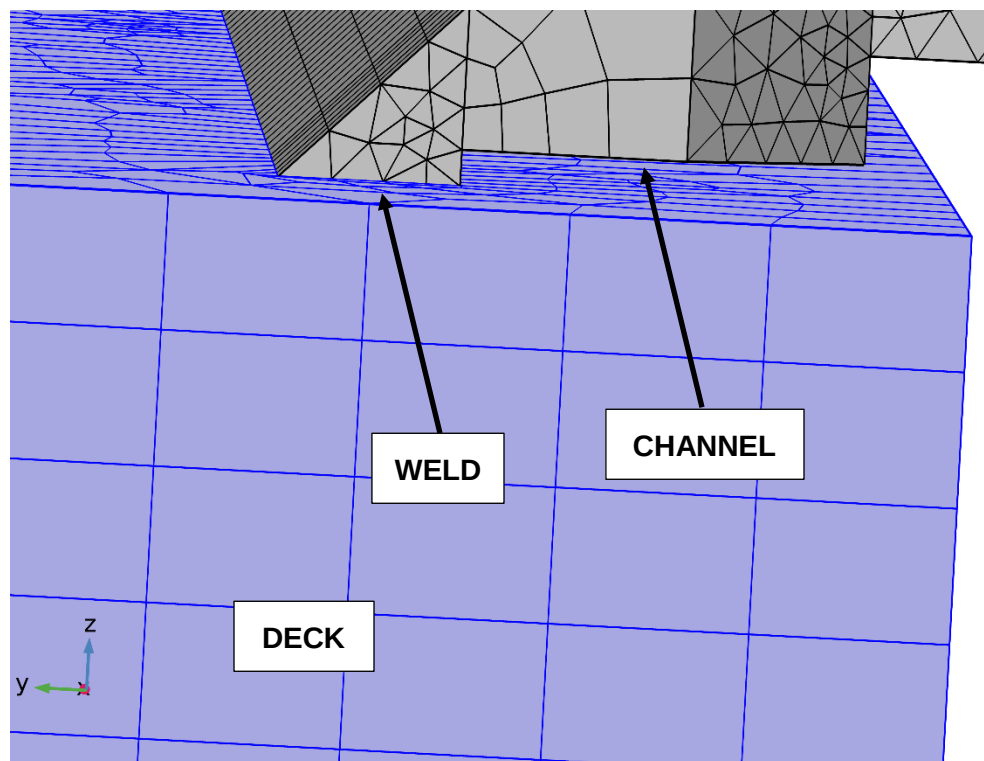


Figure 35. Illustration of Intentionally Produced Gap in the Finite Element Model

6.4.2 Type 1 Results – An Illustration

Using Table 26, an illustration is presented for the Type 1 configuration with a formed channel section that has continuous welds. Referring to the database, the geometry is shown in Figure 36. The left hand image is generated from file “02 01 Geom.png”, indicating this is Model 02 shown in the link shown in Section 6.4.1. The image on the right hand side is file “02 02 Geom.png”, which is an alternate view (see Table 26).

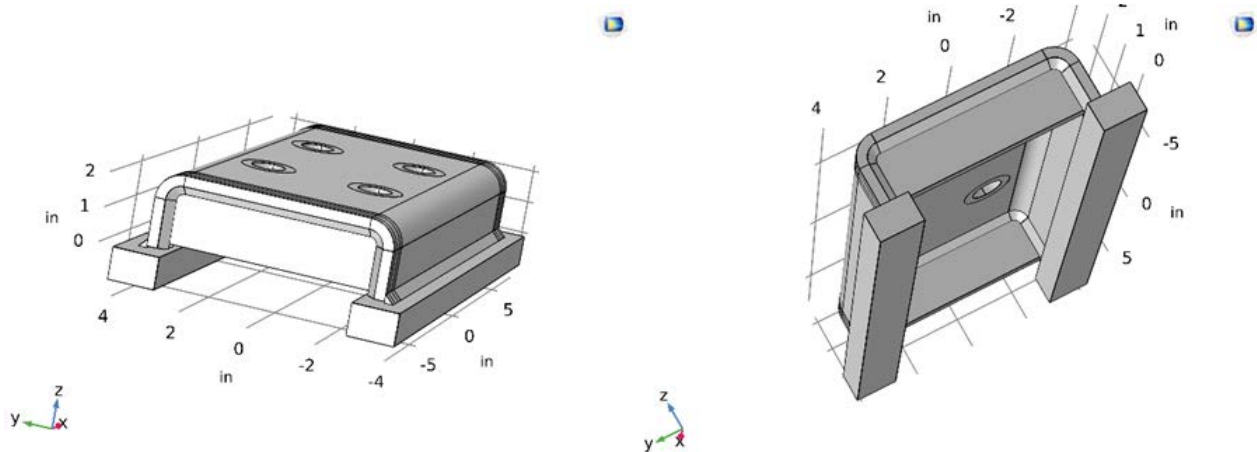


Figure 36. Example of a Model Produced Using Data from Table 26

The 3D Von Mises stresses are shown in Figure 37 and consists of 3 image files which are identified in the caption (listed from the top to bottom: files “02 03 Mises.png,” “02 04 Mises.png,” and “02 05 Mises.png”; refer to Table 26).

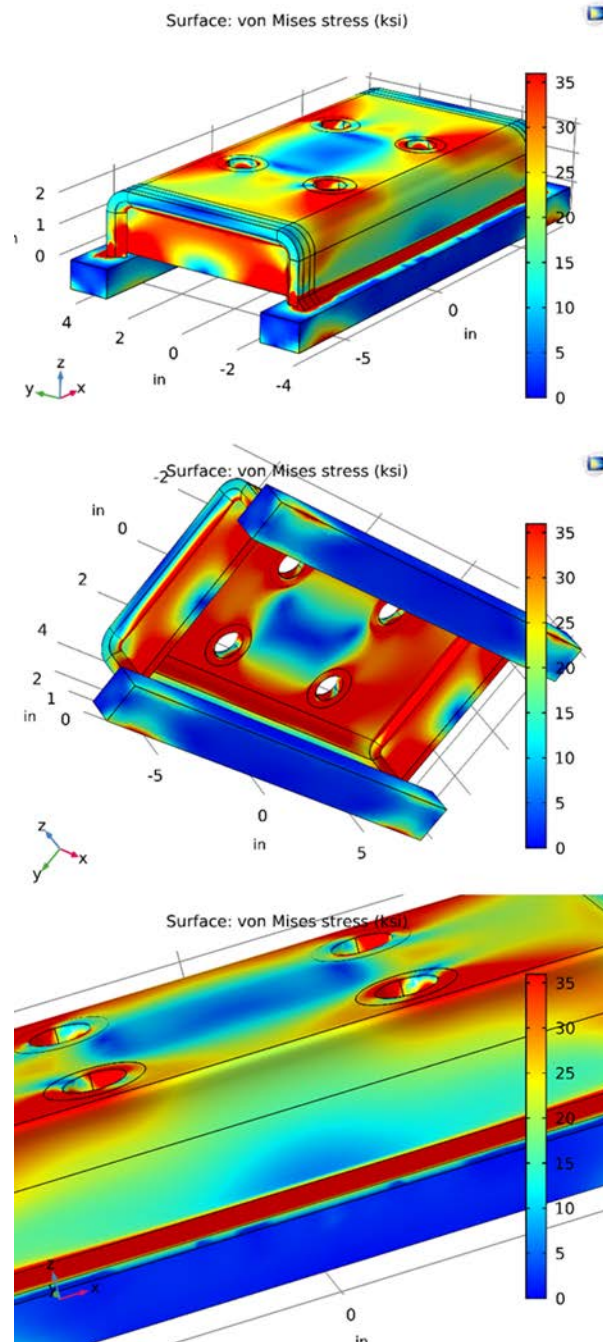


Figure 37. Von Mises Stress in 3D

A slice is made on a 45-deg plane through the “1” weld (shown in red on the left hand image of Figure 38). The image on the left hand side in Figure 38 shows a distant view of the outline of the entire model. The image on the right in the same figure shows a close up for the area in which the data are available (this cut does not include the end effect areas near the gusset plate but includes the main part of the weld).

In general, stresses are constant along the length of the weld with some end effects. The close-up area of the 45-deg cut plane is taken at the center, i.e. $x = 0$ to demonstrate the stresses.

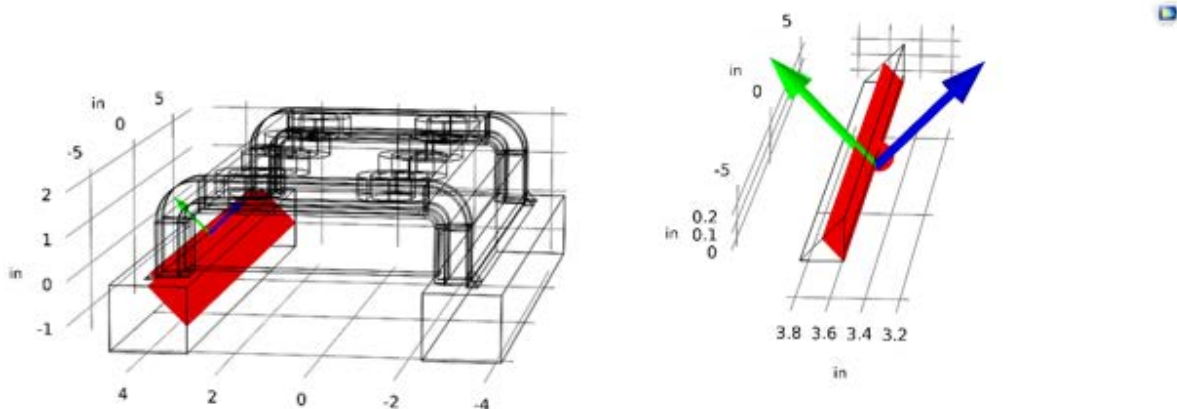


Figure 38. Example of the 45-Degree Slice Plane Along the Throat from the Root to the Face

On the 45-deg slice plane, the Von Mises stress, the normal stress to the plane, and the shear stress in the plane will be reported for both the left side weld “1” and right side weld “2.” The stresses calculated by the COMSOL finite element program are global in nature, i.e. are (x, y, z) coordinates. In addition, the software will calculate the principal directions and principal stresses and can do so on any plane as well.

However, to compute the normal stress on to the plane and the shear in the plane, the global stresses need to be resolved using a coordinate transformation. The result will allow computations to determine the acceptance required by Box 3 (shear) and Box 5 (bending) in the acceptance criteria (Figure 32). Equations 10 and 11 show the coordinate transformation required to compute the surface normal vector (Equation 10) and the surface traction vector (Equation 11).

$$t_n = t \cdot n \quad (10)$$

$$t_s = [I - n \otimes n]t \quad (11)$$

Where:

- n is the surface normal vector
- t is the stress state in the continuum
- t_n is the normal stress vector on the 45-deg plane
- t_s is the traction stress vector in the 45-deg plane

Figure 39 and Figure 40 are the Von Mises stresses on the 45-deg plane, with Figure 39 being the “1” weld located on the left side of Figure 33 and Figure 39 being the “2” weld located on the right side of Figure 33.

For Figure 39, the left hand image is a distant view showing almost the entire length of the weld from $-4 < x < +4$. The right hand image of Figure 38 is a close up view with $x = 0$. The ordinate shows the length along the plane with 0 being the root (bottom) and the top being the face of the weld. These are files “02 06 Mises1 – 45 deg.png” and “02 06a Mises1 – 45 deg.png” (refer to

Table 26).

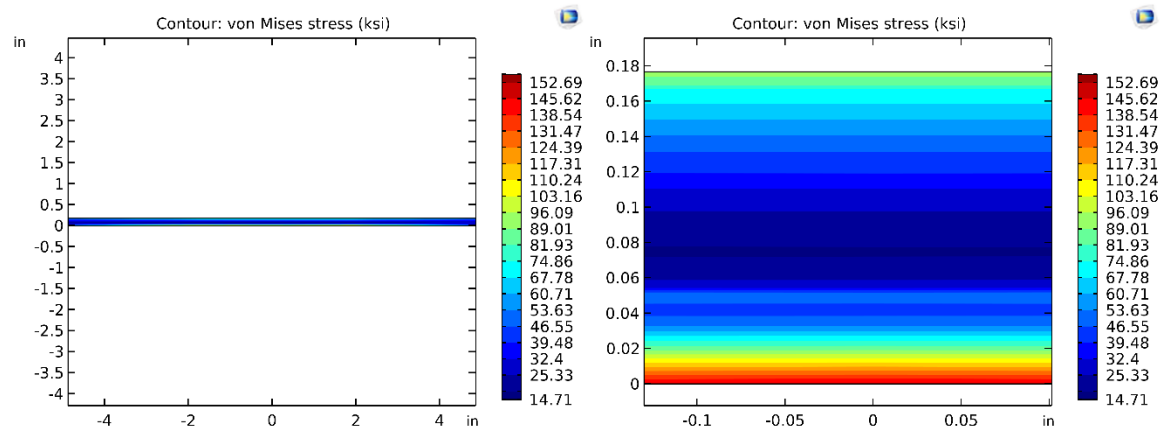


Figure 39. Von Mises Stress in the 2D Plane Located at 45-deg on the “1” Weld

For Figure 40, the left hand image is a distant view showing almost the entire length of the weld from $-4 < x < +4$. The right hand image of Figure 39 is a close up view at $x = 0$. The ordinate shows the length along the plane with 0 being the root (bottom) and the top being the face of the weld. These are files “02 07 Mises1 – 45 deg.png” and “02 07a Mises1 – 45 deg.png” (refer to

Table 26).

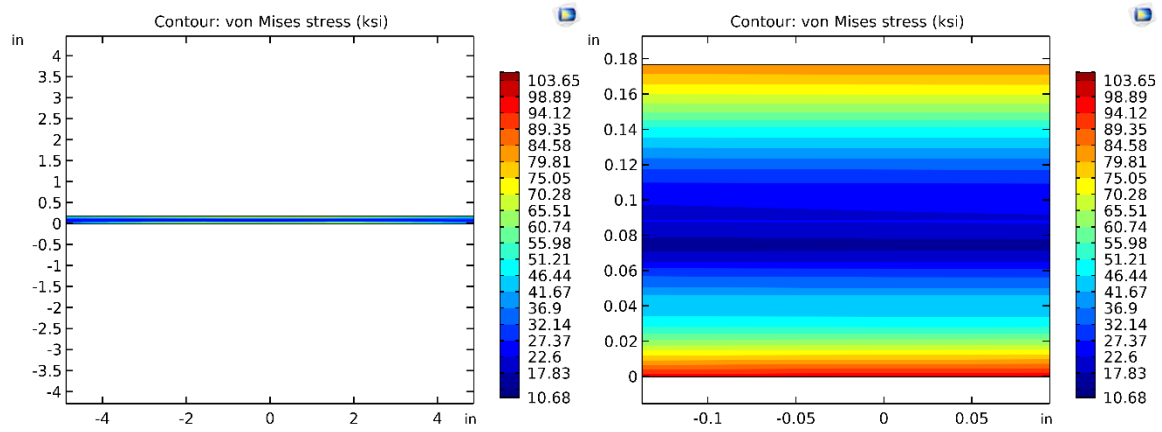


Figure 40. Von Mises Stress in the 2D Plane Located at 45-deg on the “2” Weld

Figure 41 is the normal stress on the “1” plane and Figure 42 is the shear stress on the “1” plane.

For Figure 41, the left hand side is a contour plot showing all values of stress and the right hand side is a plot of all stresses greater than the acceptance criterion (36 ksi), where the blue area is less than 36 ksi and the red areas are everything above 36 ksi.

Note the scale and the inequality in the top caption; these are files “02 08 Norm1 – 45deg.png” and “02 08a Norm1.png” (refer to Table 26) and also note that this is the region near where $x = 0$ (see the abscissa).

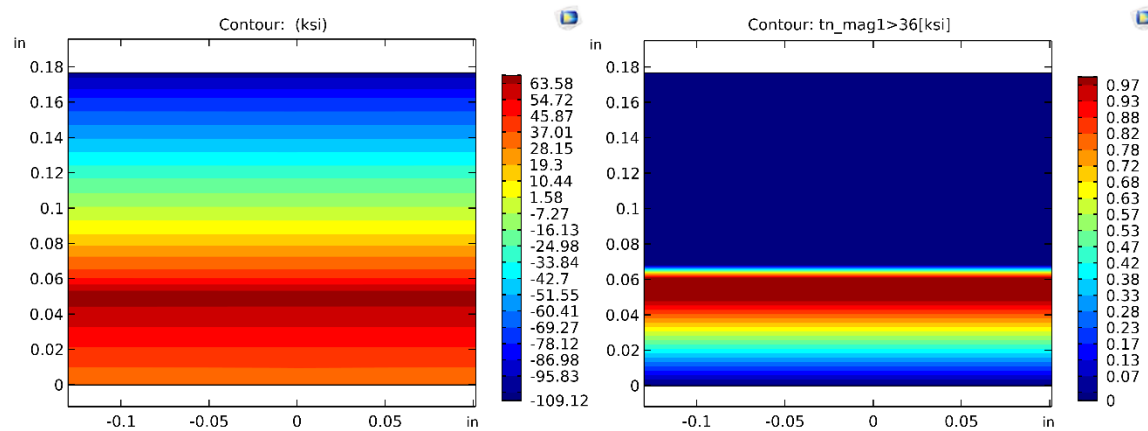


Figure 41. Stress Normal to the 45-deg Plane on the “1” Weld

For Figure 42, the left hand side is a contour plot showing all values of stress and the right hand side is a plot of all stresses greater than the acceptance criterion (20.86 ksi), where the blue area is less than 20.86 ksi and the red areas are everything above 20.86 ksi

Note the scale and the inequality in the top caption; these are files “02 09 Shear1 – 45deg.png” and “02 09a Shear1.png” (refer to Table 26); the area that is above the acceptance criterion for shear is in the root. Note that this is the area of the weld where $x = 0$ (see the abscissa).

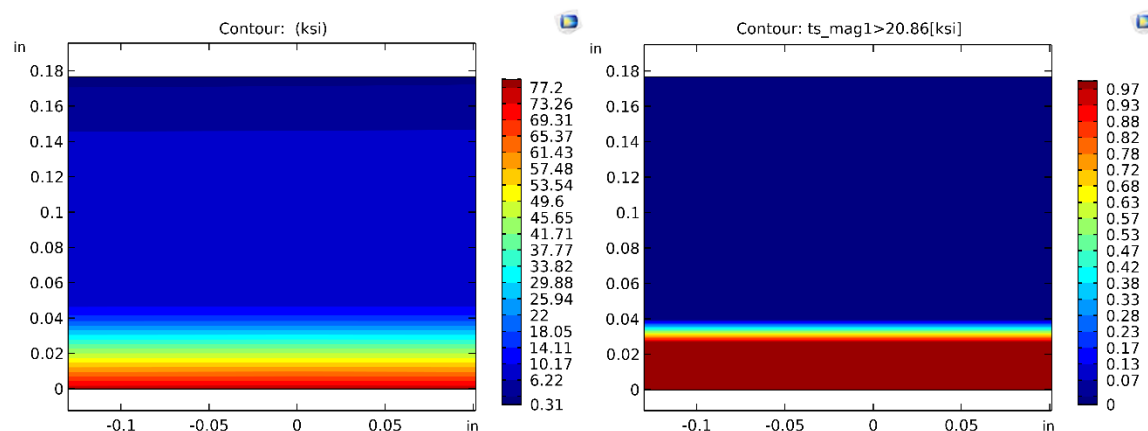


Figure 42. Shear Stress on the 45-deg Plane on the “1” Weld

Figure 43 is the normal stress on the “2” plane and Figure 44 is the shear stress on the “2” plane.

For Figure 43, the left hand side is a contour plot showing all values of stress and the right hand side is a plot of all stresses greater than the acceptance criterion (36 ksi), where the blue area is less than 36 ksi and the red areas are everything above 36 ksi

Note the scale and the inequality in the top caption; these are files “02 10 Norm2 – 45deg.png” and “02 10a Norm2.png” (refer to Table 26) and also note that this is the region near where $x = 0$ (see the abscissa).

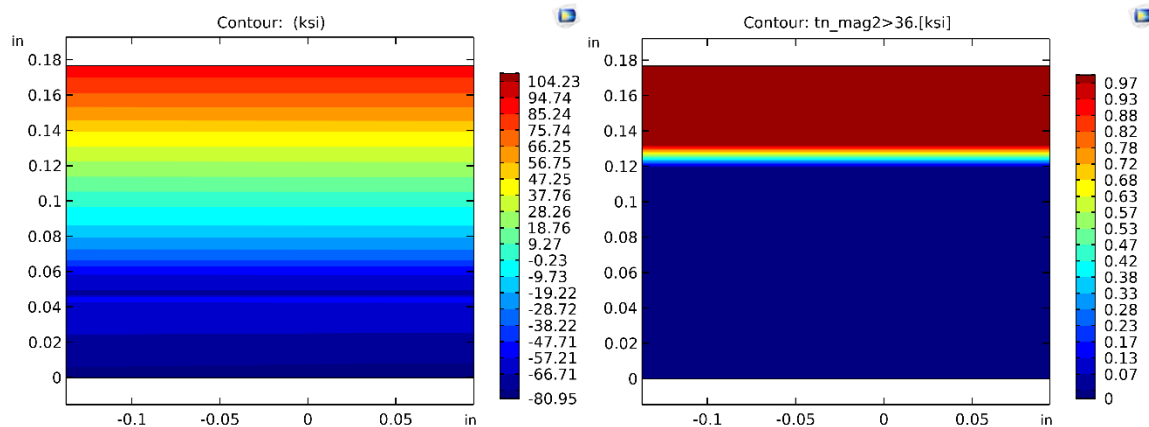


Figure 43. Stress Normal to the 45-deg Plane on the “2” Weld

For Figure 44, the left hand side is a contour plot showing all values of stress and the right hand side is a plot of all stresses greater than the acceptance criterion (20.86 ksi), where the blue area is less than 20.86 ksi and the red areas are everything above 20.86 ksi

Note the scale and the inequality in the top caption; these are files “02 11 Shear2 – 45deg.png” and “02 11a Shear2.png” (refer to Table 26). The area that is above the acceptance criterion for shear is in the root. Note that this is the area of the weld where $x = 0$ (see the abscissa).

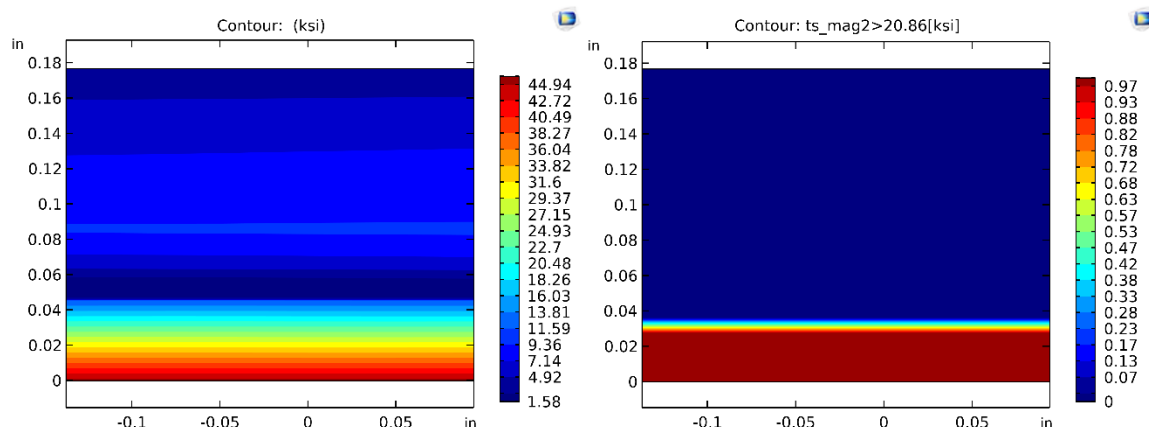


Figure 44. Shear Stress on the 45-deg Plane on the “2” Weld

Figure 45 shows the traverse lines for examining the principal stresses (max and min) in order to evaluate the fatigue criterion of the acceptance criteria (Box 6 in Figure 32). A traverse is made from the root of the weld along a line, located at $x = 0$ in 3 directions: along the horizontal leg, along the 45-deg throat and along the vertical leg. If the weld is intermittent, the traverse is made at the center of the weld – not necessarily at $x = 0$.

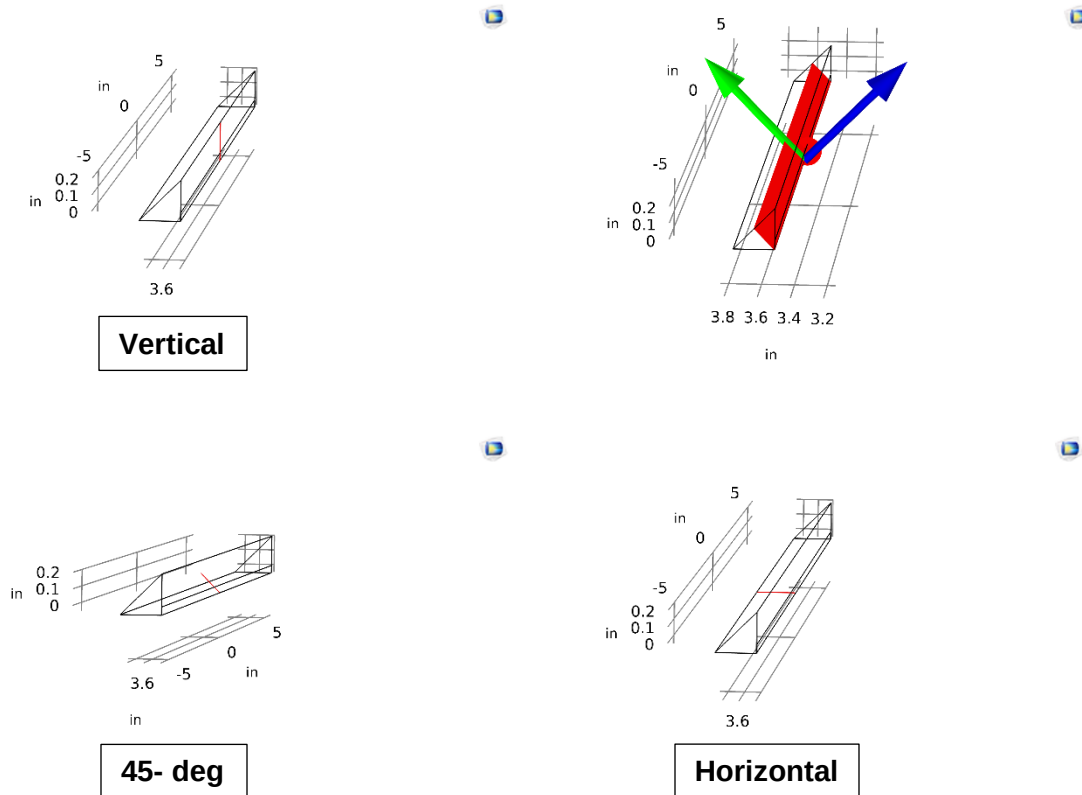


Figure 45. Orientation of Line Plots for Principal Stress Values

Figure 46 shows the results of the principal stress traverse along a path for Weld “1” and Figure 47 shows the results for Weld “2.”

Principal stresses (max and min) for Weld “1” include a traverse from the root outward in the vertical, 45-deg diagonal, and horizontal directions at the midpoint along the x-axis of the weld

Note the size of the gap as shown in Figure 35 is about 0.050-inch and the stress results are higher in this region (see the black vertical lines in Figure 45); these are files “02 12 Princ1 – 45 deg.png,” “02 14 Princ1 H.png,” and “02 15 Princ1 V.png” (refer to Table 26).

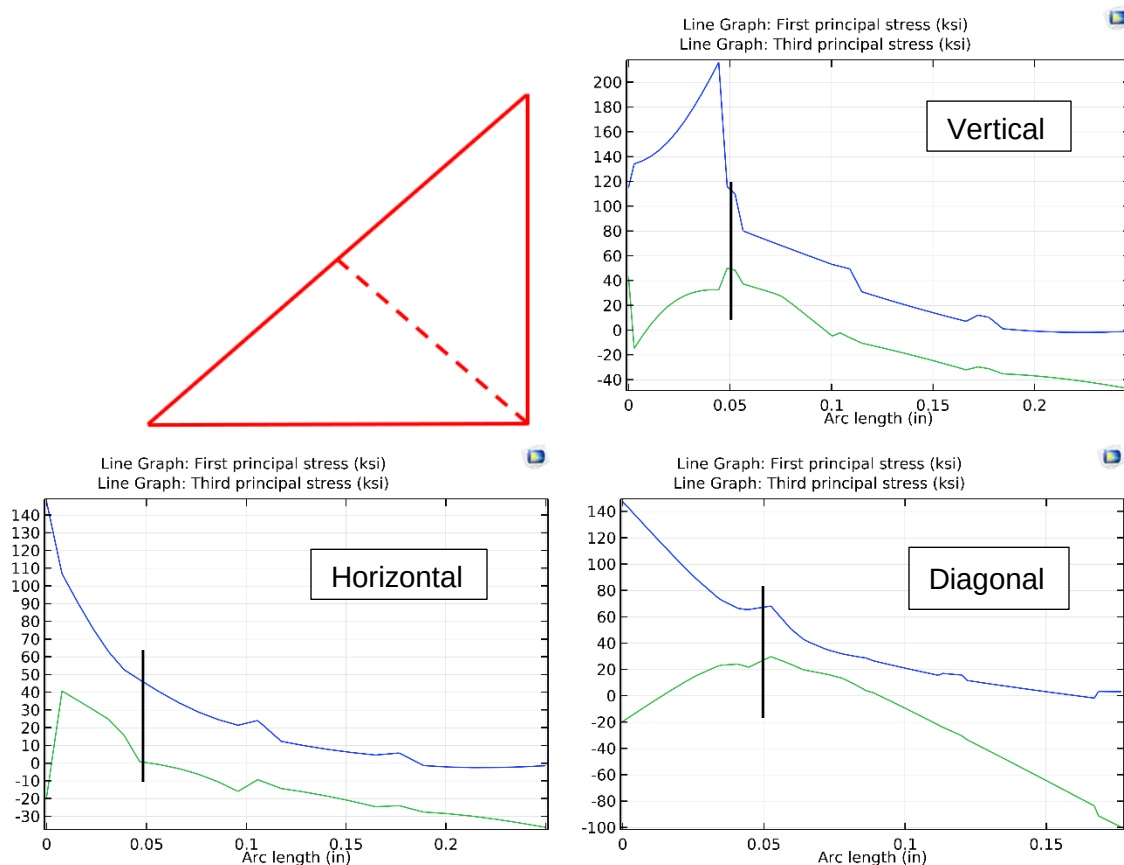


Figure 46. Principal stresses (max and min) for Weld “1”

For Weld “2”, the principal stresses (max and min) for a traverse from the root outward in the vertical, 45-deg diagonal, and horizontal directions at the midpoint along the x-axis of the weld are shown in Figure 47.

Note the size of the gap as shown in Figure 35 is about 0.050-inch and the stress results are higher in this region (see the black vertical lines in Figure 47); these are files “02 13 Princ2 – 45 deg.png,” “02 16 Princ2 H.png,” and “02 17 Princ1 V.png” (refer to Table 26).

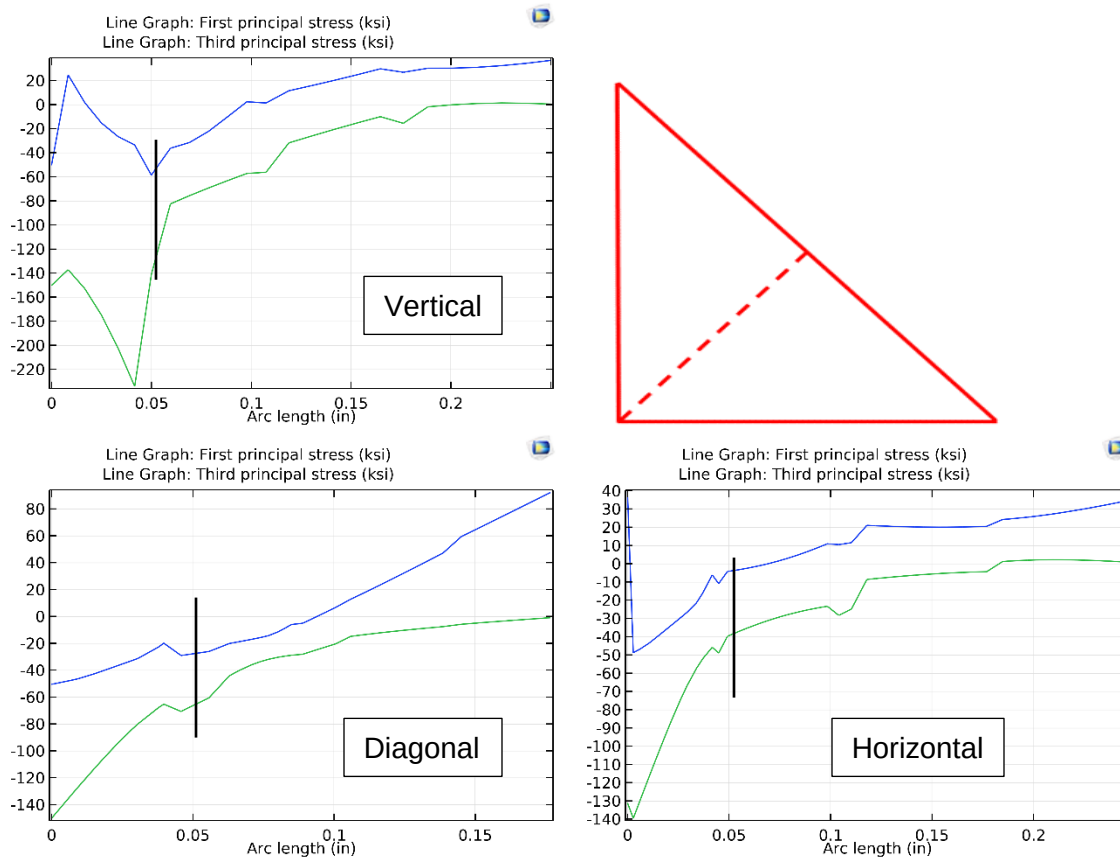


Figure 47. Principal stresses (max and min) for Weld “2”

The localized stress criterion of the acceptance criteria (Box 4 in Figure 32) is evaluated by plotting the max principal stress on a 45-deg plane across the throat in an area of highest local stress (in this instance near the gusset plate). The corners, near the ends of the welds, are typically the highest stressed areas. Figure 48 shows the location of the plane used to obtain the stress results and Figure 49 shows a plot of the max principal stress on a 45-deg plan in Weld "2" at the maximum negative x-dimension; the is file "02 18 PrincPeak - 45 deg.png" (refer to Table 26).

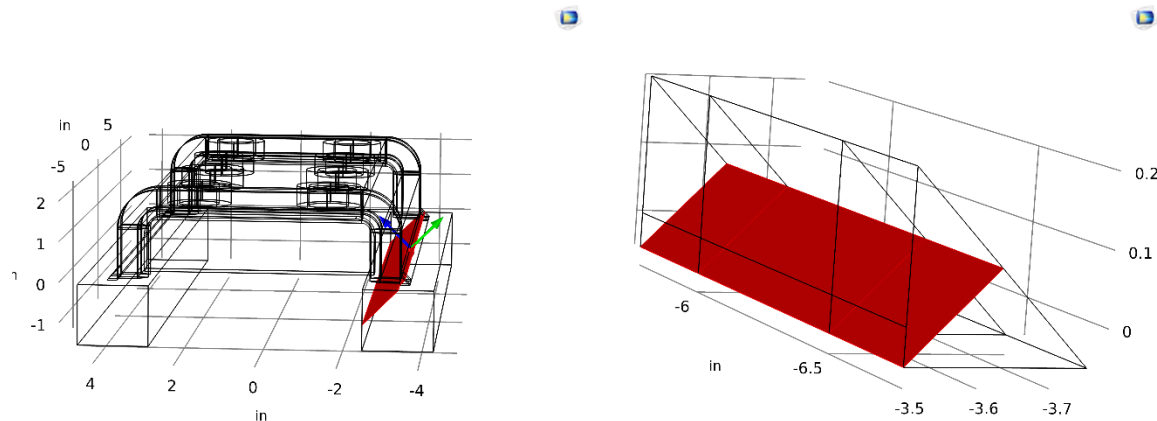


Figure 48. Area of Highest Stresses Used for Evaluation of Acceptance Criterion

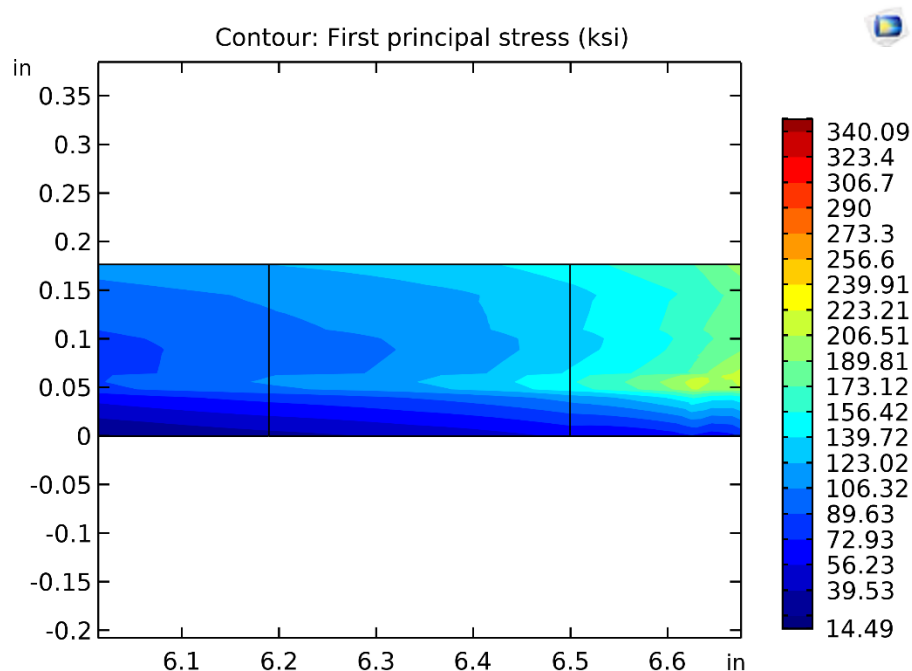


Figure 49. Plot of Max Principal Stress on a 45-deg Plane in Weld "2"

6.4.3 “Screening Tool” for Evaluation of Welds for Further Study

In order to be acceptable for use, per the acceptance criteria (Figure 32), all of the proposed stress types would need to be evaluated. However, during the investigation, it was noted that an examination of the maximum shear values on the 45-deg plane (Box 3 in the acceptance criteria) for the “1” and “2” welds is an easy way to determine if further investigation is required. Figure 43 and Figure 44 for the Type 1 connection indicate that most of the weld, with the exception of the area near the root, is less than the 20.86 ksi required to pass the test. Hence, examination of the maximum shear would indicate for the Type 1 connection having a formed channel, the shear stress would indicate that further evaluation is indicated.

Alternatively, when the use of lap plates is required, almost all of the connections fail the maximum shear stress evaluation and hence, would not be candidates for further evaluation. The results are given in Tables 27-31 (failures highlighted in yellow).

For the screening tests shown in Tables 27-31, results show that discontinuous welds and lap plates adversely affect the load carrying capability of the channel sections.

Table 27. Results of Screening Test for Type 1 Connection

Connection Type	Model Number	Description	Result of Screening
1 – Formed	02	Base Case, Continuous Welds	Further Investigation
	05	Base + Lap	No Pass
	08	Discontinuous Welds (4-inch)	No Pass
	11	Discontinuous Welds (1-inch)	No Pass
	14	Base + Lap + Cap	Further Investigation
	29	Discontinuous + Lap	No Pass
	32	Discontinuous + Lap	No Pass
	35	Discontinuous + Lap + Cap	No Pass
	38	Discontinuous + Lap + Cap	Maybe
1 – Structural	01	Base Case, Continuous Welds	Further Investigation
	04	Base + Lap	No Pass
	07	Discontinuous Welds (4-inch)	No Pass
	10	Discontinuous Welds (1-inch)	No Pass
	13	Base + Lap + Cap	Further Investigation
	28	Discontinuous + Lap	No Pass
	31	Discontinuous + Lap	No Pass
	34	Discontinuous + Lap + Cap	No Pass
	37	Discontinuous + Lap + Cap	Maybe

Table 28. Results of Screening Test for Type 2 Connection

Connection Type	Model Number	Description	Result of Screening
2 - Formed	16	Base, Continuous Welds	Further Investigation
	17	Discontinuous	No Pass
	18	Base + Lap	No Pass
	19	Discontinuous + Lap	No Pass
2 – Structural	40	Base, Continuous	Further Investigation
	41	Discontinuous	No Pass
	42	Base + Lap	No Pass
	43	Discontinuous + Lap	No Pass

Table 29. Results of Screening Test for Type 3 Connection

Connection Type	Model Number	Description	Result of Screening
3 – Formed	20	Base, Continuous Welds	Further Investigation
	21	Discontinuous	No Pass
	22	Base + Lap	Further Investigation
	23	Discontinuous + Lap	No Pass
3 – Structural	44	Base	Further Investigation
	45	Discontinuous	No Pass
	46	Base + Lap	Further Investigation
	47	Discontinuous + Lap	No Pass

Table 30. Results of Screening Test for Type 4 Connection

Connection Type	Model Number	Description	Result of Screening
4 – Formed	24	Base	Further Investigation
	25	Discontinuous	Further Investigation
	26	Base + Lap	No Pass
	27	Discontinuous + Lap	No Pass
4 – Structural	48	Base	Further Investigation
	49	Discontinuous	Further Investigation
	50	Base + Lap	No Pass
	51	Discontinuous + Lap	No Pass

Table 31. Results of Screening Test for Type 5 Connection

Connection Type	Model Number	Description	Result of Screening
5 - Formed	03	Base	Further Investigation
	06	Base + Lap	No Pass
	09	Discontinuous Welds (4-inch)	No Pass
	12	Discontinuous Welds (1-inch)	No Pass
	15	Base + Lap + Cap	Further Investigation
	30	Discontinuous + Lap	No Pass
	33	Discontinuous + Lap	No Pass
	36	Discontinuous + Lap + Cap	No Pass
	39	Discontinuous + Lap + Cap	Further Investigation

6.4.4 Conclusion

A modelling and simulation program was performed on 51 different geometric configurations of channels. The modeling demonstrated that, typically for the base case which has continuous welds, no lap plates and no cap plates that 1/4-in. welds merit further investigation and perhaps approval for use.

However, the addition of lap plates, which is permitted by the fabrication specifications, is not capable of supporting the worst case loading scenarios that were used in the modeling. Intermittent welds that were observed in a typical 'trial run' installation were also shown to be not capable of supporting the required loads. The use of cap plates was shown to greatly improve the predicted stress in some situations.

A model was built to simulate the drop weight tests that were performed (as was illustrated in Section 6.2.3.6). The model was built using handbook values for the expected impact and could possibility be improved in accuracy by using experimental data to validate the model further.

6.5 Task 5 KG Effects of Taller Channels

6.5.1 Availability of Taller Channels

If the interface of the LARS base and the SITS were higher above the deck, with the height of the SITS channels or formed channels larger, this would increase the access for welding of the channel to deck as well as other associated welds, such as the lap plates welds, both top and bottom, as well as the end cap welds. This could allow more length of interface to be welded rather than making larger welds in fewer areas, speeding the installation.

This added height can come from several possible design changes. One option would replace the channels with taller channels that could be bent from plate. A second option would replace the standard channel with channels that have taller flanges (in Figure 50, the standard channel is shown on the left hand side and the taller flange channel is on the right hand side). There are no standard structural C channels with longer flanges. There are standard structural MC channels that include the MC7x19.1 with about 1.2 inch longer flanges.

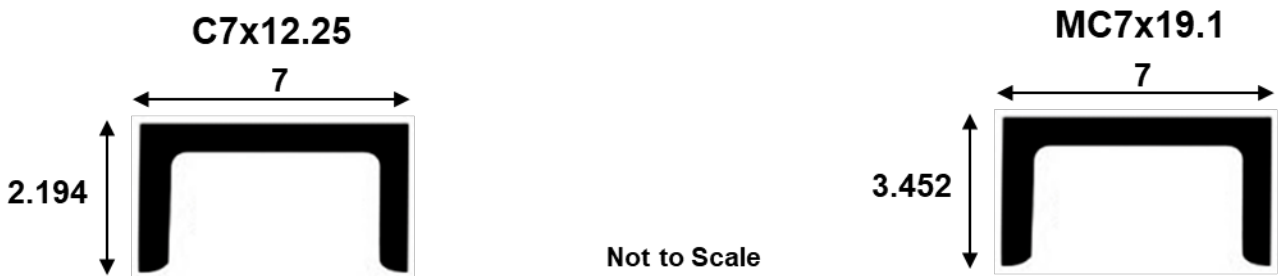


Figure 50. Comparing Standard Structural Channel with Increase Flange Height Channel

A third way would be to pile up two channels in an “A” pattern with two butt welds joining the two channels, as illustrated in Figure 51. Two channels could also be put together to make a square of the same height, but that would place the material of the lower channel web against the deck, where it would provide no stiffness advantage. The “A” pattern channel replacement can be pre-fabricated, so the butt weld is not on critical path.

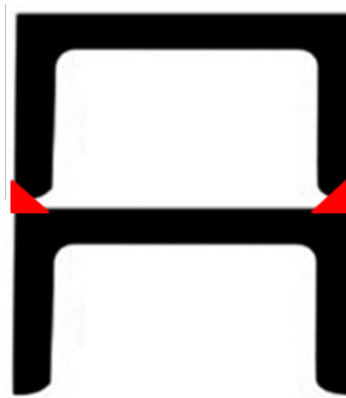


Figure 51. Welded Channels in an “A” Pattern

6.5.2 General Design Consequences of Taller Channels

One of the consequences of a taller SITS would be an increase in the vertical center of gravity (VCG) of the entire system. The calculations on Page 14 of drawing 7411191J, for instance, show that the design using the LARS base Rev. 1 has a VCG of the inboard condition at 7.97 ft. Three other conditions are assessed. Each of these conditions would be part of the assessment of the acceptability of the combination of VOO and rescue system.

KG is the distance of the center of gravity of the VOO from the keel. Two related centers are the center of buoyancy and the center of rotation of the ship. Both the center of buoyancy and the center of rotation will not be affected by adding the LARS to the upper deck, but KG will be increased slightly by the increase in VCG of the system above the datum point on the deck and thus of the system above the keel. This could conceivably affect the allowable sea states that can be sustained with the LARS in place.

The KG of the resulting ship with the rescue system in place will be assessed as part of the VOO choice and acceptance process. The assessment process can accommodate the limited effects of having the mass of the LARS base and the equipment that it supports higher off the VOO deck.

There have already been cases where the deck has been built up locally because it did not have sufficient flatness for the SITS system. The MV Dominator required local 1-inch thick deck reinforcements to be added before addition of the SITS in some locations, for instance.

Similarly, the addition of lap plates may increase the VCG if they raise the height relative to the deck datum position. Lap plates have mostly been used for allowing the SITS top to meet its flatness requirements and do not have the direct purpose of increasing VCG, but a non-flat deck may require the slight increase in VCG.

6.5.3 Local Consequences of Additional Height

The vertical position of the LARS base relative to the deck will affect the required positions of nearly all of the other systems, so a unified expectation of simply raising the all components of the system to match the increase in height of the SITS for the LARS base appears to be the best first approximation.

The amount of additional height needed to valuably increase welding access can be considered based on the beam sizes commonly used in the LARS base and the positions of welds beneath those beams. Considering a primary beam size in the central regions of the LARS base as 7-inch wide.

In the current design the situation without lap plates can allow 2.2 inches minimum above the deck below a LARS base beam flange for the fillet weld position. This is not enough to allow a hand with a torch. With lap plates there is slightly more room to reach the lower weld of the lap plates to the deck (4.2 inch), but less room for the upper weld between the lap plates and the lower surface of the beam, given the 1 inch of overlap (2.2 inch).

Adding an additional 1.2 inch by using the MC channels would still only leave 3.3 inches above the deck, still not enough room for a hand with a torch, much less the ability to follow where the torch is moving with the eyes. With lap plates, that would still be only 2.3 inches with the 1-inch overlap that is the minimum allowed.

Higher structures between the deck and the LARS base that would allow the welding torch to reach beneath the beam with reasonable torch angles would need to be 6 to 7 inches tall. At that height, even the A-frame design with doubled current channels would not be sufficient.

6.5.4 Conclusions

While MC7×19.1 channels or formed equivalents would allow an additional 1.2 inch of height above the deck for the SITS to LARS base interface, the additional clearance will have minimal effect on the regions that can be welded below the LARS base beams. The ability to improve the welding situation with a workable structure design of significantly larger channels than this does not appear to be feasible.

6.6 Estimates of Welding Time Savings

6.6.1 Estimation Method

The value of the changes to the welding of the SITS to the deck are considered in this section in terms of the reduction of time for welding on critical path. This assessment considered the changes to the weld plan by using estimates of the time to weld each channel section to the deck.

Two methods of assessment were used. One used only the estimated arc-on time, as a function of weld pass number and weld length. The other estimate accommodates several considerations, including welding arc on-time, the cleaning time after welding time for getting ready to start an arc and time for moving between locations. Both estimates include the presence or absence of lap plates. Others are not included, such as the positioning of the channel on the deck and the effort to coordinate with other trades.

One factor considered as an option but not ultimately included is the amount of extra effort to weld adjacent to a region without sufficient access for welding. These regions have the LARS base beams directly above which prevent access, but also limit access to the adjacent regions.

Rather than perform the assessment based on only the time that the arc is on, EWI has included estimates for additional parameters, as shown in Table 32. This approach covers the welder time when the arc is not on as a function of the arrangement of welds.

Table 32. General Parameters for Determining Welding Time on Critical Path

Parameter	Units
Welding speed	Inches / minute
Moving between welding locations	Minutes
Getting ready to start at a location	Minutes
Cleaning after welding	Inches / minute

An important consideration in weld time is the difference between single-pass and multi-pass welds. A 5/16-in. leg length is generally considered the maximum that can be placed by manual fillet welding by the processes considered for this welding. A 1/4-in. leg length weld can be made in 1 pass reliably, but a 3/8-in. leg fillet weld would normally be made in three passes – one at the root, one against the deck, and a final fill pass against the channel.

Four sizes of weld are considered: a fillet with a 1/4-in. leg, a fillet with 3/8-in. leg, a butt weld with 1/4-in. fillet, and a butt weld with 3/8-in. fillet.

The 1/4-in. weld is expected to be made in a single pass. The 3/8-in. weld is expected to be made in three passes. The three passes are expected to be welded at the same welding speed each as the single 1/4-in. pass. Similarly, the butt welds are assumed to be made with an additional pass using the same speed.

The number of lap plates will vary with the deck condition. An estimate of the effect of additional lap plate welding is made by assuming that lap plate welds have the same length as the weld to the deck and are 1/4-in. fillet welds. 60% of locations that might have lap plates are assumed to have them installed.

The time was estimated based on all preparations being made, all materials at hand, and the weld being made along with all the other SITS welds to the VOO. Tacking of the materials to be welded is assumed to have already occurred.

Single estimate values for the parameters have been tested, as given in Table 33. It should be noted that the estimates shown in Table 33 (primarily welding speed) are using the assumption that Flux Cored Arc Welding (FCAW) will be used and not Shielded Metal Arc Welding (SMAW); FCAW has increased deposition rates compared to SMAW. Therefore the welding speed parameter would be reduced using SMAW (the estimated welding speed for SMAW was not determined).

Table 33. Estimated Values for Determining Welding Time on Critical Path

Parameter	Value	Units
Welding speed	12	Inches / minute
Moving between welding locations	1	Minutes
Getting ready to start at a location	1	Minutes
Cleaning after welding	20	Inches / minute

6.6.2 Calculation of a Weld Replacement and Time Savings on a Local Area

A simple example was chosen from Detail A on drawing 7412772B from an area where the RCS is connected to the SITS. The estimated time for the welding process is calculated for the stitches shown in Detail A of Figure 52 as 2 hours 10 minutes. Using the modified layout of welding shown on the right hand side of Figure 52 with 1/4-in. continuous fillet welds, where access is available, gave a total time of 48 minutes.

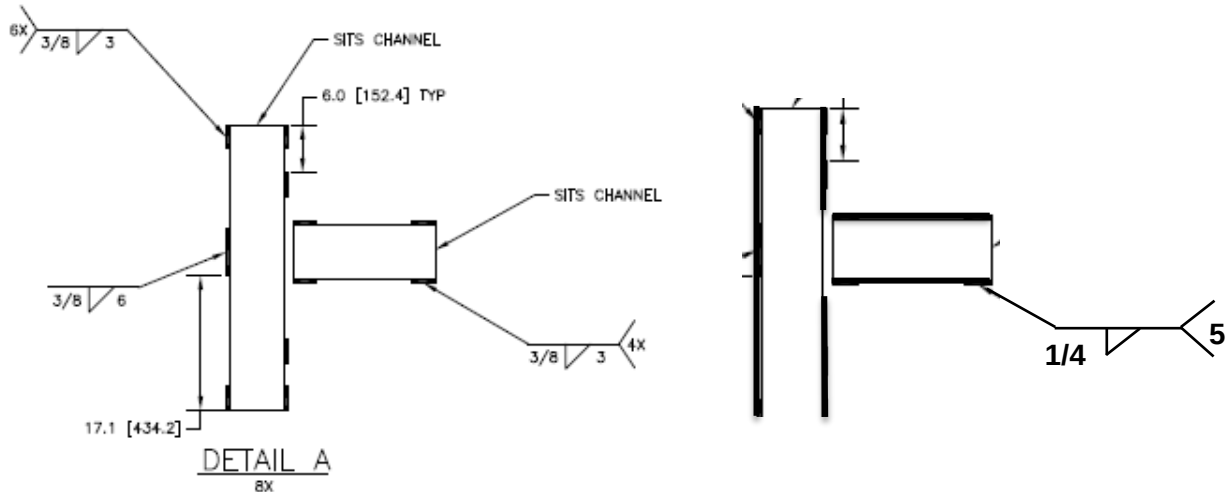


Figure 52. Original and Modified Welding Layout using 1/4-in. Continuous Fillet Welds

6.6.3 Improvement Calculation for Single-Pass 1/4-inch Welds Forward of LARS Base

One area that appeared to have potential for weld time savings were the areas welded with 3/8-in. fillet welds forward of the LARS Base, which are shown in:

- Drawing 7412772 (Revision B) for the RCS installation and
- Drawing 7413251, which adds additional channels in Detail H and replaces the Detail A and Detail B designs.

There are also differences between the two drawings regarding the length of channels on Details D and G, but these relate only to a need for further revision of 7413251. The added details on Drawing 7413251 for Details A, B, and H have 1/4-in. welds, so any changes to these would require a different approach.

EWI considered three variants of welding in the area forward of the LARS base: replacing 3/8-in. welds with continuous welds, replacing the 3/8-in. welds with stitch welds of the same length as currently used, and replacing only those 3/8-in. welds that were designed with lengths less than 6 inches.

These were reviewed against the history of why the weld sizes, lengths, and positions were chosen. Oceaneering Inc.'s document TM304952 provides the earliest description of the choices of weld sizes from 2008.

These sizes were chosen based on a 3/8-in. minimum fillet size and a 3-in. minimum fillet length. Areas adjacent to a bolt with a 3,000 lbf. vertical load were chosen to be welded with 6-in. continuous weld length. Oceaneering's analysis included a calculation of the forces on groups of channel nodes, showing generally good safety factors.

Oceaneering included the effect of the deck structure in 2011 in Technical Memorandum 040111-01 SRDRS Van SITS Weld Reduction Analysis. At this time, they lengthened some of the welds by increasing 3-in. welds to either 4- or 5-in. long on some details. Both of these analyses were performed on the RCS configuration of the SITS, working to an earlier revision of 7412772.

Based on the original design approach of having some welds be continuous welds 6-in. long or more based on adjacent bolt loads, EWI preferred the approach of redesigning the welding to provide the same length welds with 3/8-in. leg length for any weld 6-in. long or longer, but switching to 1/4-in. leg welds for all shorter length welds.

These 1/4-inch leg welds can be of equivalent area by extending the 3-in. welds to 4.5-in., the 4-in. welds to 6-in., and the 5-in. welds to 7.5-in. These modifications are shown in Figures 53-55.

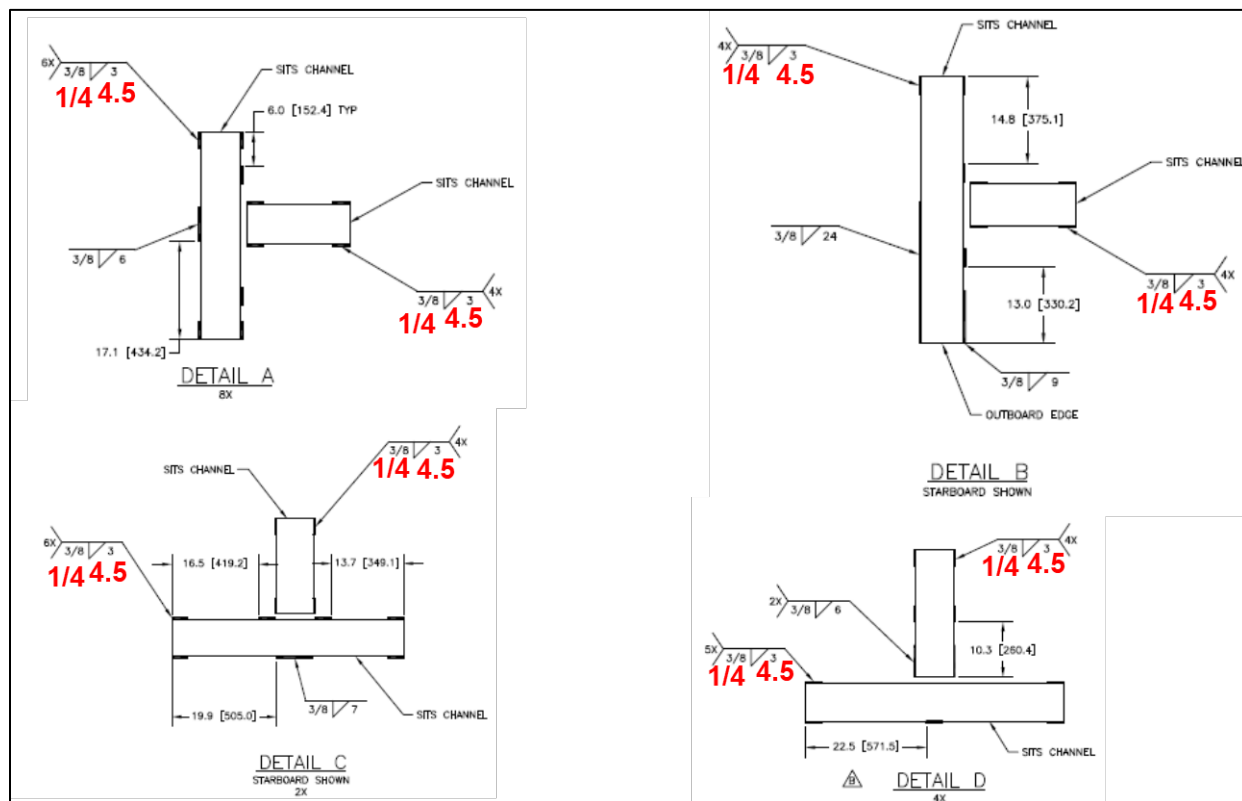


Figure 53. Modified Welding Layout with Extending 3-in. Long Fillet Welds to 4.5-in. Long Fillet Welds

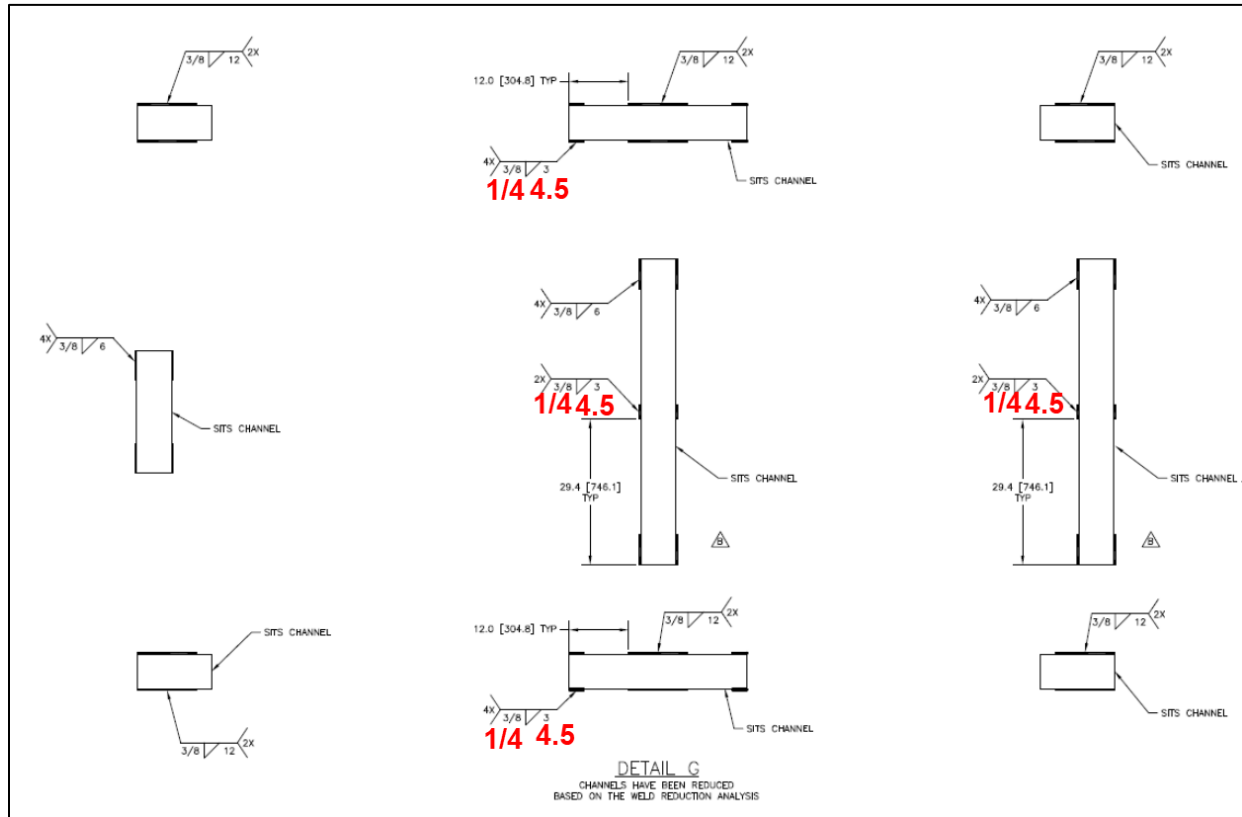


Figure 54. Modified Welding Layout with Extending 3-in. Long Fillet Welds to 4.5-in. Long Fillet Welds

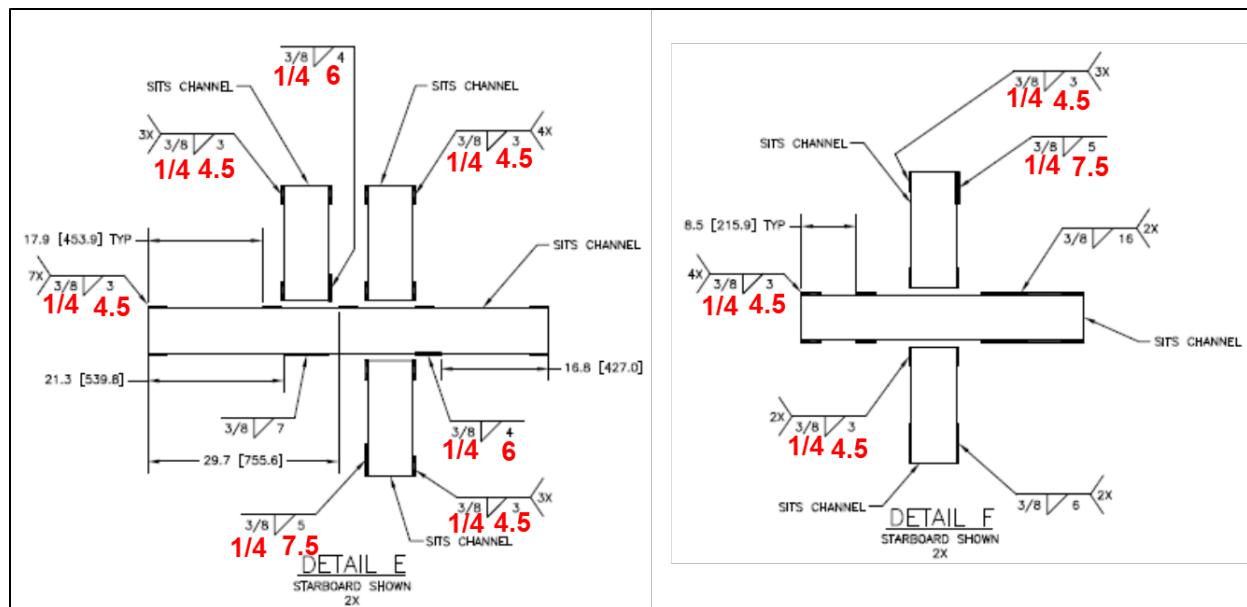


Figure 55. Modified Welding Layout with Various Fillet Weld Extensions

The results can also be applied to Details C through G on Drawing 7413251. As noted above, a revision of Drawing 7413251 is expected that will cause the channel lengths and weld sizes for this drawing to match those on Drawing 7412772 Revision B for Details D and G.

The comparison calculation of weld time shows a savings of arc on-time of 15.7 hours. The savings for the more general welding time estimate is 32.3 hours. If the welding is performed by 10 welders, this reduction in welding time would be 3.2 hours.

7.0 Benefits Analysis

The primary desired benefit of this project was reduction in weld time on critical path for installation of the SITS on the VOO. While a general reduction to weld time by a change to smaller welds was not found, a specific change to welds shorter than 6-in. long in areas forward of the LARS base was found to provide savings in weld time of about 3 hours under reasonable assumptions of activity time and conditions. This change can be justified by comparing to the previous justification for the weld sizing of welds in this area.

8.0 Implementation (Progress/Status)

Before the potential savings in welding time can be implemented for welds forward of the LARS base (as described in Section 6.6.3), the recommendations in this report will have to be sent to NAVSEA for review. Upon satisfactory review, the report will then be sent to the planning yard (in this case, Portsmouth Naval Shipyard) for their review. The planning yard will make recommendations and then the PMS 391 program office will make a recommendation; a particular VOO has not been determined for potential implementation.

9.0 Issues / Problems / Workaround (if applicable)

The program was designed to check for available opportunities for reduction of weld time for the SITS channels to the deck. This program did not attempt to calculate the loading in other adjacent members of the structure. By not assessing the structural members within the LARS base or the deck, the project could not allow for re-distribution of loading in the LARS base area and had to use the node by node calculation level available from Drawing 7411192. This was not sufficient to allow a new welding size to be selected for welds in the LARS base area.

An analysis with a larger scope may be able to find additional reductions in weld size in this area. Reductions in welding time were found in other areas where different information on loading was available.

Per Revision 1 of the project schedule, the Task 2.0 drop tower testing was expected to occur during January to February in 2019; drop tower testing did not occur until April 2019. The Task 2.0 schedule was pushed out multiple months due to difficulty in obtaining EH-36 material for the drop tower testing.

Originally EH-36 plate was going to be purchased and then sent to a fabrication company to have it formed into channel. Quotes for EH-36 material were received prior to the project starting (as part of the proposal process). When it became time to order the material after the project kickoff meeting occurred, a new quote was obtained and it stated that EH-36 would not be received from the mill until June 2019. EWI was then informed by Phoenix Int'l. of the fabrication company that they use for their channel material.

Ultimately it took many months to receive the formed channel material from the fabrication company, again due to EH-36 material not being readily available (and the fact that EH-36 only comes in plate form and is not produced in shapes, such as channel).

Once the channel material was obtained and welded to the deck plate, testing of the example channel to deck welds in the drop weight system was successfully completed. The test results included cracking in the welds, which did not progress to induce cracking in the channel and plate.

With the cracking present, the tests cannot be used to demonstrate that larger loads or more rapid loads beyond the design case can be applied to the SITS system without damage that would affect subsequent use. Less severe impact conditions might be used to achieve this demonstration.

Although much effort was involved in the acquisition of EH-36 material for testing, it was later discovered that EH-36 is not a critical path element for channel installation on a VOO.

10.0 Lessons Learned

The LARS base system places demands on the channel and deck system that can be better assessed with a larger system assessment compared to an assessment that is applied only to the channels, deck, and the welds between them.

Impact testing of model channel to deck welds shows that impact can induce much greater localized stresses than equivalent loading statically, sufficient to cause cracking high toughness welds. The lack of cracking in previous SRS implementations shows that the impact loads tested in this program greatly exceed those found in real service.

Modifications of the welding plan for the area of the SITS forward of the LARS base can save welding time while providing equivalent resistance. A welding plan that saves about 3 hours when applied by 10 welders has been recommended as a new welding plan for this area. The changes allow single pass welds to be made in place of three-pass welds in areas without high stress concentrations.

11.0 Conclusions and Recommendations

The spreadsheet tool that was used for Task 1.0 efforts could potentially be used to estimate the reserve capacity of the C-channel connection system as whole, similar to the analysis of a large bolt pattern.

The modeling efforts demonstrated that, typically for the base case that use continuous 1/4-in. welds and does not use lap plates or cap plates, these welds could merit further investigation and potential approval for use.

The addition of lap plates, which is permitted by the fabrication specifications, is not capable of supporting the worst case loading scenarios that were used in the modeling. Intermittent welds that were observed in a typical 'trial run' installation were also shown to be not capable of supporting the required loads. The use of cap plates was shown to greatly improve the predicted stress in some situations.

Revising the welding plan for the area forward of the LARS base can save welding time while providing equivalent resistance. A welding plan that saves about 3 hours when applied by 10 welders has been recommended by EWI as a new welding plan for this area. The changes allow single pass welds to be made in place of three-pass welds in areas without high stress concentrations.

Modifications of the LARS base area welding to accommodate areas of incomplete access for welders can be further assessed based upon the partial weld models included in this report. A larger system assessment using this information can address this. Full determination of the LARS base would require more extensive modeling efforts that would need to account for all forces acting on all channels and the varying sea states that could be encountered was beyond the scope of this project.

12.0 Technology Transfer Status

There were no technology transfer activities during the project period of performance.

13.0 References (as applicable)

N/A

Appendix A

Calculations of SRS-RCS LC1

Center for Naval Metalworking

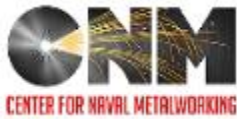
			Type	Length (in)													
	Depth (in)	7	1	13.5													
	Width (in)	2.2	2	92.89													
			3	22													
			4	40													
			5	13.5													
		VOO					C Channel				Shear Resultants						
Node	Long (lbs)	Athw (lbs)	Vert (lbs)	Type	Orientation	Long (lbs)	Trans (lbs)	Vert (lbs)	Length (in)	Long	Trans	Vert	VonMises	Percent of Max			
1	-22	11484	1278		5 LL	-22	11484	1278	13.5	-0.8	425.3	315.5	917.2	21.0%			
2	241	3076	-370		5 LL	-22	11484	-370	13.5	-0.8	425.3	281.9	883.8	20.3%			
3	138	-685	-1164		5 LL	-22	11484	-1164	13.5	-0.8	425.3	311.3	912.9	20.9%			
5	6502	-2041	3869		5 LT	-22	11484	3869	13.5	-0.8	425.3	411.4	1025.0	23.5%			
8	2703	-1222	1740		5 LT	-1222	2703	1740	13.5	-45.3	100.1	171.6	353.0	8.1%			
10	530	-497	-345		5 LT	-1222	2703	-345	13.5	-45.3	100.1	120.0	281.7	6.5%			
30	26710	5414	-6076		5 LT	1762	19489	-6076	13.5	65.3	721.8	742.6	1797.2	41.2%			
31	40233	-1482	-12524		5 LT	1762	19489	-12524	13.5	65.3	721.8	981.4	2113.1	48.5%			
32	58878	-1956	-24920		5 LT	1762	19489	-24920	13.5	65.3	721.8	1440.5	2793.0	64.1%			
33	60735	985	-22878		5 LT	1762	19489	-22878	13.5	65.3	721.8	1364.9	2676.6	61.4%			
34	39686	-599	-14879		5 LT	1762	19489	-14879	13.5	65.3	721.8	1068.6	2236.4	51.3%			
35	34496	-1805	-11348		5 LT	1762	19489	-11348	13.5	65.3	721.8	937.8	2052.9	47.1%			
36	28183	-7540	-4482		5 LT	1762	19489	-4482	13.5	65.3	721.8	683.5	1725.5	39.6%			
38	10720	-22177	-6083		5 LL	2897	-50406	-6083	13.5	107.3	-1866.9	1503.7	4156.1	95.4%			
39	2932	-37489	-8362		5 LL	2897	-50406	-8362	13.5	107.3	-1866.9	1588.1	4249.2	97.5%			
40	-489	-45652	-10931		5 LL	2897	-50406	-10931	13.5	107.3	-1866.9	1683.2	4357.7	100.0%			
41	-458	23992	-6271		5 LL	2897	-50406	-6271	13.5	107.3	-1866.9	1510.6	4163.7	95.5%			
42	1295	19591	-4684		5 LL	2897	-50406	-4684	13.5	107.3	-1866.9	1451.8	4100.5	94.1%			
43	5390	11490	-3328		5 LL	2897	-50406	-3328	13.5	107.3	-1866.9	1401.6	4047.7	92.9%			
45	15306	3585	-2291		5 LT	1644	25315	-2291	13.5	60.9	937.6	733.7	2064.8	47.4%			
46	18633	419	-6391		5 LT	1644	25315	-6391	13.5	60.9	937.6	885.6	2236.3	51.3%			
47	21981	-194	-8601		5 LT	1644	25315	-8601	13.5	60.9	937.6	967.4	2335.9	53.6%			
48	33913	-1087	-13313		5 LT	1644	25315	-13313	13.5	60.9	937.6	1142.0	2561.4	58.8%			
49	32486	904	-14122		5 LT	1644	25315	-14122	13.5	60.9	937.6	1171.9	2601.7	59.7%			
50	22461	422	-7122		5 LT	1644	25315	-7122	13.5	60.9	937.6	912.7	2268.8	52.1%			
51	15278	-3629	-3602		5 LT	1644	25315	-3602	13.5	60.9	937.6	782.3	2117.6	48.6%			
71	-325	-1927	-707		5 LT	950	-11438	-707	13.5	35.2	-423.6	326.9	928.8	21.3%			
73	-7957	-3617	-5914		5 LT	950	-11438	-5914	13.5	35.2	-423.6	519.7	1162.9	26.7%			
76	-5478	-1111	-6356		5 LT	-1111	-5478	-6356	13.5	-41.1	-202.9	403.2	785.0	18.0%			
78	403	-1282	1099		5 LL	-1111	-5478	1099	13.5	-41.1	-202.9	208.5	508.9	11.7%			
79	418	-2813	1454		5 LL	-1111	-5478	1454	13.5	-41.1	-202.9	221.6	525.3	12.1%			
80	164	-7370	2006		5 LL	-1111	-5478	2006	13.5	-41.1	-202.9	242.1	551.7	12.7%			

Appendix B

Calculations of SRS-RCS LC2

Center for Naval Metalworking

[illegible]



Center for Naval Metalworking

	Depth (in)	7	Type	Length (in)											
	Width (in)	2.2	1	13.5											
			2	92.89											
			3	22											
			4	40											
			5	13.5											
C Channel										Shear Resultants					
Node	Long (lbs)	Athw (lbs)	Vert (lbs)	Type	Orientation	Long (lbs)	Trans (lbs)	Vert (lbs)	Length (in)	Long	Trans	Vert	VonMises	Percent of Max	
42	-1751	-15622	1962	5	LL	-3225	46448	1962	13.5	-119.5	1720.3	1270.8	3710.3	100.0%	
43	-5050	-9394	1374	5	LL	-3225	46448	1374	13.5	-119.5	1720.3	1249.0	3688.0	99.4%	
44	-14694	-12907	1193	1	Special										
44T	-1263	-19514	1193	1	LL	-1263	-19514	1193	13.5	-46.8	-722.7	544.2	1569.1	42.3%	
45	-10986	-3509	1519	5	LT	-1263	-19514	1519	13.5	-46.8	-722.7	556.3	1581.8	42.6%	
46	-12822	-1641	3572	5	LT	-1263	-19514	3572	13.5	-46.8	-722.7	632.3	1665.3	44.9%	
47	-16811	-1284	5538	5	LT	-1263	-19514	5538	13.5	-46.8	-722.7	705.2	1750.8	47.2%	
48	-27865	-495	9445	5	LT	-1263	-19514	9445	13.5	-46.8	-722.7	849.9	1934.0	52.1%	
49	-29040	-576	11168	5	LT	-1263	-19514	11168	13.5	-46.8	-722.7	913.7	2019.4	54.4%	
50	-19352	223	5305	5	LT	-1263	-19514	5305	13.5	-46.8	-722.7	696.5	1740.4	46.9%	
51	-12745	3488	2499	5	LT	-1263	-19514	2499	13.5	-46.8	-722.7	592.6	1620.8	43.7%	
52	-7207	6073	533	1	Special										
52T	-802	9389	533	1	LL	-802	9389	533	13.5	-29.7	347.7	267.4	761.5	20.5%	
53	-7207	6073	533	1	Special										
53T	-802	9389	533	1	LL	-802	9389	533	13.5	-29.7	347.7	267.4	761.5	20.5%	
54	-3913	9967	2596	1	LL	-802	9389	2596	13.5	-29.7	347.7	343.8	848.5	22.9%	
55	-905	13021	3442	1	LL	-802	9389	3442	13.5	-29.7	347.7	375.1	887.4	23.9%	
56	382	11777	2335	1	LL	-802	9389	2335	13.5	-29.7	347.7	334.1	836.8	22.6%	
57	515	6080	1838	1	LL	-802	9389	1838	13.5	-29.7	347.7	315.7	815.1	22.0%	
58	590	-406	187	1	LL	-802	9389	187	13.5	-29.7	347.7	254.5	748.2	20.2%	
59	1278	-2263	-584	1	LL	-802	9389	-584	13.5	-29.7	347.7	269.2	763.5	20.6%	
67	7866	-19678	-6363	1	LL	-802	9389	-6363	13.5	-29.7	347.7	483.3	1032.5	27.8%	
68	3156	-24381	-7442	1	LL	-802	9389	-7442	13.5	-29.7	347.7	523.2	1089.4	29.4%	
69	1167	-21587	-5735	1	LL	-802	9389	-5735	13.5	-29.7	347.7	460.0	1000.1	27.0%	
70	176	-12433	-3460	1	LL	-802	9389	-3460	13.5	-29.7	347.7	375.8	888.3	23.9%	
71	-160	228	1179	5	LT	-802	9389	1179	13.5	-29.7	347.7	291.3	787.4	21.2%	
72	-1478	-215	-1292	1	LT	-802	9389	-1292	13.5	-29.7	347.7	295.5	792.0	21.3%	
73	-4705	-1260	-4186	5	LT	-802	9389	-4186	13.5	-29.7	347.7	402.7	922.9	24.9%	
76	-11256	1520	-17059	5	LT	1520	-11256	-17059	13.5	56.3	-416.9	948.9	1797.8	48.5%	
77	-1465	70	-473	1	LT	1520	-11256	-473	13.5	56.3	-416.9	334.6	931.0	25.1%	
78	-266	-240	1533	5	LL	1520	-11256	1533	13.5	56.3	-416.9	373.9	974.8	26.3%	
79	-273	13042	-1261	5	LL	1520	-11256	-1261	13.5	56.3	-416.9	363.8	963.3	26.0%	
80	981	27096	-5103	5	LL	1520	-11256	-5103	13.5	56.3	-416.9	506.1	1139.9	30.7%	
81	-3750	3750	-15250	1	LL	1520	-11256	-15250	13.5	56.3	-416.9	881.9	1692.4	45.6%	
82	-3750	3750	250	1	LL	1520	-11256	250	13.5	56.3	-416.9	326.3	922.2	24.9%	

Appendix C

Calculations of SRS-RCS LC3

Center for Naval Metalworking

[illegible]

Appendix D

Calculations of SRS-RCS LC4

Center for Naval Metalworking

[illegible]

Appendix E

SITS Load Case 1 Data

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
CV 1	-2588	2092	-9275	567	417	44.5			17
CV 2	-2588	2092	-2189	567	417	-44.5			7
CV 3	-2588	3083	-8521	567	647.5	44.5			17
CV 4	-2588	3083	-1435	567	647.5	-44.5			8
SV 1	-5500	25500	-51826	567	417	-87.5			102
SV 2	-5500	25500	23336	759	417	-176.5			46
SV 3	-5500	25500	-45696	567	647.5	-87.5			93
SV 4	-5500	25500	29466	759	647.5	-176.5			52
GV 1	-16985	-1567	36053	378	970.5	175.6			106
GV 2	-25736	22502	-71610	475	881.5	175.6			167
GV 3	-24538	16385	57539	378	970.5	-175.6			171
GV 4	-24729	-2056	-56466	475	881.5	-175.6			130
GV 5	-2206	5410	-2343	95	970.5	43.9			66
GV 6	-3708	5610	-25540	258	881.5	43.9			102
GV 7	1655	10748	-3084	189	970.5	0			60
GV 8	-3387	14536	-28613	189	881.5	0			171
GV 9	-3517	9461	2392	95	970.5	-44			109
GV 10	133	13955	-14367	258	881.5	-44			78
PRMSGR 1	-2435	8431	-20798	501	702	-44.5			45
PRMSGR 2	-2435	8431	10949	501	766	-44.5			28
PRMSGR 3	-2435	8431	-20798	501	702	44.5			45
PRMSGR 4	-2435	8431	-12683	501	766	44.5			31
LV 1	-5500	5500	-21560	567	417	176.5			40
LV 2	-5500	5500	-6587	759	417	87.5			13
LV 3	-5500	5500	-15773	567	647.5	176.5			31
LV 4	-5500	5500	-800	759	647.5	87.5			10

Appendix F

SITS Load Case 2 Data

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
CV 1	-2588	2092	-5092	567	417	44.5			11
CV 2	-2588	2092	1994	567	417	-44.5			7
CV 3	-2588	3083	-2354	567	647.5	44.5			8
CV 4	-2588	3083	4732	567	647.5	-44.5			11
SV 1	-5500	25500	-40826	567	417	-87.5			85
SV 2	-5500	25500	34336	759	417	-176.5			57
SV 3	-5500	25500	-34696	567	647.5	-87.5			77
SV 4	-5500	25500	40466	759	647.5	-176.5			63
GV 1	-19665	-4362	45345	378	970.5	175.6			131
GV 2	-23102	19249	-62159	378	881.5	175.6			183
GV 3	-27196	19145	66778	378	970.5	-175.6			197
GV 4	-22129	1204	-47012	378	881.5	-175.6			137
GV 5	-2374	6885	6534	95	970.5	43.9			103
GV 6	-3498	6944	-15204	258	881.5	43.9			66
GV 7	1387	10783	10429	189	970.5	0			80
GV 8	-3098	14508	-14938	189	881.5	0			111
GV 9	-3647	8005	11186	95	970.5	-44			150
GV 10	301	12623	-3960	258	881.5	-44			51
PRMSGR 1	-2435	8431	7696	501	702	-44.5			23
PRMSGR 2	-2435	8431	15828	501	766	-44.5			36
PRMSGR 3	-2435	8431	-15936	501	702	44.5			36
PRMSGR 4	-2435	8431	-7804	501	766	44.5			23
LV 1	-5500	5500	-10560	567	417	176.5			23
LV 2	-5500	5500	4413	759	417	87.5			12
LV 3	-5500	5500	-4773	567	647.5	176.5			16
LV 4	-5500	5500	10200	759	647.5	87.5			17

Appendix G

Calculations of SRS LC1

Center for Naval Metalworking

			Type	Length (in)													
	Depth (in)	7	1	13.5													
	Width (in)	2.2	2	92.89													
			3	22													
			4	40													
			5	13.5													
							C Channel					Shear Resultants					
Node	Long (lbs)	Athw (lbs)	Vert (lbs)	Type	Orientation	Long (lbs)	Trans (lbs)	Vert (lbs)	Length (in)	Long	Trans	Vert	VonMises	Percent of Max			
4	1376	-554	-214	1	LT	-13	11571	-214	13.5	-0.5	428.6	277.8	884.6	14.3%			
9	1050	-884	419	1	LT	-1236	2687	419	13.5	-45.8	99.5	122.8	285.1	4.6%			
11	473	-8604	1913	1	LL	-1236	2687	1913	13.5	-45.8	99.5	178.2	362.3	5.9%			
12	10	-14435	3317	1	LL	-1236	2687	3317	13.5	-45.8	99.5	230.2	441.5	7.1%			
13	-948	-16612	4555	1	LL	-1236	2687	4555	13.5	-45.8	99.5	276.0	514.4	8.3%			
14	-3833	-12619	4190	1	LL	-1236	2687	4190	13.5	-45.8	99.5	262.5	492.7	8.0%			
22	-2933	5735	-2165	1	LL	-1236	2687	-2165	13.5	-45.8	99.5	187.5	376.1	6.1%			
23	-1234	11626	-4433	1	LL	-1236	2687	-4433	13.5	-45.8	99.5	271.5	507.1	8.2%			
24	-1679	24935	-7387	1	LL	-1236	2687	-7387	13.5	-45.8	99.5	380.9	686.5	11.1%			
25	-2323	34013	-8818	1	LL	-1236	2687	-8818	13.5	-45.8	99.5	433.9	775.1	12.5%			
26	994	33551	-15941	1	LL	-1236	2687	-15941	13.5	-45.8	99.5	697.7	1223.3	19.8%			
27	8357	22503	-8179	1	LL	-1236	2687	-8179	13.5	-45.8	99.5	410.2	735.5	11.9%			
28	15931	13490	-707	1	Special												
28T	1726	20801	-707	1	LL	1726	20801	-707	13.5	63.9	770.4	572.9	1666.6	26.9%			
29	15931	13490	-707	1	Special												
29T	1726	20801	-707	1	LL	1726	20801	-707	13.5	63.9	770.4	572.9	1666.6	26.9%			
37	40733	-37243	-4327	1	Special												
37T	2467	-55129	-4327	1	LL	2467	-55129	-4327	13.5	91.4	-2041.8	1533.0	4425.2	71.5%			
44	25529	23044	-2564	1	Special												
44T	3504	68488	-2564	1	LL	3504	68488	-2564	13.5	129.8	2536.6	1816.3	5408.3	87.4%			
52	9364	-7911	191	1	Special												
52T	1027	-12213	191	1	LL	1027	-12213	191	13.5	38.0	-452.3	328.6	970.6	15.7%			
53	9364	-7911	191	1	Special												
53T	1027	-12213	191	1	LL	1027	-12213	191	13.5	38.0	-452.3	328.6	970.6	15.7%			
54	2232	-11944	-720	1	LL	1027	-12213	-720	13.5	38.0	-452.3	348.2	990.9	16.0%			
55	128	-12654	9410	1	LL	1027	-12213	9410	13.5	38.0	-452.3	670.1	1401.8	22.7%			
56	1300	-20288	-2182	1	LL	1027	-12213	-2182	13.5	38.0	-452.3	402.4	1050.6	17.0%			
57	38	-16697	-4570	1	LL	1027	-12213	-4570	13.5	38.0	-452.3	490.8	1157.9	18.7%			
58	-430	-9244	-3381	1	LL	1027	-12213	-3381	13.5	38.0	-452.3	446.8	1103.2	17.8%			
59	-1481	-5275	-1726	1	LL	1027	-12213	-1726	13.5	38.0	-452.3	385.5	1031.5	16.7%			
67	1471	-1793	-274	1	LL	1027	-12213	-274	13.5	38.0	-452.3	331.7	973.8	15.7%			
68	1204	-5161	-1531	1	LL	1027	-12213	-1531	13.5	38.0	-452.3	378.2	1023.4	16.5%			
69	692	-11110	-3009	1	LL	1027	-12213	-3009	13.5	38.0	-452.3	433.0	1086.6	17.6%			
70	47	-10000	-2861	1	LL	1027	-12213	-2861	13.5	38.0	-452.3	427.5	1080.0	17.5%			
72	-2517	-2944	-2032	1	LT	1027	-12213	-2032	13.5	38.0	-452.3	396.8	1044.3	16.9%			
77	418	-1291	89	1	LT	-1167	-5311	89	13.5	-43.2	-196.7	169.2	455.6	7.4%			
81	-3750	3750	-15250	1	LL	-1167	-5311	-15250	13.5	-43.2	-196.7	730.7	1312.8	21.2%			
82	-3750	3750	250	1	LL	-1167	-5311	250	13.5	-43.2	-196.7	175.2	462.3	7.5%			

Appendix H

Calculations of SRS LC2

Center for Naval Metalworking

			Type	Length (in)												
	Depth (in)	7	1	13.5												
	Width (in)	2.2	2	92.89												
			3	22												
			4	40												
			5	13.5												

Appendix I

Calculations of SRS LC3

Center for Naval Metalworking

			Type	Length (in)												
	Depth (in)	7	1	13.5												
	Width (in)	2.2	2	92.89												
			3	22												
			4	40												
			5	13.5												
								C Channel						Shear Resultants		
Node	Long (lbs)	Athw (lbs)	Vert (lbs)	Type	Orientation	Long (lbs)	Trans (lbs)	Vert (lbs)	Length (in)	Long	Trans	Vert	VonMises	Percent of Max		
16	36151	-17421	-42703	4	LT	-2014	100	-42703	40.0	-25.2	1.3	542.9	941.3	26.5%		
17	16884	-192	-5942	3	LL	-2014	100	-5942	22.0	-45.8	2.3	163.9	294.8	8.3%		
18	47374	498	-9757	3	LL	-2014	100	-9757	22.0	-45.8	2.3	250.6	441.3	12.4%		
19	47957	-474	-9419	3	LL	-2014	100	-9419	22.0	-45.8	2.3	243.0	428.2	12.1%		
20	13594	-360	-12319	4	LT	-2014	100	-12319	40.0	-25.2	1.3	163.1	285.8	8.1%		
61	20052	-2707	-16369	4	LT	-1312	15513	-16369	40.0	-16.4	193.9	331.9	666.4	18.8%		
62	23250	180	-7070	3	LL	-1312	15513	-7070	22.0	-29.8	352.6	400.2	925.2	26.1%		
63	66551	-710	-13516	3	LL	-1312	15513	-13516	22.0	-29.8	352.6	546.7	1127.9	31.8%		
64	72680	714	-13177	3	LL	-1312	15513	-13177	22.0	-29.8	352.6	539.0	1116.7	31.5%		
65	48875	19990	-53766	4	LT	-1312	15513	-53766	40.0	-16.4	193.9	799.4	1425.0	40.1%		

Appendix J

Calculations of SRS LC4

Center for Naval Metalworking

			Type	Length (in)													
	Depth (in)	7	1	13.5													
	Width (in)	2.2	2	92.89													
			3	22													
			4	40													
			5	13.5													
							C Channel					Shear Resultants					
Node	Long (lbs)	Athw (lbs)	Vert (lbs)	Type	Orientation	Long (lbs)	Trans (lbs)	Vert (lbs)	Length (in)	Long	Trans	Vert	VonMises	Percent of Max			
1	-40	6640	529	5	LL	-40	6640	529	13.5	-1.5	245.9	175.6	523.4	23.0%			
2	130	2678	-639	5	LL	-40	6640	-639	13.5	-1.5	245.9	179.7	527.6	23.1%			
3	68	-839	-1229	5	LL	-40	6640	-1229	13.5	-1.5	245.9	201.5	550.7	24.2%			
5	10947	-776	8867	5	LT	-40	6640	8867	13.5	-1.5	245.9	484.4	941.0	41.3%			
8	6137	-2490	4303	5	LT	-2490	6137	4303	13.5	-92.2	227.3	392.4	801.5	35.2%			
10	601	-1046	-5	5	LT	-2490	6137	-5	13.5	-92.2	227.3	233.2	586.3	25.7%			
30	13215	3261	-2278	5	LT	1407	19633	-2278	13.5	52.1	727.1	592.4	1627.0	71.4%			
31	18793	-449	-5544	5	LT	1407	19633	-5544	13.5	52.1	727.1	713.4	1766.6	77.5%			
32	28651	-840	-12003	5	LT	1407	19633	-12003	13.5	52.1	727.1	952.6	2077.6	91.1%			
33	30489	1609	-12326	5	LT	1407	19633	-12326	13.5	52.1	727.1	964.5	2094.1	91.8%			
34	21254	890	-9054	5	LT	1407	19633	-9054	13.5	52.1	727.1	843.4	1930.8	84.7%			
35	19661	24	-7810	5	LT	1407	19633	-7810	13.5	52.1	727.1	797.3	1871.2	82.1%			
36	15032	-3550	-2931	5	LT	1407	19633	-2931	13.5	52.1	727.1	616.6	1653.7	72.5%			
38	4313	-11172	-4383	5	LL	981	-25723	-4383	13.5	36.3	-952.7	796.7	2152.0	94.4%			
39	403	-18327	-5924	5	LL	981	-25723	-5924	13.5	36.3	-952.7	853.8	2216.7	97.2%			
40	-1133	-20660	-7381	5	LL	981	-25723	-7381	13.5	36.3	-952.7	907.8	2280.2	100.0%			
41	152	10459	-1241	5	LL	981	-25723	-1241	13.5	36.3	-952.7	680.4	2028.7	89.0%			
42	860	7889	-960	5	LL	981	-25723	-960	13.5	36.3	-952.7	669.9	2018.3	88.5%			
43	1959	3510	-483	5	LL	981	-25723	-483	13.5	36.3	-952.7	652.3	2000.9	87.8%			
45	2221	634	520	5	LT	484	5718	520	13.5	17.9	211.8	169.9	471.3	20.7%			
46	624	354	-406	5	LT	484	5718	-406	13.5	17.9	211.8	165.7	466.7	20.5%			
47	1450	830	-2199	5	LT	484	5718	-2199	13.5	17.9	211.8	232.1	545.1	23.9%			
48	5709	649	-6158	5	LT	484	5718	-6158	13.5	17.9	211.8	378.7	752.2	33.0%			
49	6847	458	-3171	5	LT	484	5718	-3171	13.5	17.9	211.8	268.1	592.5	26.0%			
50	7104	675	-1966	5	LT	484	5718	-1966	13.5	17.9	211.8	223.5	534.1	23.4%			
51	2969	45	-1227	5	LT	484	5718	-1227	13.5	17.9	211.8	196.1	500.8	22.0%			
71	-199	-1415	-355	5	LT	42	-1188	-355	13.5	1.5	-44.0	42.3	105.8	4.6%			
73	-4494	-2428	-3337	5	LT	42	-1188	-3337	13.5	1.5	-44.0	152.8	275.4	12.1%			
76	-1694	-2517	-1475	5	LT	-2517	-1694	-1475	13.5	-93.2	-62.7	185.2	375.2	16.5%			
78	324	-1148	1051	5	LL	-2517	-1694	1051	13.5	-93.2	-62.7	169.5	352.3	15.4%			
79	288	-2504	1204	5	LL	-2517	-1694	1204	13.5	-93.2	-62.7	175.2	360.5	15.8%			
80	133	-2493	1229	5	LL	-2517	-1694	1229	13.5	-93.2	-62.7	176.1	361.8	15.9%			

Appendix K

SDS SITS Load Case 1 Data

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
SDC1 3	-1717	11970	-20642	378	760.3	182.5			63
SDC1 4	-9245	14558	24215	378	760.3	93.5			79
SDC1 5	2902	15069	-41991	378	374.1	182.5			118
SDC1 6	-7891	12762	21471	378	374.1	93.5			69
SDC1 7	-5271	30335	-46393	188	393	182.5			296
SDC1 8	-1599	26219	23213	283	393	93.5			124
SDC1 9	-5617	-4215	-30116	188	481	182.5			164
SDC1 10	-6802	-11060	6256	283	481	93.5			51
SDC1 11	-24680	63770	-75339	378	604.6	182.5			269
SDC1 12	6671	53970	22582	378	604.6	93.5			156
SDC2 3	-1717	11970	-20642	378	760.3	-93.5			63
SDC2 4	-9245	14558	24215	378	760.3	-182.5			79
SDC2 5	2902	15069	-41991	378	374.1	-93.5			118
SDC2 6	-7891	12762	21471	378	374.1	-182.5			69
SDC2 7	-5271	30335	-46393	283	393	-93.5			197
SDC2 8	-1599	26219	23213	188	393	-182.5			186
SDC2 9	-5617	-4215	-30116	283	481	-93.5			109
SDC2 10	-6802	-11060	6256	188	481	-182.5			77
SDC2 11	-24680	63770	-75339	378	604.6	-93.5			269
SDC2 12	6671	53970	22582	378	604.6	-182.5			156
AV/GV 1	-28235	27334	-73534	378	899	175.6			221
AV 2	-8037	7472	-18097	258	803.5	175.6			82
AV/GV 3	-31375	4545	-50656	378	899	-175.6			158
AV 4	-3890	3958	-10346	258	803.5	-175.6			46
AV 5	-1964	11823	-6877	95	803.5	-44			145
AV 6	-1789	7192	-7658	95	803.5	43.9			112
GV 1	-16985	-1567	36053	378	994.5	175.6			106
GV 2	-24538	16385	57539	378	994.5	-175.6			171
GV 3	-2206	5410	-2343	95	994.5	44			66
AV/GV 4	-5630	14076	-34884	284	905.5	44			134
GV 5	1655	10748	-3084	190	994.5	0			59
GV 6	-3387	14536	-28613	189	905.5	0			171
GV 7	-3517	9461	2392	95	994.5	-44			109
AV/GV 8	-1618	24494	-22928	284	905.5	-44			118

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
PRMSGR 1	-2435	8431	-20798	501	702	-44.5			45
PRMSGR 2	-2435	8431	2834	501	766	-44.5			18
PRMSGR 3	-2435	8431	-12683	501	702	44.5			31
PRMSGR 4	-2435	8431	10949	501	766	44.5			28
SDSGR 1	-2550	8545	2551	501	1038.2	-152.5			19
SDSGR 2	-2550	8545	11048	501	1102.2	-152.5			28
SDSGR 3	-2550	8545	-21356	501	1038.2	63.5			46
SDSGR 4	-2550	8545	-12859	501	1102.2	63.5			31
MTL1 1	-1038	1038	-6586	95	602.8	83.8			71
MTL1 2	-1038	1038	-2305	95	538.8	83.8			29
MTL1 3	-1038	1038	-1946	95	602.8	-17.3			26
MTL1 4	-1038	1038	2334	95	538.8	-17.3			29
MTL2 1	-1038	1038	-6586	95	684.5	17.3			71
MTL2 2	-1038	1038	-2305	95	620.5	17.3			29
MTL2 3	-1038	1038	-1946	95	684.5	-83.8			26
MTL2 4	-1038	1038	2334	95	620.5	-83.8			29
DTL 1	-4065	4065	-25185	284	393	-44.5			91
DTL 2	-4065	4065	-8202	284	481	-44.5			35
DTL 3	-4065	4065	-8202	284	393	44.5			35
DTL 4	-4065	4065	8781	284	481	44.5			37

Appendix L

SDS SITS Load Case 2 Data

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
SDC1 3	-4488	11876	-16052	378	760.3	182.5			54
SDC1 4	-12019	14598	28553	378	760.3	93.5			91
SDC1 5	2251	14435	-30586	378	374.1	182.5			90
SDC1 6	-8515	13352	32957	378	374.1	93.5			97
SDC1 7	-4667	26516	-34413	188	393	182.5			232
SDC1 8	-1177	30262	34392	283	393	93.5			162
SDC1 9	-4958	-8333	-18795	188	481	182.5			112
SDC1 10	-6245	-6927	16536	283	481	93.5			67
SDC1 11	-23715	59106	-49626	378	604.6	182.5			214
SDC1 12	7837	58644	46688	378	604.6	93.5			199
SDC2 3	-4488	11876	-16052	378	760.3	-93.5			54
SDC2 4	-12019	14598	28553	378	760.3	-182.5			91
SDC2 5	2251	14435	-30586	378	374.1	-93.5			90
SDC2 6	-8515	13352	32957	378	374.1	-182.5			97
SDC2 7	-4667	26516	-34413	283	393	-93.5			154
SDC2 8	-1177	30262	34392	188	393	-182.5			244
SDC2 9	-4958	-8333	-18795	283	481	-93.5			75
SDC2 10	-6245	-6927	16536	188	481	-182.5			101
SDC2 11	-23715	59106	-49626	378	604.6	-93.5			214
SDC2 12	7837	58644	46688	378	604.6	-182.5			199
AV/GV 1	-27191	22279	-57414	378	899	175.6			178
AV 2	-6445	5665	-11421	258	803.5	175.6			55
AV/GV 3	-30369	9615	-34521	378	899	-175.6			124
AV 4	-2299	5764	-3672	258	803.5	-175.6			28
AV 5	-2092	11500	703	95	803.5	-44			123
AV 6	-1918	7510	-89	95	803.5	43.9			82
GV 1	-19665	-4362	45345	378	994.5	175.6			131
GV 2	-27196	19145	66778	378	994.5	-175.6			197
GV 3	-2374	6885	6534	95	994.5	44			103
AV/GV 4	-5293	15730	-16975	284	899	44			84
GV 5	1387	10783	10429	190	994.5	0			79
GV 6	-3098	14508	-11938	189	905.5	0			101
GV 7	-3647	8005	11186	95	994.5	-44			150
AV/GV 8	-1321	22841	-4945	284	899	-44			82

Node	Long	Athw	Vert	Area	X	Y	Conf	Orientation	
PRMSGR 1	-2435	8431	7696	501	702	-44.5			23
PRMSGR 2	-2435	8431	15828	501	766	-44.5			36
PRMSGR 3	-2435	8431	-15936	501	702	44.5			36
PRMSGR 4	-2435	8431	-7804	501	766	44.5			23
SDSGR 1	-2550	8545	7642	501	1038.2	-152.5			23
SDSGR 2	-2550	8545	16157	501	1102.2	-152.5			37
SDSGR 3	-2550	8545	-16265	501	1038.2	63.5			37
SDSGR 4	-2550	8545	-7750	501	1102.2	63.5			24
MTL1 1	-1038	1038	-4511	95	602.8	83.8			50
MTL1 2	-1038	1038	-230	95	538.8	83.8			16
MTL1 3	-1038	1038	129	95	602.8	-17.3			16
MTL1 4	-1038	1038	4409	95	538.8	-17.3			49
MTL2 1	-1038	1038	-4511	95	684.5	17.3			50
MTL2 2	-1038	1038	-230	95	620.5	17.3			16
MTL2 3	-1038	1038	129	95	684.5	-83.8			16
MTL2 4	-1038	1038	4409	95	620.5	-83.8			49
DTL 1	-4065	4065	-17055	284	393	-44.5			63
DTL 2	-4065	4065	-72	284	481	-44.5			20
DTL 3	-4065	4065	-72	284	393	44.5			20
DTL 4	-4065	4065	16911	284	620.5	-82			63

Appendix M

Comprehensive List of Models

Table 1. Finite Element Runs for "Short" Sections (13.50 inch), Types 1 and 5											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
1	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D <u>Sht 2/4 & 3/4</u>	1	Structural 7413320A- 2/2	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Most common node type. Continuous weld with maximum load applied.
2	4, 11, 12, 14, 22, 23, 244, 28, 29, 37, 81 + Mirror Nodes 7413006D <u>Sht 2/4 & 3/4</u>	1	Formed-C 7412879H- 2/2 0.313 <u>thk</u>	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Most common node type. Continuous weld with maximum load applied.
3	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D <u>Sht 2/4 & 3/4</u>	5	Formed-C 7413008A- 2/2 0.500 <u>thk</u>	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Most common node type. Continuous weld with maximum load applied.
4	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes 7413006D <u>Sht 2/4 & 3/4</u>	1	Structural 7413320A- 2/2	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—but added ¾-inch <u>thk</u> lap plate, 2-inch high

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 1. Finite Element Runs for “Short” Sections (13.50 inch), Types 1 and 5

FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
5	4, 11, 12, 14, 22, 23, 244, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—but added ¾-inch <u>thk</u> lap plate, 2-inch high
6	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 <u>thk</u>	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—but added ¾-inch <u>thk</u> lap plate, 2-inch high
7	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	Same as Run 1, 2, & 3 above— discontinuous welds
8	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 <u>thk</u>	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	Same as Run 1, 2, & 3 above— discontinuous welds

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 1. Finite Element Runs for “Short” Sections (13.50 inch), Types 1 and 5

FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
9	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	Same as Run 1, 2, & 3 above— discontinuous welds
10	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	Same as Run 1, 2, & 3 above—stitch welds
11	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 thk	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	Same as Run 1, 2, & 3 above—stitch welds
12	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	No	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	Same as Run 1, 2, & 3 above—stitch welds

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 1. Finite Element Runs for “Short” Sections (13.50 inch), Types 1 and 5

FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
13	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—with added ¾-inch <u>thk</u> lap plate, 2-inch high and end caps.
14	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 <u>thk</u>	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—with added ¾-inch <u>thk</u> lap plate, 2-inch high and end caps.
15	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 <u>thk</u>	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 1, 2, & 3 above—with added ¾-inch <u>thk</u> lap plate, 2-inch high and end caps.

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 1A. Finite Element Runs for "Short" Sections (13.50 inch), Types 1 and 5

FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
28	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
29	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 thk	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
30	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
31	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 1A. Finite Element Runs for "Short" Sections (13.50 inch), Types 1 and 5											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
32	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 thk	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	
33	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	Yes	No	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	
34	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
35	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 thk	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
36	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 4 in. opposite side	
1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27. 2. All loads (x, y, z) are with respect to local coordinates along Structural.											

Table 1A. Finite Element Runs for "Short" Sections (13.50 inch), Types 1 and 5											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
37	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Structural 7413320A- 2/2	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	
38	4, 11, 12, 14, 22, 23, 24, 28, 29, 37, 81 + Mirror Nodes. 7413006D Sht 2/4 & 3/4	1	Formed-C 7412879H- 2/2 0.313 thk	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	
39	3, 8, 10, 34, 35, 38 + Mirror Nodes 7413006D Sht 2/4 & 3/4	5	Formed-C 7413008A- 2/2 0.500 thk	Yes	Yes	-10143	-25521	6995	¼-inch fillet 7413006D 2/4	Continuous 1- side, 1 in. on either end opposite side	

1. All models of Types 1 and 5 configurations have the maximum load applied, although maximum load occurs only at Node 27.
2. All loads (x, y, z) are with respect to local coordinates along Structural.

Table 2. Finite Element Runs for "Long" Sections (92.89 inch), Type 2											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
16	66 7412879H 7413006D Sht 2/4 & 3/4	2	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous fillet. No cap.
17	66 7412879H 7413006D Sht 2/4 & 3/4	2	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	16.5 in weld on 26.4 in centers	Same as Run 16 above, discontinuous welds.
18	66 7412879H 7413006D Sht 2/4 & 3/4	2	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 16 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high. No cap.
19	66 7412879H 7413006D Sht 2/4 & 3/4	2	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	16.5 in weld on 26.4 in centers	Same as Run 18 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high and discontinuous welds.

3. There are no caps shown for this particular node. Lap plates are included in the matrix for Node 66, since they are allowed everywhere.

Table 2A. Finite Element Runs for "Long" Sections (92.89 inch), Type 2											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
40	66 7412879H 7413006D Sht 2/4 & 3/4	2	Structural 7413320A- 2/2	No	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous fillet. No cap.
41	66 7412879H 7413006D Sht 2/4 & 3/4	2	Structural 7413320A- 2/2	No	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	16.5 in weld on 26.4 in centers	Same as Run 16 above, discontinuous welds.
42	66 7412879H 7413006D Sht 2/4 & 3/4	2	Structural 7413320A- 2/2	Yes	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 16 above, but added ¼-inch <u>thk</u> lap plate, 2-inch high. No cap.
43	66 7412879H 7413006D Sht 2/4 & 3/4	2	Structural 7413320A- 2/2	Yes	No	-50706	102380	-67150	¼-inch fillet 7413006D 2/4	16.5 in weld on 26.4 in centers	Same as Run 18 above, but added ¼-inch <u>thk</u> lap plate, 2-inch high and discontinuous welds.

3. There are no caps shown for this particular node. Lap plates are included in the matrix for Node 66, since they are allowed everywhere.

Table 3. Finite Element Runs for "Short Medium" Sections (22.00 inch), Type 3											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
20	63 7411192C- 7/14 7413006D	3	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous weld.
21	63 7411192C- 7/14 7413006D	3	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	2 in weld on 6.1 in centers	Same as Run 20 above, but discontinuous weld.
22	63 7411192C- 7/14 7413006D	3	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 20 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high
23	63 7411192C- 7/14 7413006D	3	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	2 in weld on 6.1 in centers	Same as Run 20 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high and discontinuous welds.

Table 3A. Finite Element Runs for "Short Medium" Sections (22.00 inch), Type 3											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
44	63 7411192C- 7/14 7413006D	3	Structural 7413320A- 2/2	No	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous weld.
45	63 7411192C- 7/14 7413006D	3	Structural 7413320A- 2/2	No	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	2 in weld on 6.1 in centers	Same as Run 20 above, but discontinuous weld.
46	63 7411192C- 7/14 7413006D	3	Structural 7413320A- 2/2	Yes	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 20 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high
47	63 7411192C- 7/14 7413006D	3	Structural 7413320A- 2/2	Yes	No	66551	-710	-13916	¼-inch fillet 7413006D 2/4	2 in weld on 6.1 in centers	Same as Run 20 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high and discontinuous welds.

Table 4. Finite Element Runs for “Long Medium” Sections (40.00 inch), Type 4

FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
24	65 7412879H 7411192C- 7/14	4	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous welds.
25	65 7412879H 7411192C- 7/14	4	Formed 7412879H- 2/2 0.313 <u>thk</u>	No	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	19.8 in weld on 27.9 in centers	Same as Run 24 above, with discontinuous welds.
26	65 7412879H 7411192C- 7/14	4	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 24 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high.
27	65 7412879H 7411192C- 7/14	4	Formed 7412879H- 2/2 0.313 <u>thk</u>	Yes	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	19.8 in weld on 27.9 in centers	Same as Run 24 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high and discontinuous welds.

Table 4A. Finite Element Runs for "Long Medium" Sections (40.00 inch), Type 4											
FEA Run	Node	Type	Structural/ Formed	Lap Plate	Cap	Load Axial, lbs (X)	Load Athwart, lbs (Y)	Load Vertical, lbs, (Z)	Weld Size at Base	Weld Length	Comments
48	65 7412879H 7411192C- 7/14	4	Structural 7413320A- 2/2	No	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Base case (ideal) with continuous welds.
49	65 7412879H 7411192C- 7/14	4	Structural 7413320A- 2/2	No	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	19.8 in weld on 27.9 in centers	Same as Run 24 above, with discontinuous welds.
50	65 7412879H 7411192C- 7/14	4	Structural 7413320A- 2/2	Yes	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	Continuous (Ideal)	Same as Run 24 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high.
51	65 7412879H 7411192C- 7/14	4	Structural 7413320A- 2/2	Yes	No	19990	48875	-53766	¼-inch fillet 7413006D 2/4	19.8 in weld on 27.9 in centers	Same as Run 24 above, but added ¾- inch <u>thk</u> lap plate, 2- inch high and discontinuous welds.