Optimization of Rib-to-Deck Welds for Steel Orthotropic Bridge Decks

PUBLICATION NO. FHWA-HRT-17-020
FEBRUARY 2017

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report documents fatigue testing results of full-scale geometries of various orthotropic rib-to-deck weld geometries. The Federal Highway Administration undertook this study in order to assess these weld geometries and potentially provide performance data that might alleviate restrictive fabrication specifications. Currently, these restrictions are reducing the competitiveness of orthotropic steel decks versus other alternatives. Parameters explored in the research were welding process, weld penetration, and fit-up tolerance. The results showed that fatigue resistance could be assured in design through simple fabrication rules that define the weld leg size and target penetration and, if implemented, should make rib-to-deck welds more fabricator-friendly to produce while still maintaining reliability against fatigue failures.

This report will benefit those interested in the design and fabrication of steel orthotropic bridge decks, including State transportation departments, steel bridge fabricators, design consultants, and researchers.

Cheryl Richter
Director, Office of Infrastructure
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-17-020	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Optimization of Rib-to-Deck Welds for Steel Orthotropic Bridge Decks		5. Report Date February 2017 6. Performing Organization Code:
7. Author(s) J.M. Ocel, B. Cross, W.J. Wright, and H. Yuan		8. Performing Organization Report No.
9. Performing Organization Name and Address Office of Infrastructure Research & Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296 Virginia Polytechnic Institute and State University Civil and Environmental Engineering Department 1880 Pratt Drive Blacksburg, VA 24060-6343		10. Work Unit No. 11. Contract or Grant No. DTFH61-04-C-00029 including Task Orders 28–30 DTFH061-10-D-00017 including Task Order 2
12. Sponsoring Agency Name and Address Office of Infrastructure Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report, October 2009–July 2012 14. Sponsoring Agency Code HRDI-40

15. Supplementary Notes
Justin Ocel (HRDI-40) conducted the testing at Turner-Fairbank Highway Research Center, was the technical monitor of all task orders, and prepared the final report with assistance from onsite contractor staff under both contracts. The Contracting Officer's Representative for both contracts was Fassil Beshah (HRDI-40).

16. Abstract
Orthotropic steel decks have been widely used over the decades, especially on long-span bridges as a result of their lightweight and fast construction. However, fatigue cracking problems have been observed in the welds in many cases because of wheel loads. The rib-to-deck welds need special care because they are directly located under wheel loads and are subjected to both local and global stress effects.

When this research began, the current practice in the United States was to use a one-sided partial penetration weld joining the rib and deck plates together with a minimum of 80-percent penetration requirement. Melt-through and blow were also considered rejectable defects. Restrictive requirements such as these result in a very narrowly defined welding procedure with little tolerance for variation. In practice, this leads to numerous weld repairs and rigorous inspection requirements that drive up the cost of orthotropic deck fabrication.

This study shows that the 80-percent penetration requirement can be significantly relaxed because fatigue performance was largely dictated by weld size and not penetration. A simple correlation is provided between weld size and penetration to guarantee American Association of State and Highway Transportation Officials category C fatigue performance that should provide for more relaxed fabrication specifications. Finally, specimens fabricated with purposeful fit-up gaps were found to close provided the original gap did not exceed 0.020 inch.

17. Key Words Local structural stress, steel bridge, orthotropic steel deck, fatigue testing	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 121	22. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AASHTO	American Association of State and Highway Transportation Officials
CAFT	constant amplitude fatigue threshold
GMAW	gas metal arc welding
HLAW	hybrid laser arc welding
ID	identification
IIW	International Institute of Welding
LRFD	load-and-resistance factor design
LSS	local structural stress
MSE	mean square error
SAW	submerged arc welding
TFHRC	Turner-Fairbank Highway Research Center
VT	Virginia Tech

INTRODUCTION

BACKGROUND

Many steel orthotropic bridge decks have been built over the last 60 years in Europe, the United States, Japan, and many other countries. The origin of this bridge deck type dates back to the "orthotropic plate" patent issued in Germany in 1948.[1] The major advantages of steel orthotropic decks include their light weight, rapid erection, and easy assembly. The original patent claimed that the steel consumption could be reduced by half. With these advantages, orthotropic bridge decks have been widely used on long-span highway, movable, cable-stayed, and suspension bridges because of their light weight. They have also been used on other types of bridges where fast construction is desired, such as temporary bridges and bridges in high population density areas. Orthotropic steel decks are also a common solution for redecking old bridges because of their easy assembly.

A steel orthotropic deck typically consists of a steel deck plate with welded stiffeners or ribs parallel to each other in the longitudinal direction. Transverse cross beams are typically used to support the ribs and provide stiffness in the transverse direction. The transverse cross beams typically serve as floor beams transferring the deck loads to the main structure. These floor beams are often integrated with the deck structure where the top flanges of the floor beams are often formed by the deck plate itself. The stiffening ribs can be open shapes, such as plates, inverted T-sections, angles, and channels or closed box-type ribs with different geometric shapes; trapezoidal closed ribs are the most common. Figure 1 is an illustration of a typical trapezoidal close-rib steel orthotropic deck panel where the large flat surface is the deck plate (with the stripes indicating typical lane markings) and the small trapezoids under the deck plate are the closed ribs. The first orthotropic steel deck with closed ribs was constructed in Germany in 1954. Compared to open stiffeners, the closed ribs have many advantages. First, closed ribs can transfer the traffic load much more efficiently in the transverse direction. As a result, closed ribs can have wider spacing than open ribs. This results in fewer ribs and therefore lighter weight compared to open-rib systems. Second, closed ribs can provide much higher flexural and torsional rigidity in the longitudinal direction, allowing longer spans to be achieved. In other words, fewer cross-beams are required, thereby reducing the deck self-weight and the number of welds associated with the cross-beams. Finally, because single-sided welds are used to attach the closed ribs to the deck versus double-sided welds for open ribs, the number of rib-to-deck welds is reduced by half. However, the one-sided welds cause quality control and inspection issues that can be a disadvantage for closed ribs.

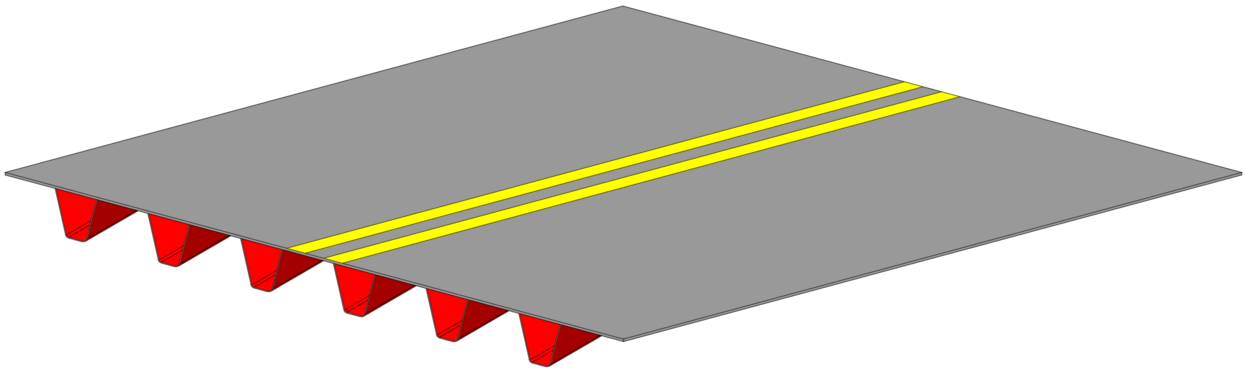


Figure 1. Illustration. Typical closed-rib steel orthotropic deck panel.

To overcome the disadvantages of one-sided welding and prevent premature fatigue failure, more careful consideration is needed to design rib-to-deck welds. Many of the earlier vintage orthotropic decks with closed ribs experienced fatigue cracking problems. There was a lack of knowledge about fatigue and a lack of guidance in the structural design codes. The complex stress state present at the rib-to-deck welds makes fatigue design even more difficult. Many orthotropic decks before the late 1970s were constructed under this state of knowledge. The quest for lighter self-weight led to relatively thin deck plates in the structural design. However, many of the designs with thinner deck plates were vulnerable to high local stress effects from wheel loads. The contribution of the wheel-load effect was not fully considered in early deck designs, and many bridges experienced fatigue cracking problems. Compared to main structural members, orthotropic steel decks tend to have a higher incidence of fatigue problems because of the local effects of wheel loads. Wheel loads cause large local stress variations, stress reversals, and an increased number of stress cycles that must be considered in fatigue design.

Steel orthotropic decks have been part of engineering practice and extensively studied in Europe for decades. Partially to the result of the use of relatively thin deck plates, premature fatigue cracking was observed in many European countries. (See references 2 through 6.) Steel orthotropic decks have also been widely constructed in the United States with mixed experiences relating to fatigue behavior. The situation has been steadily improving as more knowledge becomes available on how to improve fatigue resistance.

OBJECTIVES

The first objective of this study was to determine the effect of weld process and geometry on the fatigue resistance of the rib-deck weld. This was accomplished by fatigue testing a series of 159 specimens with different welding processes and different levels of weld penetration under two different loading regimes. A statistical analysis of the data was used to determine the effect each variable has on fatigue resistance.

The second objective of this research was to optimize the size and shape of rib-to-deck welds as the basis of the detailing requirements. At the time the project began (2008), the fourth edition of the American Association of State Highway and Transportation Officials (AASHTO) *Load-and-Resistance Factor Design* (LRFD) *Bridge Design Specification* was the current version.[7] Article 9.8.3.7.2 stated that "Eighty percent partial penetration welds between the webs of a closed rib and the deck plate should be permitted," and the commentary states that "Such welds, which require careful choice of automatic welding processes and a tight fit, are less susceptible to fatigue failure than full penetration groove welds requiring backup bars."[7](pp. 9–23) This provision was commonly perceived as rib-to-deck welds requiring a minimum penetration of 80 percent with a tight fit not to exceed 0.01 inch. An upper bound on penetration is typically applied such that the welds cannot have blow-through or melt-through that creates defects inside the ribs. In reality, because of the thin rib plate thickness that is commonly used in steel orthotropic decks, 80 percent penetration without melt-through or blow-through is difficult to achieve consistently, and, because of to the natural waviness of hot-rolled plate, the tight fit-up was also difficult to consistently achieve. A more tolerant penetration requirement is needed to reduce the need for weld repairs and increase fabrication efficiency. However, any relaxation of the 80 percent penetration must not increase the potential for fatigue cracking.

The last objective of this research was to validate the level 3 design approach currently published in the seventh edition of the AASHTO *LRFD Bridge Design Specification* (here forth referred to as AASHTO BDS in the remainder of this document) for the design of rib-to-deck welds.[8] This approach adopts a local structural stress (LSS) methodology for fatigue design where three-dimensional finite element models are used to characterize the stress state near weld toes. Stress is interrogated at two points away from the weld toe and then extrapolated to a theoretical stress at the weld toe that is used in the fatigue assessment. Fatigue life data collected in this project will be compared to the extrapolated LSSs based on finite element analysis of the specimens.

APPROACH

Fatigue resistance is typically characterized into S-N curves where fatigue test data is plotted based on the stress range (S) and the number of cycles to failure (N) on a logarithmic scale. Most previous orthotropic deck research used full-scale components to conduct fatigue testing. While this provides an accurate representation of a real structure in terms of boundary conditions and stress fields, the cost of specimens and testing equipment is prohibitively expensive. This research took a different approach where full scale was maintained but through a small test specimen. In this case, a full-thickness deck plate and full-scale rib are welded together into a panel that varied between 3 and 6 ft in length. This creates a full-scale geometry, and the residual welding stresses should be commensurate with a real structure. However, instead of testing the panel to only acquire one fatigue data point, the panel was sectioned into 4-inch-wide specimens, and loads were applied to the rib while supporting the deck, which caused out-of-plane (from the viewpoint of an entire deck) flexing of the rib, placing the weld in a high demand. While this loading pattern does not create a realistic stress pattern in the specimen as compared to a real deck, the concept does allow for rapid and cheap comparison of many specimens testing a variety of different variables on an equal playing ground.

It can be argued that sectioning of the panel reduces the residual stress and that the weak-link concept is lost. The weak-link concept can be illustrated when placing an entire panel under a fatigue test. Likely, that panel will develop a single fatigue crack at some localized point where there is an internal discontinuity within the weld. However, if that panel were sectioned into many smaller specimens, then that localized discontinuity is only within one of them, and that specimen will likely have the lowest fatigue resistance. The argument is that the distribution of fatigue life attained from many specimens extracted from one panel may be different than the distribution produced from testing many single panels. The researchers believe that it was more important to generate a large population of data rather than a small population.

EXPERIMENTAL STUDY

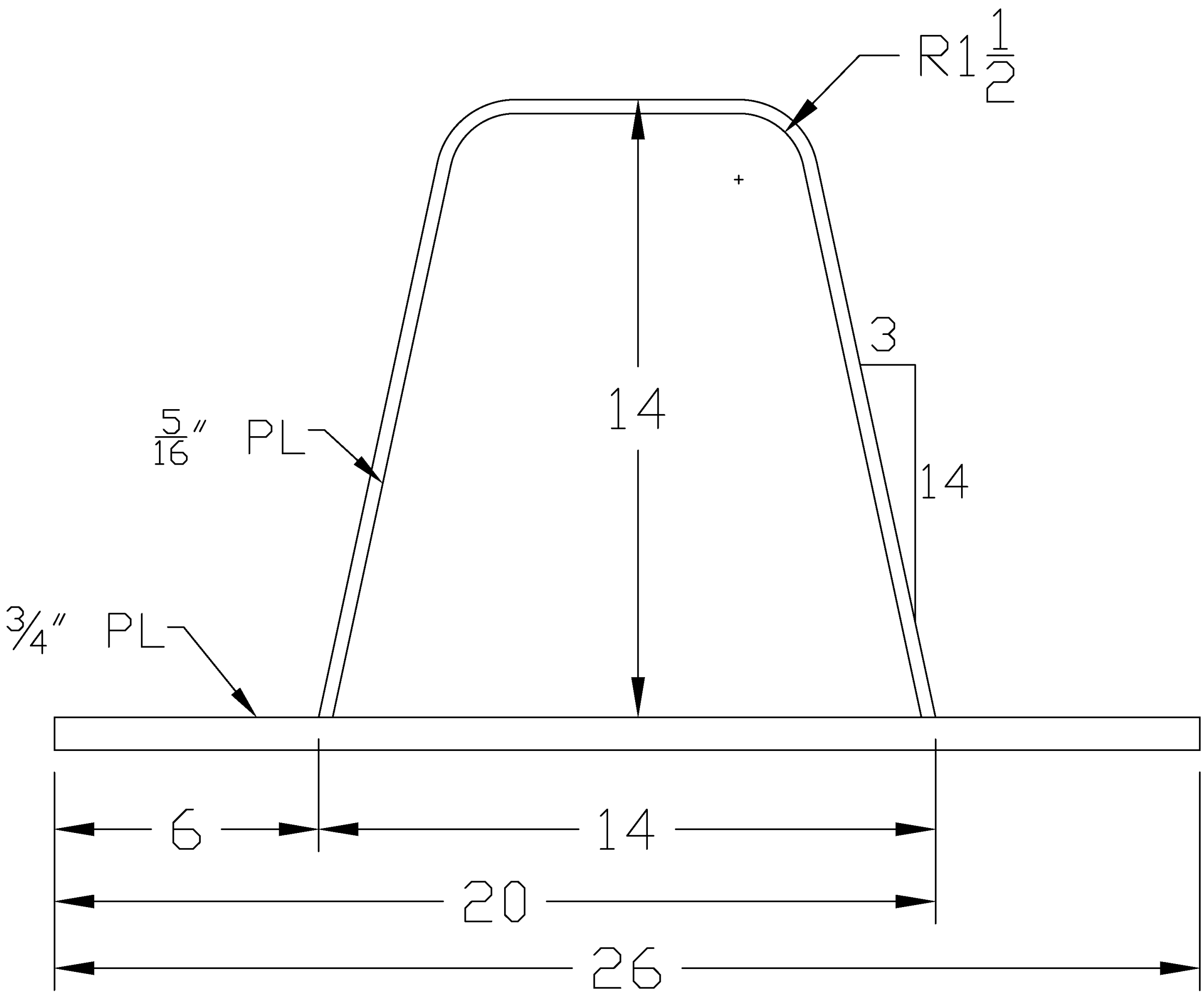
SPECIMEN FABRICATION

Either 3- or 6-ft-long weldments were fabricated from a single rib and flat plate meant to represent the deck plate. Two fabricators were used to make the specimens. Most specimens were made by a prominent steel bridge fabricator using typical weld processes. Specimens welded with hybrid laser arc welding (HLAW) were made by a small business that specializes in HLAW. HLAW was integrated into the test program because it produces a higher-quality weld that may lead to higher fatigue resistance.

After welding, the panel was transversely sectioned with a bandsaw to isolate individual 4.25-inch-wide test specimens. The saw-cut edges of the specimens were milled to provide uniform specimen width of 4 inches. Also, a hole was drilled through the flat bottom of the rib plate to enable mounting in the loading frame. The tack weld locations were marked on each specimen to determine whether tack welds influenced the fatigue crack initiation location.

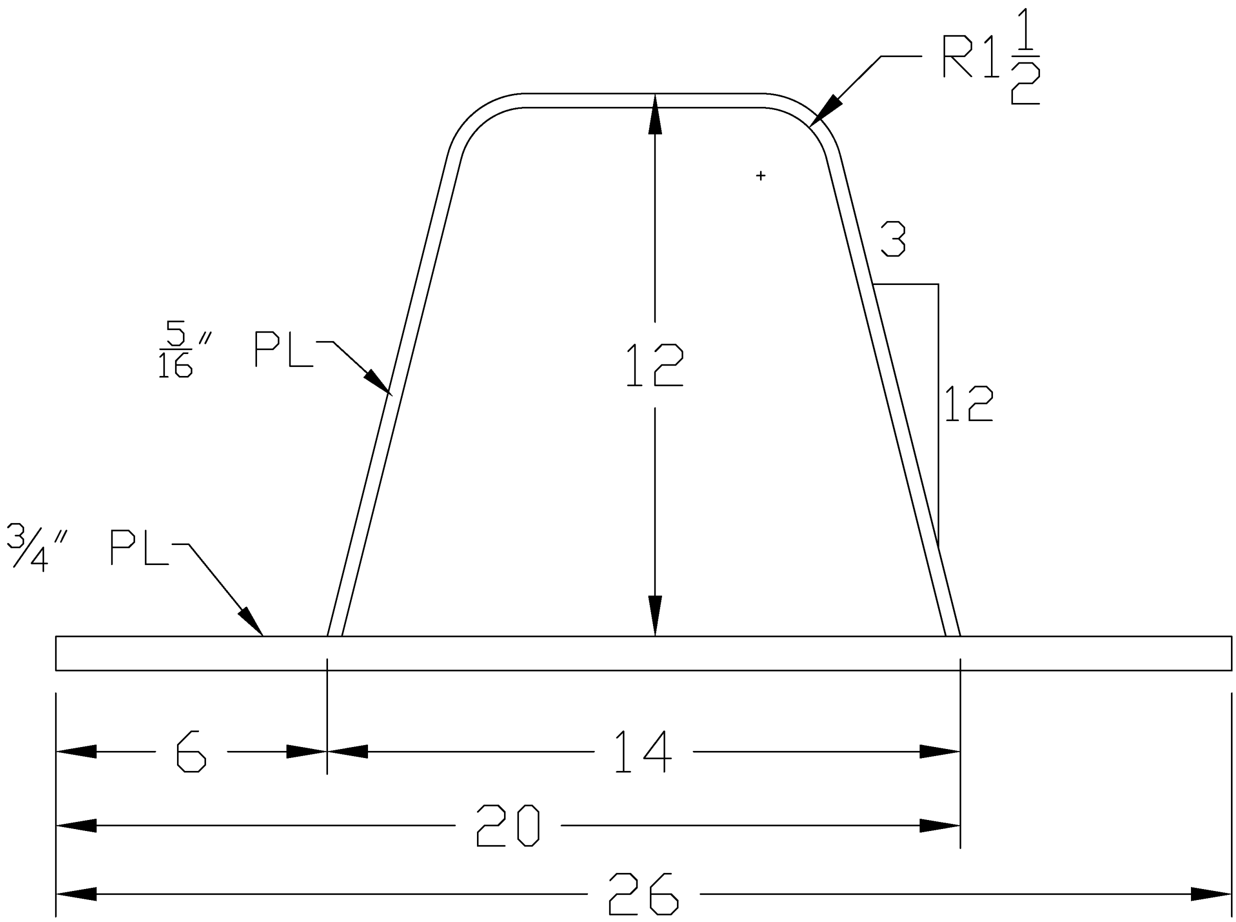
Schematics of each panel sectioning and specimen naming conventions can be found in appendix A.

Welded panels were procured in four distinct batches throughout the life of the project. A byproduct of this was the rib geometry changed slightly from one batch to another. Because this affects the loading of the specimen, figure 2 through figure 4 show the variation in the specimen geometries referred to as types 1–3 rib geometries. Type 1 specimens used a $^{3}/_{4}$-inch-thick deck plate and a $^{5}/_{16}$-inch-thick rib that was nominally 14 inches tall. Type 2 specimens used a $^{3}/_{4}$-inch-thick deck plate and a $^{5}/_{16}$-inch-thick rib that was nominally 12 inches tall. Type 3 specimens used a $^{5}/_{8}$-inch-thick deck plate and a $^{5}/_{16}$-inch-thick rib that was nominally 12 inches tall.



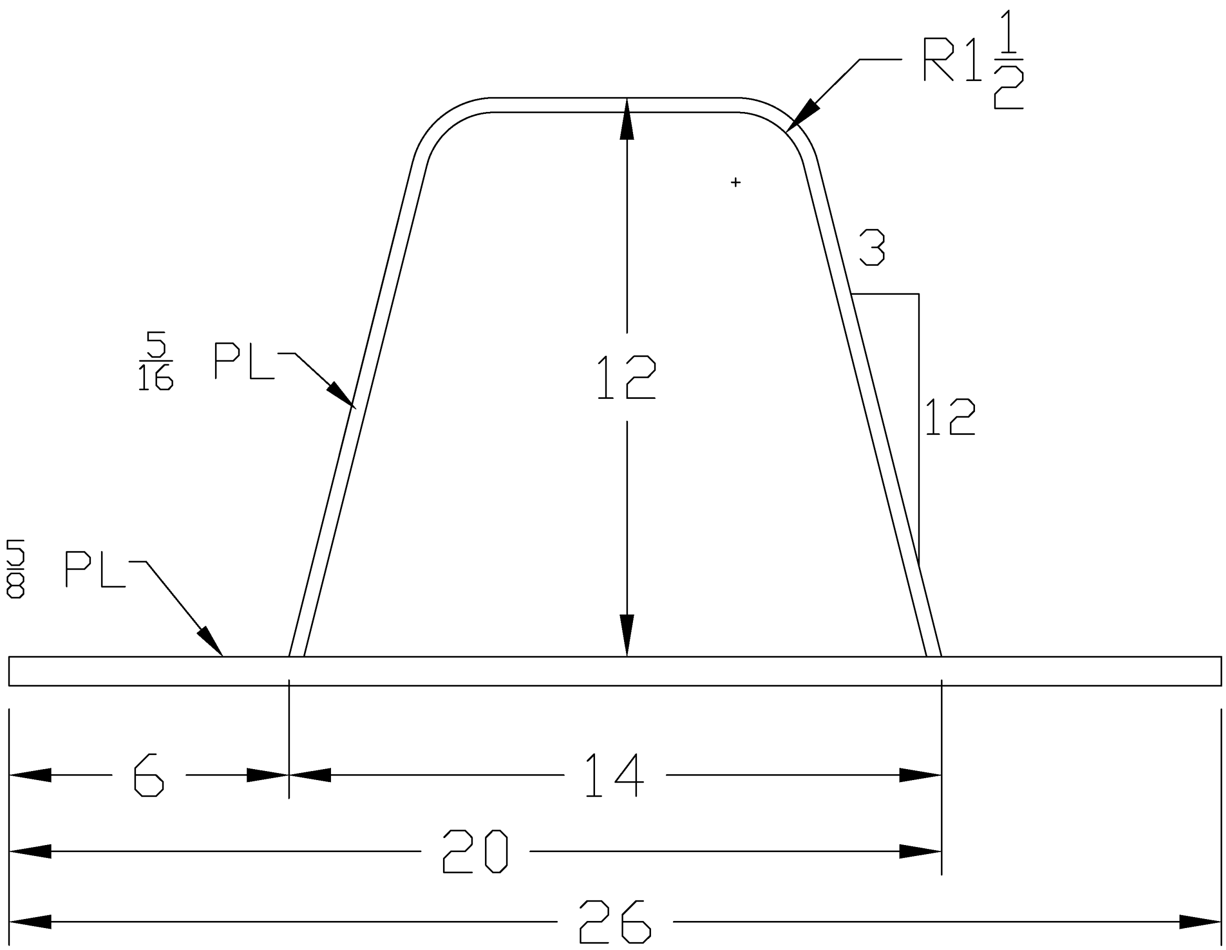
Units = Inches.

Figure 2. Illustration. Type 1 rib geometry.



Units = Inches.

Figure 3. Illustration. Type 2 rib geometry.



Units = Inches.

Figure 4. Illustration. Type 3 rib geometry.

The specimen geometries shown in figure 2 through figure 4 represent the as-designed rib, though it was noted during the project that the as-built geometry did deviate from the ideal geometry, but the deviation was not quantified in the project. For instance, the top of the rib was not always parallel to the deck plate, the rib legs were not always perfectly symmetrical, and the height of the rib varied.

TEST MATRIX

Table 1 highlights the major variables explored in the program: welding process, weld penetration, edge preparation, and fit-up gap.

Table 1. Test specimen series.

Series Name	Rib Geometry	Welding Process	Target Penetration (percent)	Rib Plate Beveling	Intentional Fit-up Gap (inches)	Number of Specimens
GM8	Type 1	GMAW	80	None	0	16
SA8	Type 1	SAW	80	None	0	16
SA6	Type 1	SAW	60	None	0	8
SA4	Type 1	SAW	40	None	0	8
SA2	Type 1	SAW	20	None	0	8
FIL	Type 1	SAW	None	None	0	8
LP1	Type 1	HLAW	100	Beveled	0	14
LP2	Type 1	HLAW	100	Beveled	0	13
LP3	Type 1	HLAW	100	Beveled	0	14
OB	Type 2	SAW	None	Beveled (5 degrees over)	0	16
UB	Type 2	SAW	None	Beveled (5 degrees under)	0	16
OG1	Type 3	SAW	60–100	None	0.02	16
OG2	Type 3	SAW	60–100	None	$^{1}/_{32}$	16
W	Type 3	SAW	60–100	Beveled	0.02	16

GMAW = Gas metal arc welding.
SAW = Submerged arc welding.

Three welding processes were explored: GMAW, SAW, and HLAW. It was suggested that weld quality may be a factor between the three processes and may lead to different fatigue lives.

Weld penetration is an obvious variable that may control fatigue life because this is a partial penetration weld under a tensile load. Because partial penetration welds inherently leave an unfused section of the rib at the root, it creates a notch-like defect that could spawn weld root failures. As the penetration value increased, it was thought the fatigue resistance would commensurate.

Edge preparation and fit-up gap are interrelated to the weld penetration, and figure 5 illustrates the differences. Because the rib is trapezoidal, the rib walls intersect the deck plate at a non-normal angle; therefore, without edge preparation, only a corner of the rib wall touches the deck plate prior to welding. This creates a larger face gap than root gap when there is no edge preparation. This requires more weld consumable to fill the larger gap; however, no edge preparation results in larger penetration because there is less base metal to melt in the rib wall, and the wire is able to get closer to the root. When the edge is prepared by milling, it is able to sit flat on the deck plate prior to welding, resulting in less penetration because more rib wall base metal has to be melted. From a fabrication standpoint, edge preparation is not desirable because of the added expense/time in handling the plate and conducting the milling operation. The fit-up gap is related to just the root gap. Because of the natural waviness of hot-rolled plates, a root gap is inevitable, but a tolerance should be provided, and this is referred to as the “fit-up gap.” Larger fit-up gaps can lead to melt-through and blow-through during welding, and small fit-up gaps can increase the cost of fabrication.

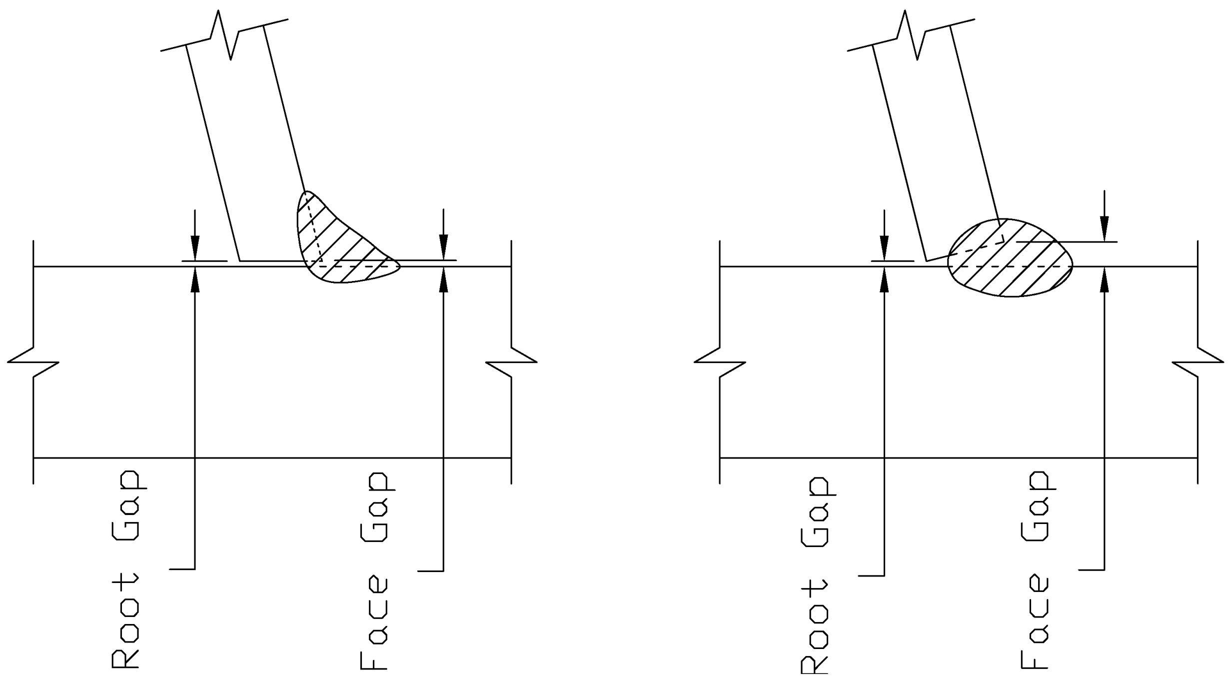


Figure 5. Illustration. Comparison of rib edge preparation: beveled (left) and no preparation (right).

Table 1 also shows horizontal division lines depicting the four distinct batches in which specimens were procured and tested. The first batch of panels was the GM8, SA8, SA6, SA4, SA2, FIL, and LP series. The variable that was targeted was the penetration of the weld and whether it was process dependent. The number in the series title correlates to the target percent penetration (in 10s of percent), GM means that it was made with GMAW, and SA means that it was made with SAW. The FIL series was made with SAW, but the intent was that it would literally be a fillet weld with very little penetration. Because of the face gap from no edge penetration on the rib, the GMAW and SAW processes were unable to attain penetration values less than approximately 60 percent despite attempts to make it vary from 0 to 80 percent. The LP series were made with HLAW, which is inherently intolerant of gaps and by its very nature required edge preparation. The HLAW process was able to consistently achieve 100 percent penetration. Because the two conventional weld processes achieved a consistent penetration, welding process was not considered a variable, and fit-up gap and edge preparation were considered a larger player in achieving the desired weld penetration.

The OB and UB series panels were designed to investigate the influence of the weld root gap and whether weld root failures could be forced to happen. This was done by using an intentionally 5-degree overbeveled and underbeveled edge preparation, as shown in figure 6. The OB specimens were prepared with a bevel angle greater than the rib angle, resulting in a root gap that was open before welding. The UB series had a bevel angle less than the rib angle, resulting in a closed root gap before welding. Despite this bevel preparation, weld shrinkage due to cooling of the weld metal caused the root gaps to close after welding in both series. However, the different bevel preparation resulted in different amounts of contact pressure at the root. The UB series showed definite plastic distortion where the two plates were pressed together from weld shrinkage. This was less evident in the OB series, where the root gap had to close before pressure could develop. Because the OB series did not result in the desired open root gap, they were all saw-cut at the root to open the gap before testing. The saw cuts were performed carefully to avoid contact with the weld, thereby preserving the natural situation at the tip of the root notch. Additionally, half of the UB series had their roots saw-cut. Figure 7 shows typical saw cuts on both the OB and UB specimens.

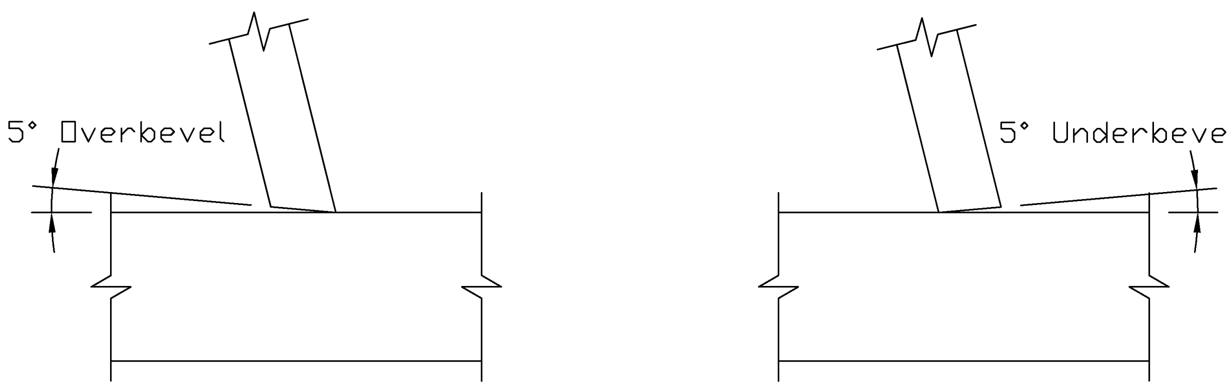


Figure 6. Illustration. Overbeveled (left) and underbeveled (right) edge preparation.

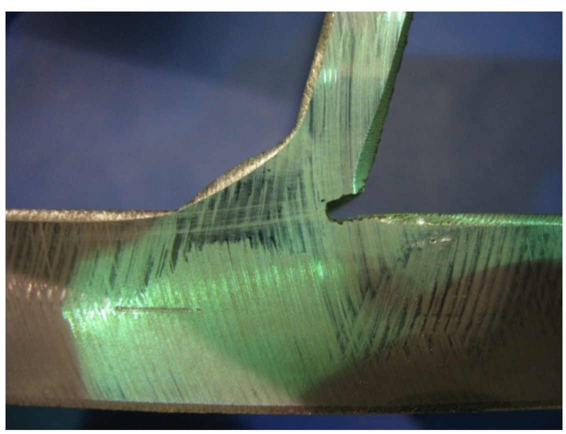
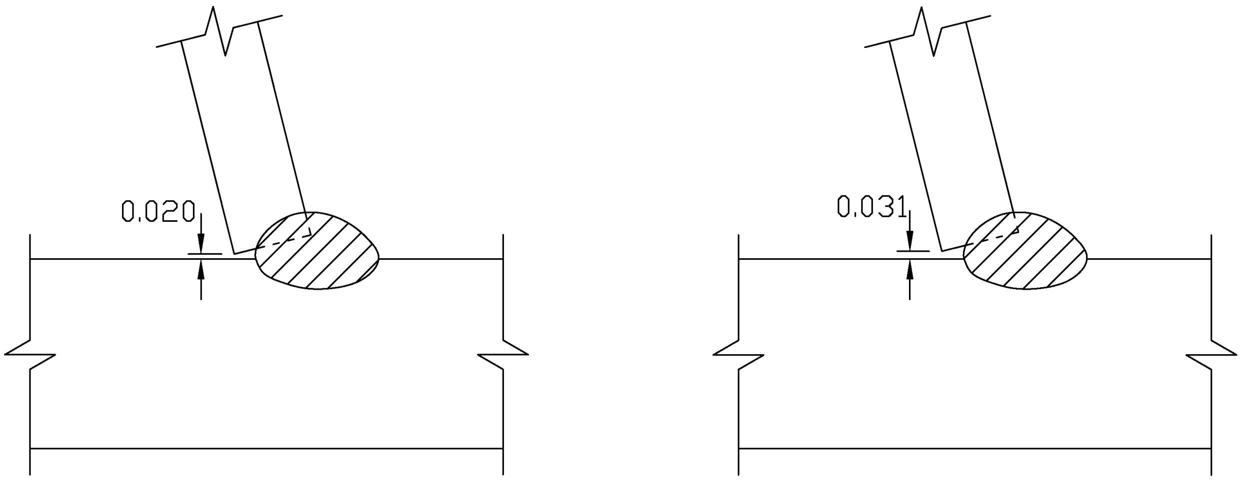


Figure 7. Photo. Typical saw cuts introduced at the weld roots on the OB and UB series specimens.

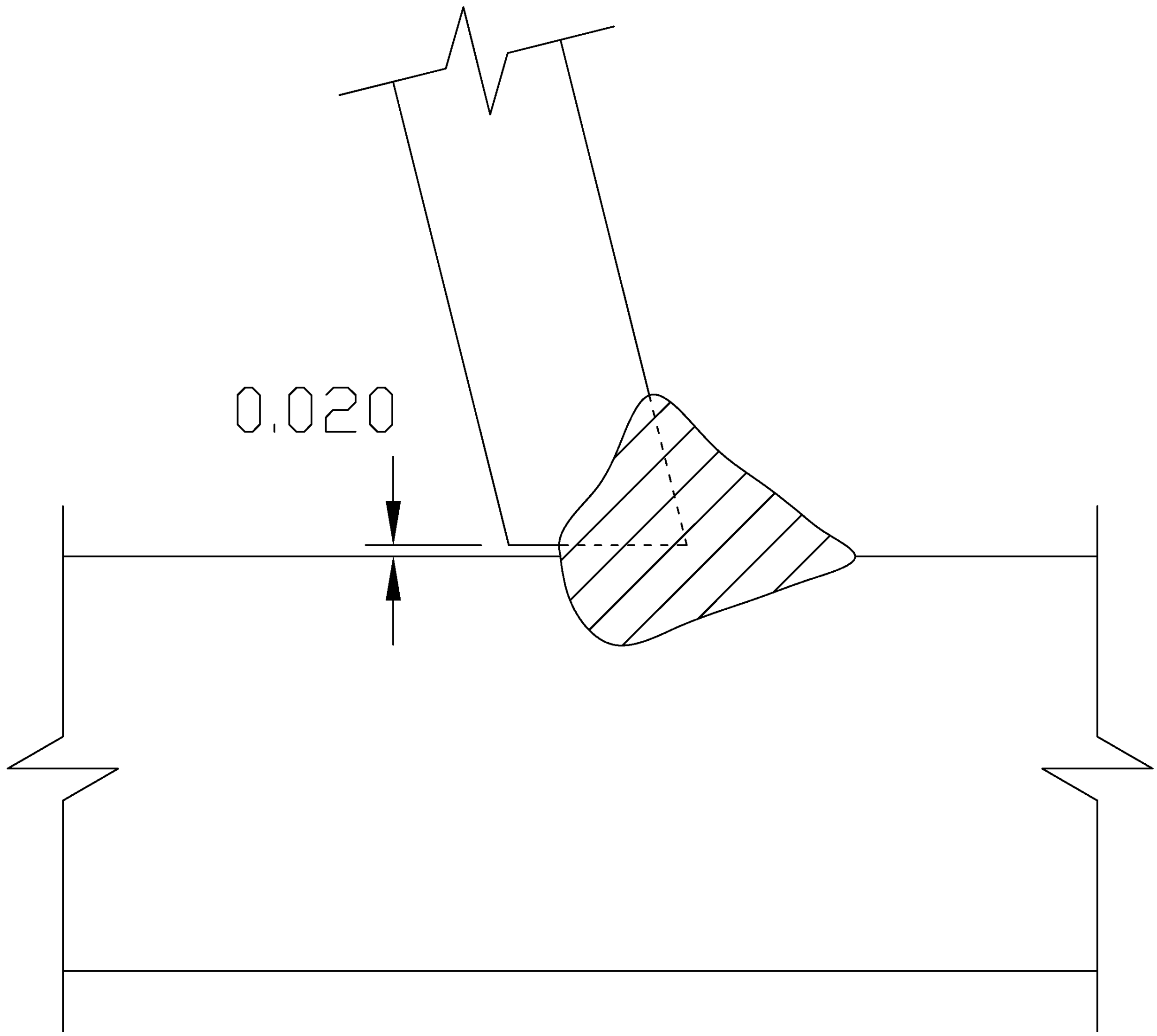
The OG series was meant to explore the effect of potential fit-up gaps that naturally occur as a result of the waviness of hot-rolled plates. No bevel preparation was used. The fabricator used jacks to either lift the rib up or push it down before tacking the rib in place prior to welding. The gap was set using feeler gauges and was mostly uniform along the length of the panel prior to welding. The OG1 panel had an intentional 0.020-inch gap placed where the OG2 panel had an intentional 0.031-inch gap. This is illustrated in figure 8.



Units = Inches.

Figure 8. Illustration. Intentional fit-up gaps in OG1 panel (left) and OG2 panel (right).

The last panel fabricated was the W series and was meant to include all the lessons learned from the previous sets of panels to attain a target penetration of 70 percent with variance allowed between 60 and 100 percent. The edge was bevel prepared by the fabricator to attain better control over the penetration. In addition, a 0.020-inch fit-up gap was purposely introduced. This is illustrated in figure 9.



Units = Inches.

Figure 9. Illustration. Fit-up gap and edge preparation for W series.

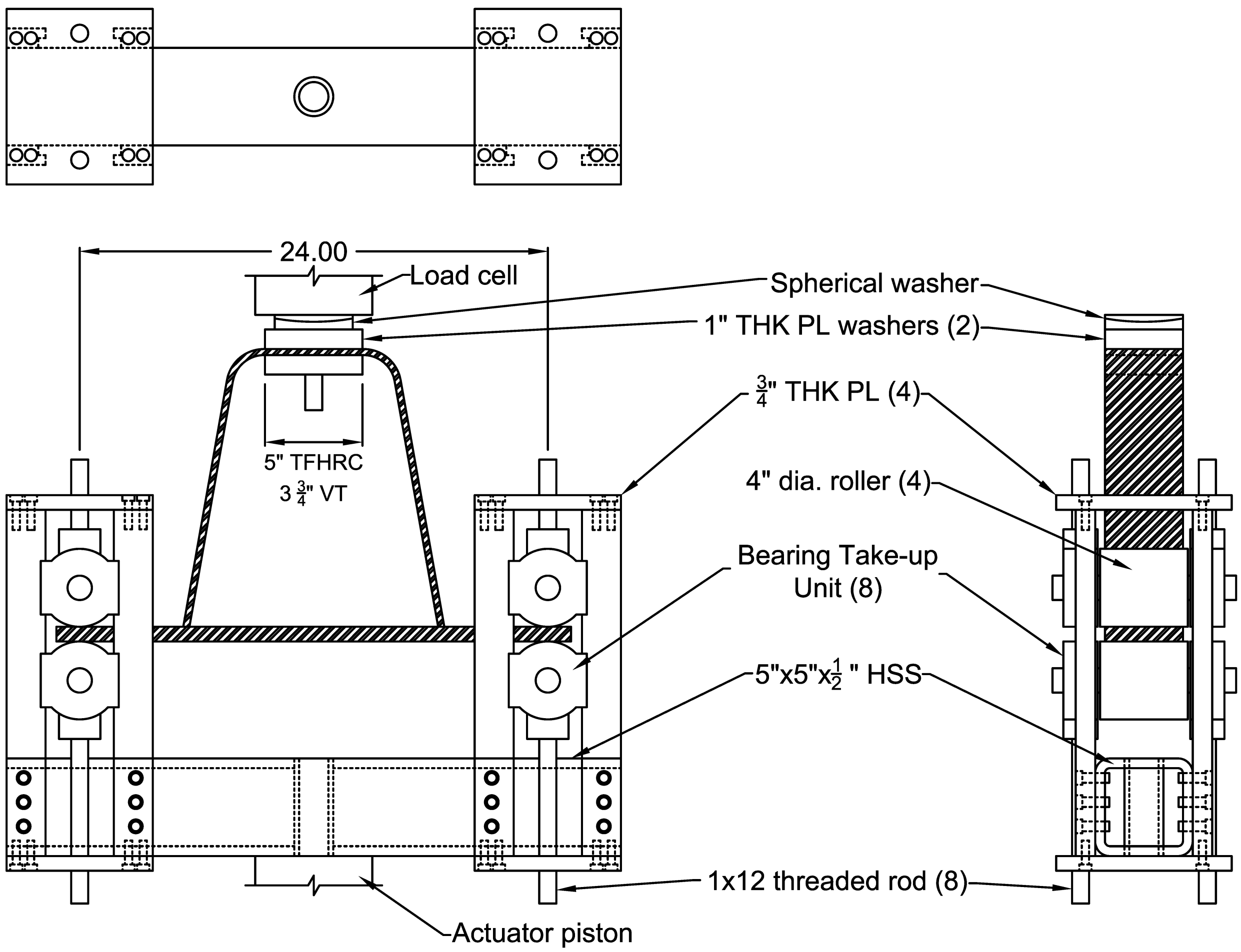
Residual stress is a key factor in the fatigue performance of welded joints; therefore, tests were performed at different load ratios (*R*-ratios) to study their effect on fatigue life, though this is not reflected in table 1. The *R*-ratio represents the ratio between the minimum and maximum loads of the applied load cycle. The stress cycle is under full tension when $R = 0$, and it is under an equal tension-compression stress reversal when $R = -1$. Only ratios of 0 and −1 were explored in this program. Comparison of fatigue results from the two test conditions can help determine how much of the compression stress range is being placed in relative tension as a result of superposition of residual stresses. The $R = 0$ test condition will provide a lower bound for fatigue life. Each test series had a blend of specimens tested at both load ratios.

TEST SETUP AND PROCEDURE

Fatigue tests were conducted concurrently at both the Structures Laboratory at the Turner-Fairbank Highway Research Center (TFHRC) and the Structures Laboratory at Virginia Tech (VT). Each testing site both used closed-loop, servo valve-controlled hydraulic testing frames. The following subsections describe the loading fixture and testing procedures.

Test Setup

Two customized test fixtures were fabricated to hold a specimen and facilitate applying loads in the universal testing machines. An illustration of the customized fixture is shown in figure 10. Conceptually, the fixture was a spreader beam that supported four adjustable rollers. The rollers were meant to clamp the deck plate so it could resist full load reversals. Each of the rollers was supported by two take-up bearings. The bearings could allow some angular adjustment so the rollers could be adjusted to be parallel to the deck plate surface. The welded test specimens had a certain amount of plate distortion induced by welding. The angular adjustment capability of the rollers was essential to allow the rollers to adapt to the specimen and prevent distortional twisting that could cause error in the applied stress range. This fixture was mounted to either the actuator piston or load cell, depending on the preference of each test site.



Units = Inches.

Figure 10. Illustration. Test setup.

The flat of the rib attached to the other side of the machine from the customized fixture. To uniformly load across the width of the rib, the rib was sandwiched between two thick plate washers. The thick plate washers were 5 inches long at TFHRC but only 3.75 inches long at VT. This is specifically noted because it slightly altered the loading in the specimens between the two testing sites. In addition, since the rib flat was typically not parallel to the deck plate, spherical washers were placed between the thick plate washer and the testing machine to ensure the deck plate sat parallel to the hollow structural section of the customized fixture.

Photos of the fixture and a specimen mounted into the testing frames at each of the test sites are shown in figure 11 and figure 12.

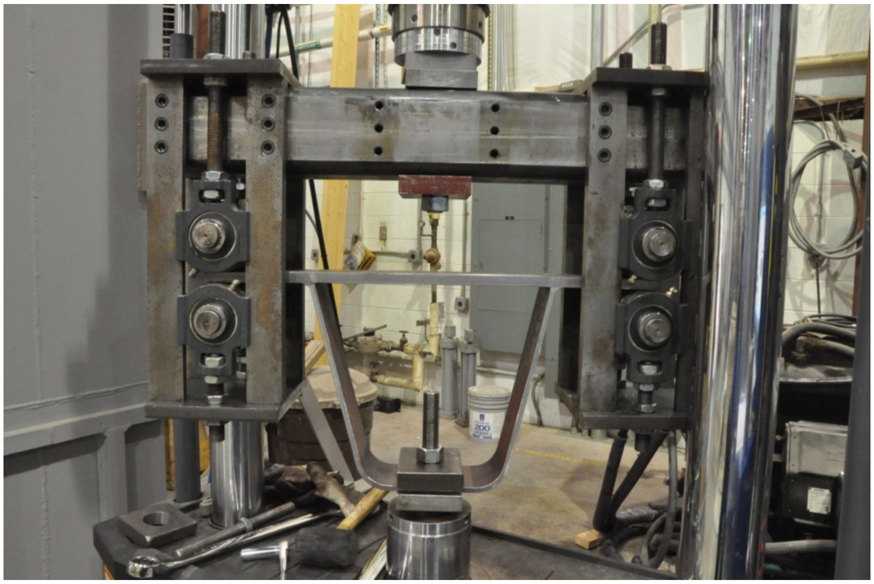


Figure 11. Photo. Test setup at VT.

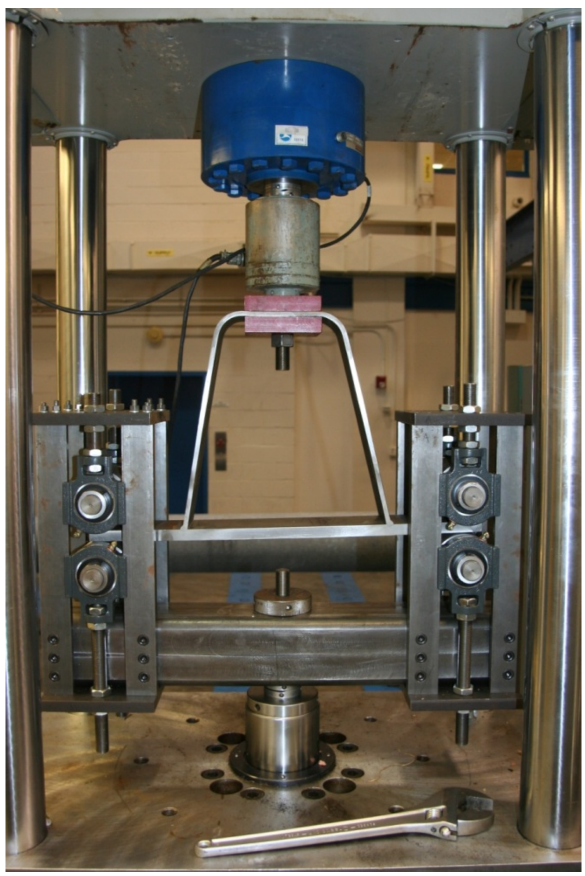


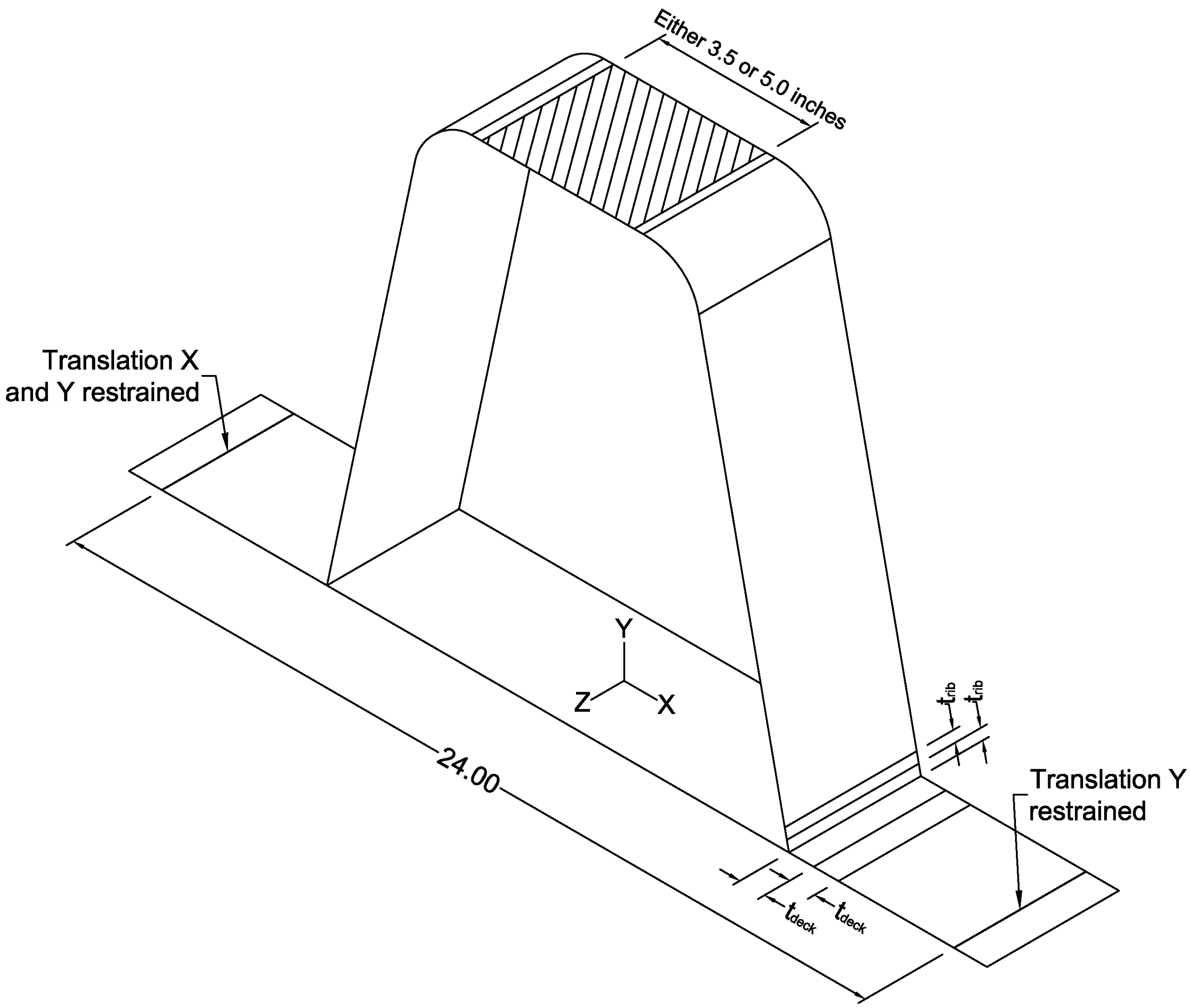
Figure 12. Photo. Test setup at TFHRC.

Test Procedure

Consistent boundary conditions between specimens were essential to minimize scatter in the test results. Ideally, the top and bottom rollers should have provided ideal boundary conditions. However, excessive clamping force between the two rollers could potentially add some fixity. The stress state at the potential cracking locations was expected to change dramatically if fixed-end conditions existed instead of the ideal rollers. Too much clamping force from the rollers on the deck plate could cause roller friction that would effectively create a semi-fixed boundary condition. Too little clamping force would introduce slip in the load path and allow the specimen to bang and vibrate in the test fixture under load reversal. Therefore, an installation procedure was initiated to measure and limit the clamping force to ensure that the ideal roller boundary condition was present. After a few trials, the clamping force was set to 70 lb on each side (140 lb in total). The force was measured by monitoring the load cell output during the clamping procedure while in displacement control. Rollers on one side of the deck plate were brought into contact with the deck plate equally until the load cell read 140 lb, and then the rollers on the other side were brought into contact until the load cell registered 0 lb. It was observed that the rollers were still able to rotate freely at this clamping force level.

LSS ANALYSIS

The specimens were analyzed according to the level 3 design procedures outlined in AASHTO BDS to attain the LSS range. This design philosophy is based on the International Institute of Welding (IIW) document entitled *Recommendations for Fatigue Design of Welded Joints and Components*.[9] The LSS is defined via linear extrapolation of surfaces stress near the weld toe to the weld toe location. AASHTO BDS adopted the IIW coarse meshing option where the mesh size at the weld has element dimensions of approximately *t* by *t*, where *t* is the plate thickness. The IIW method requires extrapolating stresses from 0.5*t* and 1.5*t* distance away from the weld toe. It is further suggested that stresses are taken at mid-side nodes, suggesting that quadratic element formulations are used. This also requires two rows of elements, each *t* long, meshed on the extrapolated side of the weld toe. This is better shown in figure 13 where the geometry of the mid-plate thickness is shown. At the line defining the weld toe, two parallel lines are offset up the rib (generally in the Y direction) and across the deck plate (in the X direction). These parallel lines are offset by the thickness of the respective plates. Only one element width would be meshed between these parallel lines, and the mesh would be seeded across the width of the specimen (in the Z direction) such that the element width would be approximately *t*.



Units = Inches.

Figure 13. Illustration. Partitioning of specimen.

Since each lab used a different-sized thick plate washer to clamp the rib to the testing machine, each model was analyzed considering these two boundary conditions. Figure 13 shows a hatched area at the top of the rib. This hatched area was either 3.75 or 5 inches in the X direction for the specimens tested at VT and TFHRC, respectively. This area of the rib was modeled with a shell thickness of 2 inches to represent the added stiffness provided by the two thick plate washers. A unit point load was applied at the center of the hatched area to represent the applied load to the specimen. Because the specimens remained elastic, the results from this unit load analysis were multiplied by the applied load range to attain LSS ranges.

Finite element models were constructed with an analysis program capable of capturing nonlinear material and nonlinear geometric behavior; however, the models were fully elastic following the level 3 design procedure. A typical mesh is shown in figure 14. The mesh may appear discontinuous at the intersection of the rib and deck. With the restriction of approximately *t* by *t* element dimensions, it becomes difficult to attain a continuous mesh when there are large disparities in the plate thicknesses, such as this case, where the deck plate is over twice as thick as the rib plate. However, the analysis program has the capability of enforcing surface-based tie constraints between different parts. In this case, the rib and deck are modeled as individual parts and then assembled together with tie constraints to represent the weld. Tie constraints have no volume or mass; they merely enforce compatibility between two meshes. This enforces compatible displacements and rotations between the incompatible meshes through interpolation between node regions. Therefore, the rib and deck plates could be modeled with their respective *t* by *t* element dimensions within the same model.

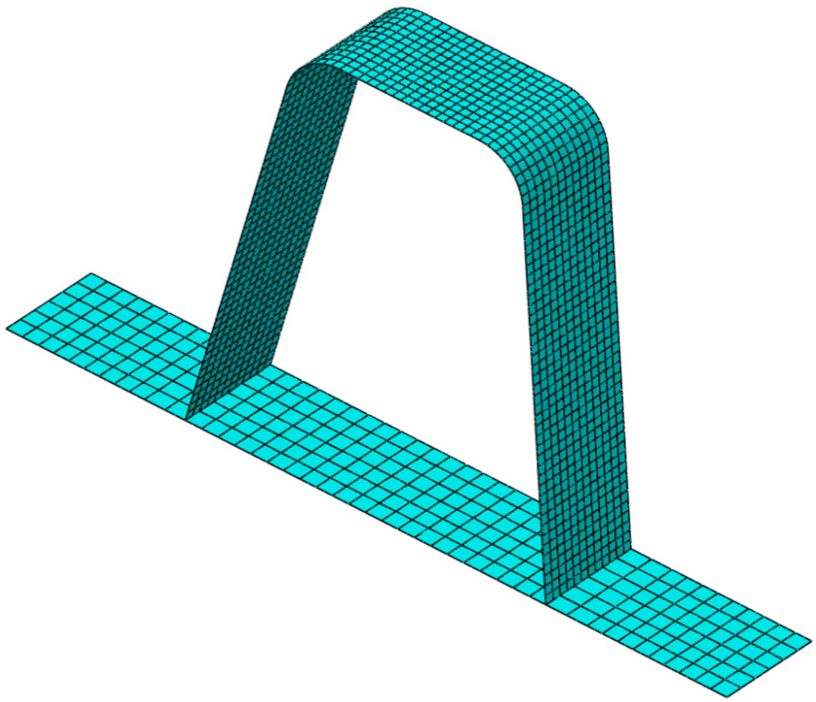


Figure 14. Illustration. Meshed specimen.

As mentioned previously, only a unit load was modeled at the middle of the rib top. The resulting stress contours through a typical specimen is shown in figure 15 superimposed on the deflected shape. This contour plot shows the stresses at the element surfaces near the weld toe; these are in a direction perpendicular to the weld toe. The local structural extrapolation required interrogation of mid-side nodes at a distance of 0.5 and 1.5 plate thicknesses from the intersection. In AASHTO BDS, these are called the $f_{0.5}$ and $f_{1.5}$ stresess, and they should be in the direction perpendicular to the weld toe. The illustration shown in figure 16 is a zoomed-in view of figure 15 to just the weld region. Also shown by black dots are the mid-side nodes where the $f_{0.5}$ and $f_{1.5}$ stresses are taken for both the rib and deck plate. The model ignored the geometry of the weld as a simplification, and, because of this, the extrapolation was to the plate intersection, not the location of the theoretical weld toe. This was done for two reasons: (1) it was thought this would be a conservative assumption, and (2) all of the welds tested had quite a variation in weld geometry, so it would have been burdensome to model every specimen in lieu of just ignoring the weld.

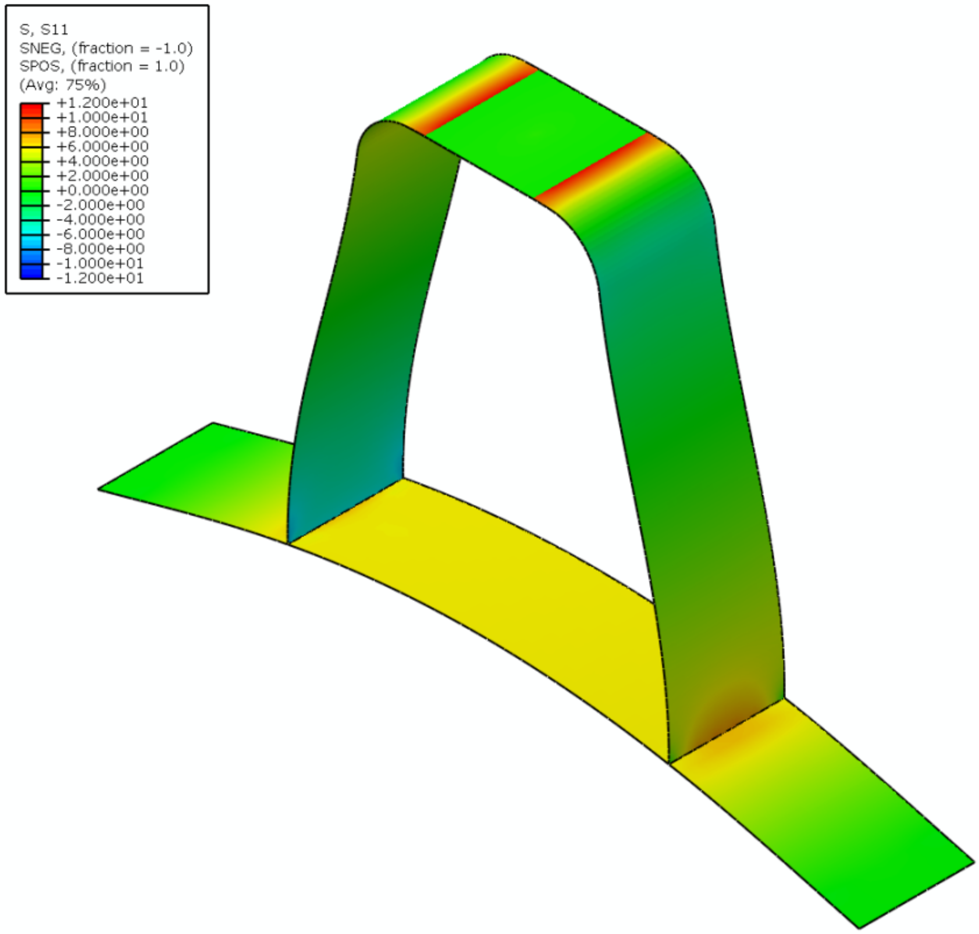


Figure 15. Illustration. Membrane stress in specimen under unit load.

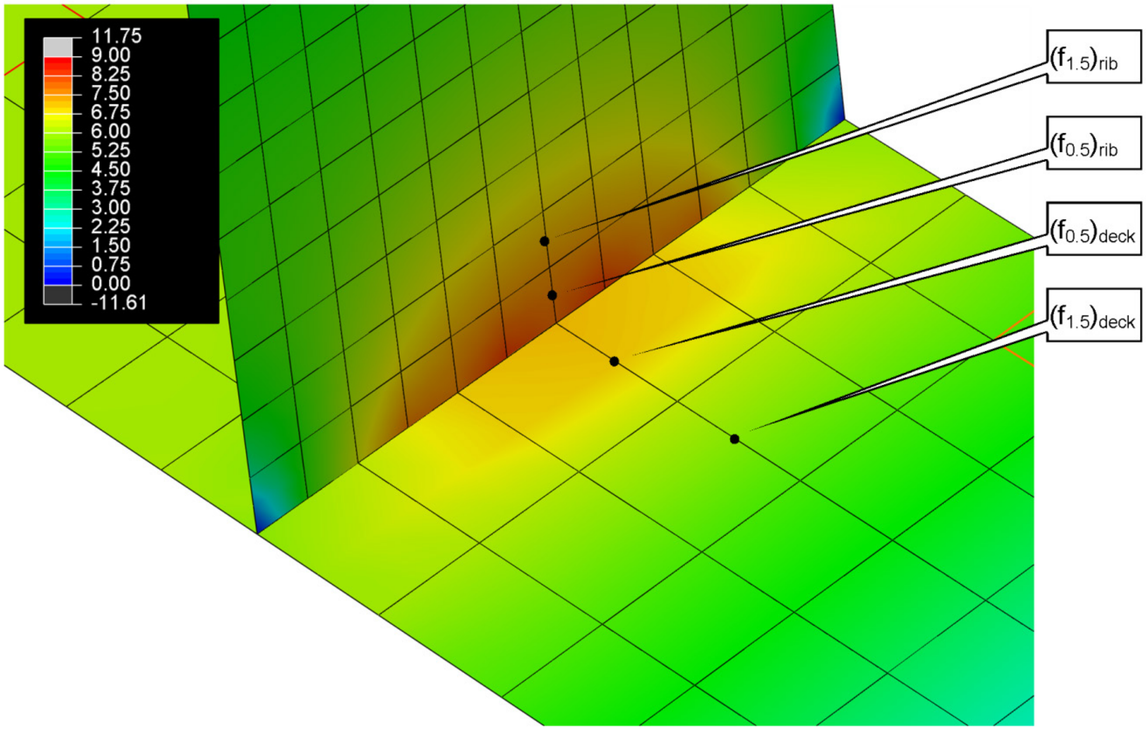


Figure 16. Illustration. Extrapolation points from rib and deck plate.

LSS results from all the models are shown in table 2 through table 4, respectively, for the types 1–3 specimen geometries. Because the models were based on unit loads, the $f_{0.5}$ and $f_{1.5}$ stresses reported are from the unit load. The f_{lss} stress is the actual LSS based on extrapolation. Because of the unit load analysis, all stresses are reported in units of ksi per kip of load. This was purposeful because in the fatigue analysis of the specimens, the f_{lss} value only had to be multiplied by the load range applied to the specimen to attain the total LSS range.

Table 2. LSSs from unit load for type 1 geometry.

Test Lab	Location	$f_{0.5}$ (ksi)	$f_{1.5}$ (ksi)	f_{lss} (ksi)
TFHRC	Deck plate	6.662	5.327	7.330
	Rib wall	7.053	6.522	7.318
	Weld root	4.710	4.319	4.906
VT	Deck plate	6.663	5.328	7.331
	Rib wall	7.682	7.085	7.981

Table 3. LSSs from unit load for type 2 geometry.

Location	$f_{0.5}$ (ksi)	$f_{1.5}$ (ksi)	f_{lss} (ksi)
Deck plate	6.663	5.331	7.329
Rib wall	8.246	7.581	8.579
Weld root	5.906	5.378	6.170

Table 4. LSSs from unit load for type 3 geometry.

Test Lab	Location	$f_{0.5}$ (ksi)	$f_{1.5}$ (ksi)	f_{lss} (ksi)
TFHRC	Deck plate	9.734	7.692	10.755
	Rib wall	11.035	10.174	11.466
VT	Deck plate	9.733	7.692	10.754
	Rib wall	11.457	10.547	11.912

Because of the boundary condition differences between the two labs, table 2 and table 4 report different f_{lss} values for each lab, as those rib geometries were tested at each lab. The type 2 geometry in table 3 was only tested at VT.

Finally, it can be noted that in table 2 and table 3, LSSs are also reported at the weld root. The LSS method was never intended for characterizing the stress state at a weld root. However, in this research, some specimens failed from the weld root, and, to plot those failures relative to all the other data, the LSS was extrapolated on the inside surface of the rib wall to represent the LSS of the weld root.

RESULTS

The raw data for all of the fatigue results are shown in table 5 through table 17 for all of the different series of panels tested. Each table reports the minimum and maximum loads applied to the specimen, the total force range, the load ratio, the percent penetration that was achieved (calculated as the projection of rib thickness onto the deck plate by the penetration measured along the deck plate), failure mode (either in the deck plate, rib wall, or weld root), LSS, and the number of cycles to failure. Finally, the tables report the root condition that existed in the as-welded condition.

Table 5. GM8 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
GM8-1	2.75/–2.75	–1	5.50	Close	72.7	Deck weld toe	40.32	888,807
GM8-2	0.00/5.00	0	5.00	Close	73.3	Runout	36.65	20,000,655
GM8-3	0.00/2.75	0	2.75	Close	79.0	Deck weld toe	20.16	18,253,515
GM8-4	2.50/–2.50	–1	5.00	Close	67.0	Weld root	24.53[a]	6,060,816
GM8-5	2.75/–2.75	–1	5.50	Close	81.2	Deck weld toe	40.32	770,672
GM8-6	2.50/–2.50	–1	5.00	Close	79.1	Deck weld toe	36.65	1,517,705
GM8-7	2.75/–2.75	–1	5.50	Close	83.0	Deck weld toe	40.32	751,609
GM8-8	0.00/5.00	0	5.00	Close	69.3	Deck weld toe	36.65	302,451
GM8-9	1.25/–1.25	–1	2.50	Close	84.1	Runout	18.33	10,000,000
GM8-10	0.00/5.00	0	5.00	Close	85.3	Deck weld toe	36.65	296,571
GM8-11	2.50/–2.50	–1	5.00	Close	88.8	Deck weld toe	36.65	1,390,062
GM8-12	2.00/–2.00	–1	4.00	Close	87.8	Deck weld toe	29.32	2,112,094
GM8-13	1.25/–1.25	–1	2.50	Close	94.5	Runout	18.33	10,000,000
GM8-14	0.00/6.00	0	6.00	Close	77.9	Deck weld toe	43.98	146,635
GM8-15	2.50/–2.50	–1	5.00	Close	96.5	Deck weld toe	36.65	863,459
GM8-16	2.50/–2.50	–1	5.00	Close	83.3	Deck weld toe	36.65	1,657,918

[a]LSS analysis is only applicable to the analysis of weld toe cracking. LSS range reported is based on extrapolation of stresses on the inside surface of the rib.
ID = Identification.

Table 6. SA8 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
SA8-1	2.50/−2.50	−1	5.00	Close	58.5	Rib weld toe	39.91	689,134
SA8-3	2.50/−2.50	−1	5.00	Close	53.0	Rib weld toe	39.91	3,732,998
SA8-4	2.50/−2.50	−1	5.00	Close	76.2	Rib weld toe	39.91	2,321,046
SA8-5	2.50/−2.50	−1	5.00	Close	73.8	Deck weld toe	36.66	3,332,973
SA8-6	2.50/−2.50	−1	5.00	Close	66.5	Deck weld toe	36.66	2,623,398
SA8-7	2.50/−2.50	−1	5.00	Close	67.9	Rib weld toe	39.91	3,399,577
SA8-8	2.50/−2.50	−1	5.00	Close	56.0	Rib weld toe	39.91	2,743,534
SA8-9	2.75/−2.75	−1	5.50	Close	53.4	Rib weld toe	43.90	283,556
SA8-10	2.50/−2.50	−1	5.00	Close	51.9	Rib weld toe	39.91	869,732
SA8-11	2.75/−2.75	−1	5.50	Close	60.4	Rib weld toe	43.90	617,702
SA8-12	2.75/−2.75	−1	5.50	Close	73.1	Deck weld toe	40.32	1,930,296
SA8-13	2.75/−2.75	−1	5.50	Close	72.7	Deck weld toe	40.32	1,782,037
SA8-14	0.00/5.00	0	5.00	Close	71.6	Deck weld toe	36.66	1,417,734
SA8-15	0.00/5.00	0	5.00	Close	67.1	Deck weld toe	36.66	943,434
SA8-16	0.00/5.00	0	5.00	Close	74.4	Deck weld toe	36.66	927,241

Table 7. SA6 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
SA6-1	0.00/5.00	0	5.00	Close	72.8	Deck weld toe	36.65	317,140
SA6-2	0.00/5.00	0	5.00	Close	70.0	Deck weld toe	36.65	257,016
SA6-3	0.00/5.00	0	5.00	Close	66.2	Deck weld toe	36.65	286,626
SA6-4	2.75/−2.75	−1	5.50	Close	71.3	Deck weld toe	40.32	629,917
SA6-5	2.75/−2.75	−1	5.50	Close	65.4	Deck weld toe	40.32	2,074,221
SA6-6	2.75/−2.75	−1	5.50	Close	72.3	Deck weld toe	40.32	860,759
SA6-7	2.75/−2.75	−1	5.50	Close	69.3	Deck weld toe	40.32	588,156
SA6-8	2.75/−2.75	−1	5.50	Close	64.7	Deck weld toe	40.32	521,486

Table 8. SA4 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
SA4-1	2.75/−2.75	−1	5.50	Close	58.3	Deck weld toe	40.32	643,413
SA4-2	2.75/−2.75	−1	5.50	Close[a]	62.6	Deck weld toe	40.32	540,472
SA4-3	2.75/−2.75	−1	5.50	Close	57.0	Deck weld toe	40.32	607,547
SA4-4	2.75/−2.75	−1	5.50	Close	59.5	Deck weld toe	40.32	840,760
SA4-5	2.75/−2.75	−1	5.50	Close	61.8	Deck weld toe	40.32	649,093
SA4-6	0.00/5.00	0	5.00	Close	58.2	Deck weld toe	36.65	294,621
SA4-7	0.00/5.00	0	5.00	Close	52.3	Deck weld toe	36.65	300,716
SA4-8	0.00/5.00	0	5.00	Close	66.1	Deck weld toe	36.65	407,819

[a]Side opposite the failure did have an open gap.

Table 9. SA2 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
SA2-1	2.75/−2.75	−1	5.50	Close	89.1	Deck weld toe	40.32	750,996
SA2-2	2.75/−2.75	−1	5.50	Close	66.8	Deck weld toe	40.32	2,690,351
SA2-3	2.75/−2.75	−1	5.50	Close	71.4	Deck weld toe	40.32	708,693
SA2-4	2.75/−2.75	−1	5.50	Close	65.2	Deck weld toe	40.32	381,990
SA2-5	2.75/−2.75	−1	5.50	Close	62.0	Deck weld toe	40.32	534,364
SA2-6	0.00/5.00	0	5.00	Close	64.1	Deck weld toe	36.65	258,639
SA2-7	0.00/5.00	0	5.00	Close	71.4	Deck weld toe	36.65	222,741
SA2-8	0.00/5.00	0	5.00	Close	64.5	Deck weld toe	36.65	238,136

Table 10. FIL series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
FIL-1	0.00/5.00	0	5.00	Close	66.1	Deck weld toe	36.65	308,351
FIL-2	0.00/5.00	0	5.00	Close	58.5	Deck weld toe	36.65	352,981
FIL-3	0.00/5.00	0	5.00	Close	64.2	Deck weld toe	36.65	302,927
FIL-4	2.75/−2.75	−1	5.50	Close	67.2	Deck weld toe	40.32	698,763
FIL-5	2.75/−2.75	−1	5.50	Close	62.8	Deck weld toe	40.32	855,918
FIL-6	2.75/−2.75	−1	5.50	Close	65.1	Deck weld toe	40.32	2,179,319
FIL-7	2.75/−2.75	−1	5.50	Close	46.4	Deck weld toe	40.32	870,418
FIL-8	2.75/−2.75	−1	5.50	Close	69.6	Deck weld toe	40.32	529,113

Table 11. LP1 and LP2 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
LP1-1	0.00/5.00	0	5.00	None	100	Deck weld toe	36.65	278,209
LP1-2	0.00/5.00	0	5.00	None	100	Deck weld toe	36.65	193,114
LP1-3	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	302,479
LP1-4	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	235,185
LP1-5	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	315,624
LP1-6	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	367,003
LP1-7	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	367,875
LP1-8	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	407,218
LP1-9	3.00/−3.00	−1	6.00	None	100	Deck weld toe	43.98	381,539
LP1-10	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	513,805
LP1-12	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	552,488
LP1-13	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	492,048
LP1-14	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	435,953
LP1-15	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	404,372
LP2-1	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	1,788,904
LP2-2	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	2,956,726
LP2-3	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	2,898,356
LP2-4	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	2,448,412
LP2-5	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	3,276,984
LP2-6	1.60/−1.60	−1	3.20	None	100	Deck weld toe	23.46	2,440,312
LP2-7	1.60/−1.60	−1	3.20	None	100	[b]	23.46	635,000
LP2-8	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	2,021,012

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
LP2-9	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	741,520
LP2-10	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	967,256
LP2-11	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	1,138,650
LP2-12	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	861,537
LP2-13	0.00/3.20	0	3.20	None	100	Deck weld toe	23.46	992,876
LP2-14[a]	0.00/3.20	0	3.20	None	Not measured	Deck weld toe	23.46	1,320,314

[a]This specimen was not HLAW welded; it was just fillet welds used to hold the rib in place for HLAW.
[b]Data quality was questionable due to lack of documentation for this particular specimen, and, based on unusually low fatigue resistance, it was not included in any analysis.

Table 12. LP3 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
LP3-0[a]	2.75/−2.75	−1	5.50	None	Not measured	Deck weld toe	40.32	1,262,905
LP3-1	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	471,293
LP3-2	0.00/5.00	0	5.00	None	100	Deck weld toe	36.65	208,968
LP3-3	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	251,375
LP3-4	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	338,584
LP3-5	0.00/5.00	0	5.00	None	100	Deck weld toe	36.65	169,658
LP3-6	2.75/−2.75	−1	5.50	None	100	Deck weld toe	40.32	474,830
LP3-7	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	302,748
LP3-8	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	425,770
LP3-9	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	361,781
LP3-10	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	502,781
LP3-11	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	477,681
LP3-12	0.00/4.00	0	4.00	None	100	Deck weld toe	29.32	430,735
LP3-13[a]	0.00/3.20	0	3.20	None	Not measured	Deck weld toe	23.46	5,407,198

[a]This specimen was not HLAW welded; it used fillet welds to hold the rib in place for HLAW.

Table 13. OB series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
OB-1	2.50/−2.50	−1	5.00	Open	45.2	Weld root	30.85[a]	647,879
OB-2	2.50/−2.50	−1	5.00	Open	65.1	Weld root	30.85[a]	981,142
OB-3	2.50/−2.50	−1	5.00	Open	67.0	Weld root	30.85[a]	2,385,939
OB-4	2.50/−2.50	−1	5.00	Open	80.6	Weld root	30.85[a]	1,376,487
OB-5	0.00/5.00	0	5.00	Open	66.5	Deck weld toe	36.65	574,148
OB-6	0.00/5.00	0	5.00	Open	66.3	Deck weld toe	36.65	688,273
OB-7	2.75/−2.75	−1	5.50	Open	66.0	Weld root	33.94[a]	1,076,871
OB-8	2.75/−2.75	−1	5.50	Open	70.1	Weld root	33.94[a]	618,383
OB-9	2.50/−2.50	−1	5.00	Open	76.3	Weld root	30.85[a]	2,451,238
OB-10	2.50/−2.50	−1	5.00	Open	52.8	Weld root	30.85[a]	1,056,726
OB-11	2.50/−2.50	−1	5.00	Open	54.2	Weld root	30.85[a]	996,626
OB-12	2.50/−2.50	−1	5.00	Open	65.8	Weld root	30.85[a]	1,316,952
OB-13	0.00/5.00	0	5.00	Open	67.7	Deck weld toe	36.65	990,806
OB-14	0.00/5.00	0	5.00	Open	57.1	Deck weld toe	36.65	979,089
OB-15	2.75/−2.75	−1	5.50	Open	64.8	Rib weld toe	47.18	660,272
OB-16	2.75/−2.75	−1	5.50	Open	51.6	Weld root	33.94[a]	768,171

[a]LSS analysis is only applicable to the analysis of weld toe cracking. LSS range reported is based on extrapolation of stresses on the inside surface of the rib.

Table 14. UB series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
UB-1	2.50/–2.50	–1	5.00	Close	65.1	Deck weld toe	36.65	1,359,570
UB-2	2.50/–2.50	–1	5.00	Close	68.8	Weld root	30.85[a]	694,734
UB-3	2.50/–2.50	–1	5.00	Close	65.1	Rib weld toe	42.90	2,011,029
UB-4	2.50/–2.50	–1	5.00	Close	60.7	Deck weld toe	36.65	1,372,641
UB-5	0.00/5.00	0	5.00	Close	65.6	Deck weld toe	36.65	386,829
UB-6	0.00/5.00	0	5.00	Close	66.2	Deck weld toe	36.65	474,226
UB-7	2.75/–2.75	–1	5.50	Close	72.9	Deck weld toe	40.31	1,292,525
UB-8	2.75/–2.75	–1	5.50	Close	70.7	Deck weld toe	40.31	1,182,601
UB-9	2.50/–2.50	–1	5.00	Open	76.4	Deck weld toe	36.65	2,024,920
UB-10	2.50/–2.50	–1	5.00	Open	69.8	Runout	36.65	4,725,868
UB-11	2.50/–2.50	–1	5.00	Open	54.6	Weld root	30.85[a]	1,483,203
UB-12	2.50/–2.50	–1	5.00	Open	54.0	Weld root	30.85[a]	1,590,018
UB-13	0.00/5.00	0	5.00	Open	45.4	Rib weld toe	42.90	448,014
UB-14	0.00/5.00	0	5.00	Open	64.4	Deck weld toe	36.65	591,939
UB-15	2.75/–2.75	–1	5.50	Open	64.9	Weld root	33.94[a]	856,676
UB-16	2.75/–2.75	–1	5.50	Open	57.4	Rib weld toe	47.18	1,177,345

[a]LSS analysis is only applicable to the analysis of weld toe cracking. LSS range reported is based on extrapolation of stresses on the inside surface of the rib.

Table 15. OG1 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap[a] (inches)	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
OG-1	2.75/–2.75	–1	5.50	0.000	[b]	Rib weld toe	65.52	716,527
OG-2	2.75/–2.75	–1	5.50	0.000	[b]	Deck weld toe	59.15	674,990
OG-3	2.75/–2.75	–1	5.50	0.000	[b]	Deck weld toe	59.15	536,828
OG-4	—	—	—	0.000	—	—	—	—
OG-5	—	—	—	0.000	—	—	—	—
OG-6	—	—	—	0.013 0.000	—	—	—	—
OG-7	—	—	—	0.005 0.000	—	—	—	—
OG-8	—	—	—	0.006 0.000	—	—	—	—
OG-9	—	—	—	0.006 0.007	—	—	—	—
OG-10	—	—	—	0.000	—	—	—	—
OG-11	—	—	—	0.000	—	—	—	—
OG-12	—	—	—	0.000	—	—	—	—
OG-13	—	—	—	0.000	—	—	—	—
OG-14	—	—	—	0.000 0.003	—	—	—	—
OG-15	—	—	—	0.000 0.009	—	—	—	—
OG-16	—	—	—	0.000 0.007	—	—	—	—

[a]The target pre-weld gap was 0.020 inch. When two numbers are presented in a cell, they represent measurements that were different on each of the rib legs.
[b]Macro-etch was never performed, so weld dimensions could not be reported.
—Specimen was accidently destroyed (no data to report).

Table 16. OG2 series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap[a] (inches)	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
OG-17	2.75/−2.75	−1	5.50	0.000	[b]	Deck weld toe	59.15	431,912
OG-18	—	—	—	0.006 0.000	—	—	—	—
OG-19	—	—	—	0.000	—	—	—	—
OG-20	—	—	—	0.000	—	—	—	—
OG-21	—	—	—	0.000	—	—	—	—
OG-22	—	—	—	0.000	—	—	—	—
OG-23	—	—	—	0.007 0.000	—	—	—	—
OG-24	—	—	—	0.000	—	—	—	—
OG-25	—	—	—	0.009 0.000	—	—	—	—
OG-26	2.75/−2.75	−1	5.50	0.000	[b]	Deck weld toe	59.15	318,523
OG-27	2.75/−2.75	−1	5.50	0.000	[b]	Deck weld toe	59.15	218,223
OG-28	—	—	—	0.000	—	—	—	—
OG-29	—	—	—	0.000	—	—	—	—
OG-30	—	—	—	0.000	—	—	—	—
OG-31	—	—	—	0.000	—	—	—	—
OG-32	—	—	—	0.000	—	—	—	—

[a]The target pre-weld gap was 0.031 inches. When two numbers are presented in a cell, they represent measurements that were different on each of the rib legs when the specimen was not tested.
[b]Macro-etch was never performed, so weld dimensions could not be reported.
—Specimen was accidently destroyed (no data to report).

Table 17. W series results.

Specimen ID	Minimum/ Maximum Loads (kips)	Load Ratio	Load Range (kips)	Root Gap	Penetration (percent)	Failure Mode	LSS Range (ksi)	Cycles to Failure
W-1	1.50/−1.50	−1	3.00	Closed	32.7	Deck weld toe	32.27	2,852,314
W-2	0.00/4.00	0	4.00	Closed	32.4	Deck weld toe	43.02	341,178
W-3	2.00/−2.00	−1	4.00	Closed	40.7	Deck weld toe	43.02	972,348
W-4	0.00/3.00	0	3.00	Closed	42.3	Deck weld toe	32.27	600,935
W-5	2.00/−2.00	−1	4.00	Closed	33.2	Deck weld toe	43.02	859,795
W-6	0.00/3.00	0	3.00	Closed	38.0	Deck weld toe	32.27	689,455
W-7	2.00/−2.00	−1	4.00	Closed[a]	47.4	Rib weld toe	45.86	795,766
W-8	0.00/3.00	0	3.00	Closed[a]	45.6	Deck weld toe	32.27	552,962
W-9	2.00/−2.00	−1	4.00	Closed	36.6	Deck weld toe	43.02	858,519
W-10	0.00/3.20	0	3.20	Closed	36.4	Deck weld toe	34.42	483,507
W-11	2.20/−2.20	−1	4.40	Open	34.9	Deck weld toe	47.32	512,260
W-12	0.00/3.20	0	3.20	Closed	40.3	Deck weld toe	34.42	403,150
W-13	2.20/−2.20	−1	4.40	Closed	46.5	Deck weld toe	47.32	655,818
W-14	0.00/3.00	0	3.00	Closed	31.4	Deck weld toe	32.27	624,567
W-15	2.00/−2.00	−1	4.00	Closed	38.5	Deck weld toe	43.02	1,211,796
W-16	0.00/3.00	0	3.00	Closed	40.0	Deck weld toe	32.27	980,335

[a]Side opposite the failure did have an open gap.

ROOT CONDITION

Root condition is controlled by fit-up tolerance between the rib and deck plate prior to welding. The root condition being open or closed was only determined visually. As previously described, the OB and UB series had many specimens with purposeful saw cuts to expose the root, and these were obviously open conditions (as shown in figure 7). The open condition can also occur naturally, as shown in the macro in figure 17, where the inside corner of the rib was not in contact with the deck plate prior to welding, and weld shrinkage did not close that gap. For the specimens that had purposeful fit-up gaps introduced, it was observed in most instances that the gap would disappear from weld shrinkage. This is mainly shown in table 15 through table 17. For the OG1, OG2, and W series specimens covered in these tables, the fabricator tack welded the rib to deck with pre-set gaps along the entire length of the panel before final welding. This was done by clamping and jacking the rib relative to the deck plate using feeler gauges to set the gap. The rib was tacked approximately every 6 inches. The OG1 and W panels had a 0.020-inch pre-weld gap, and the OG2 panel had a 0.031-inch gap.

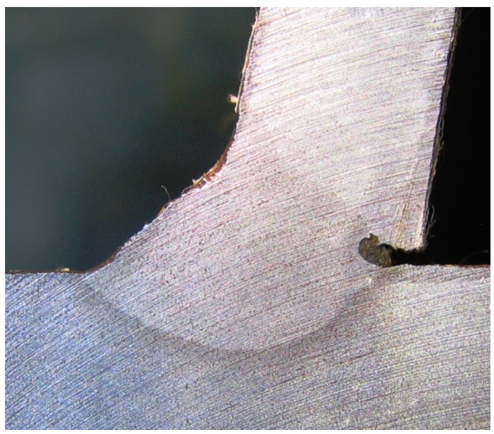


Figure 17. Photo. Macro of specimen SA4-2 (example of open root condition).

Once the OG1 and OG2 panels had been cut up into distinct specimens, feeler gauges were once again used to see if they could be inserted into the root on each side of the specimen. For the OG1 panel with a pre-weld gap of 0.020 inch, it can be seen in in table 15 that of the 32 roots, a feeler gauge could not be inserted into 25 of them. The remaining seven had measurable gaps varying from 0.003 to 0.013 inch. The OG2 panel had a pre-weld gap of 0.031 inch, and it can be seen in table 16 that of the 32 roots measured after welding, 29 had fully closed, with the remaining 3 with measurable gaps varying from 0.006 to 0.009 inch. Unfortunately, the W series specimen gaps were not measured with feeler gauges; and the determination was made strictly based on visual appearance from the weld macro of each specimen.

The closed root condition was interpreted as a condition where the unfused portion of the rib was in contact or almost in contact with the deck plate. A photo of the closed root condition is shown in figure 18; the inside corner of the rib was plastically deformed into the deck plate from the weld shrinkage. Figure 19 and figure 20 show photos from two W series specimen welds. Because this panel used a rib beveled to sit flush on the deck plate, 29 of the welds from all the specimens looked like the photo in figure 19, and this was considered to be a closed root condition. Three of the weld macros from the W series panel specimens looked like the specimen in figure 20 where there was a gap at the root (likely formed because the bevel was not fully machined), and this was considered to be an open root condition. In the closed root condition, stresses could be transferred through bearing between the rib and deck plates without large deformation to the rib.

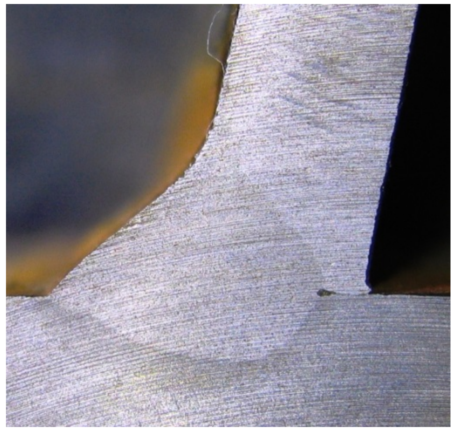


Figure 18. Photo. Macro of specimen SA6-1 (example of closed root condition).

Figure 19. Photo. Macro of specimen W-1.

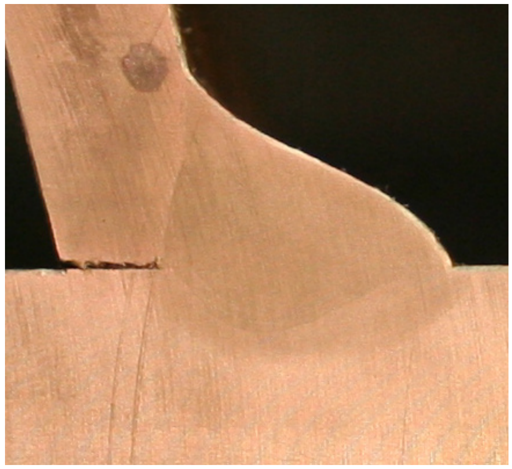


Figure 20. Photo. Macro of specimen W-11.

FATIGUE RESULTS

Several additional points should be noted when reviewing table 5 through table 17. First, all of the HLAW-welded panels achieved 100-percent penetration through visual inspection of the cross section exposed at the edge of each specimen. In fact, the weld root even had a small amount of reinforcement, indicating that penetration even exceeded 100 percent at times. However, in the tables, a value of 100 percent was assumed. Taking photos of every HLAW weld was deemed unproductive because the photos were only being used for attaining weld penetration, which was greater than or equal to 100 percent. Therefore, only 10 specimens had their weld cross sections photographed. As the program progressed, the photographs of all specimens were used to define further geometric variables beyond just penetration. However, the data for the HLAW series of panels may appear incomplete for this reason.

Second, most of the specimens from the OG1 and OG2 panel were accidently destroyed before they were tested. In addition, none of the photographs of the weld cross sections were preserved, and this gap appears in the data tables in appendix B.

The data from all specimens tested at a load ratio of −1 are plotted as blue-filled squares in figure 21 in S-N format against the AASHTO category B, C, and D curves. The heavy line represents the lower bound of the data (i.e., mean minus two standard deviations) and plots slightly above the category B curve. The data from all specimens tested at a load ratio of zero are plotted as circles in figure 22. The heavy line represents the lower bound of the data and plots just below the category C curve. The difference between these two results comes down to magnitude of residual stress and how effective the compression portion of the fatigue cycle is for $R = -1$ loading. Because it is nearly impossible to predict the load ratio in design because residual stresses are not known, it would be best to categorize the rib-to-deck weld based on tension-only loaded specimens.

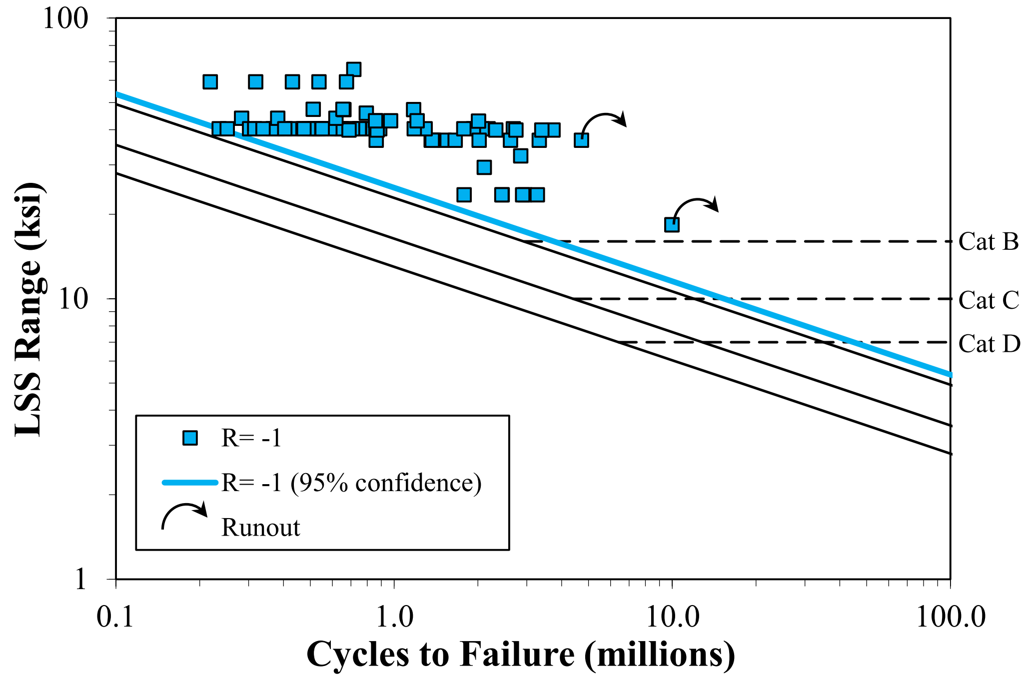


Figure 21. Graph. Plot of all *R* = −1 data.

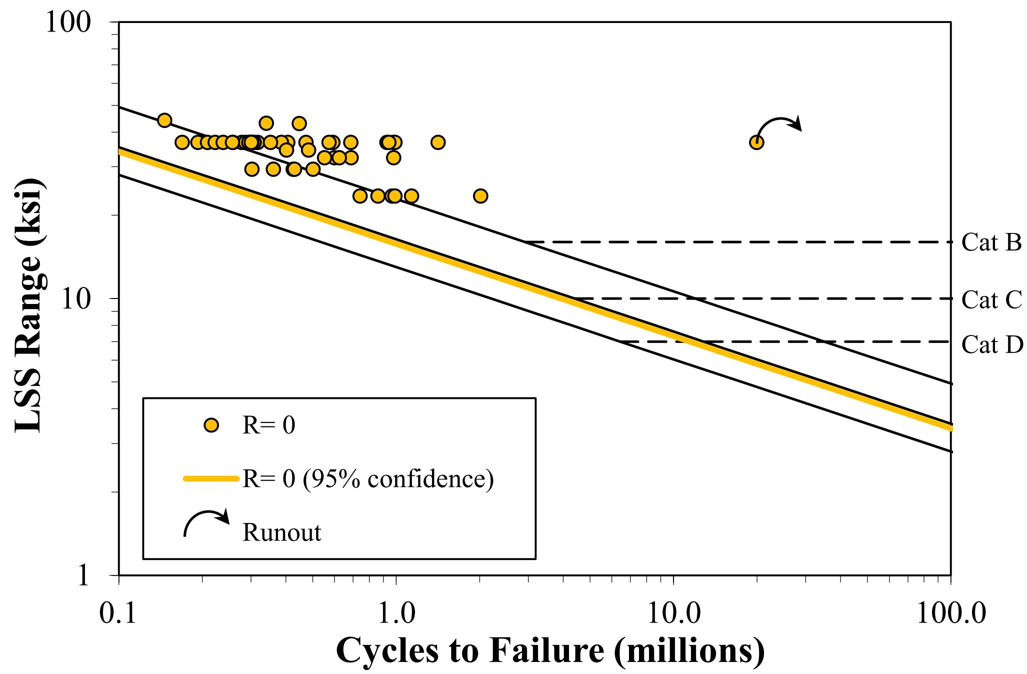


Figure 22. Graph. Plot of all *R* = 0 data.

The data from all weld root failures, which coincidently only occurred at load ratios of −1, are plotted as triangles in figure 23. The heavy green line represents the lower bound of the data and plots slightly above the category B curve. This indicates that according to the LSS procedure implemented in this document, weld root failures would be a category B detail. However, the procedure was slightly unconventional and used the LSSs on the inside of the rib wall that happened to not be at the weld toe. If the interior LSS is less than the LSS at the weld toe on the outside of the rib, then there should be no concern for weld root failures. If the interior LSS is larger, then that stress range should be compared to category B for design purposes. The specimens that suffered weld root failures had penetrations that varied between 45 and 76 percent.

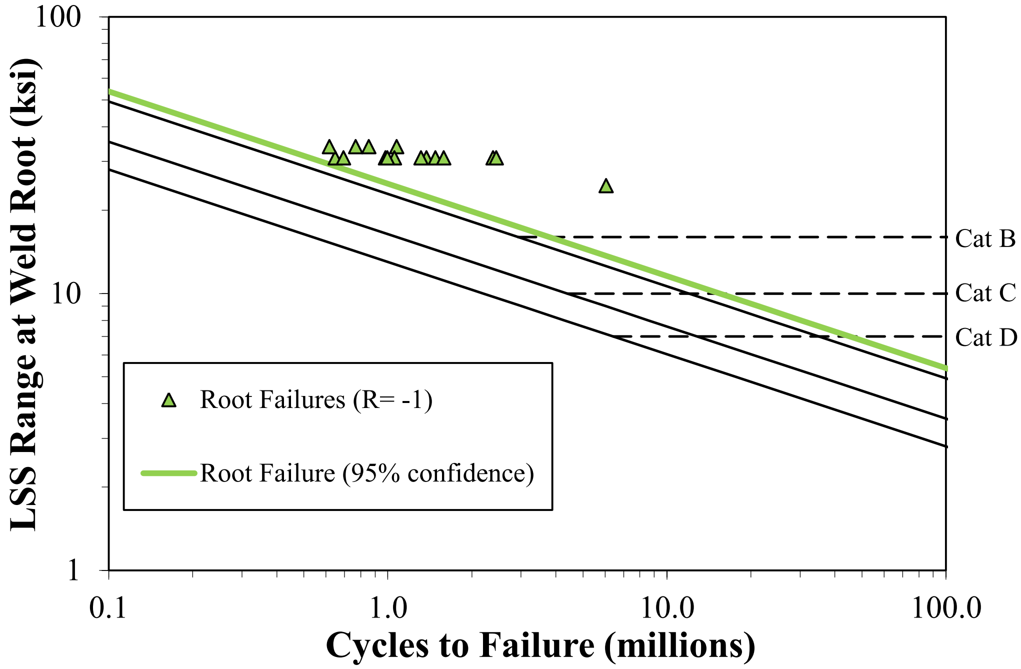


Figure 23. Graph. Plot of all root failures (*R* = −1).

Because the original hypothesis guiding the work assumed penetration had an influence on fatigue resistance, all of the $R = 0$ data are presented in S-N format in figure 24. The data were divided into three groups: penetration greater than 80 percent, penetration between 80 and 60 percent, and penetration less than 60 percent. The group representing specimens with penetration less than 60 percent demonstrated higher fatigue resistance with a lower bound just above category B. The other two groups of specimens had lower bound resistance around category C. This may indicate that penetration is not as influential on fatigue resistance as originally thought when the research began.

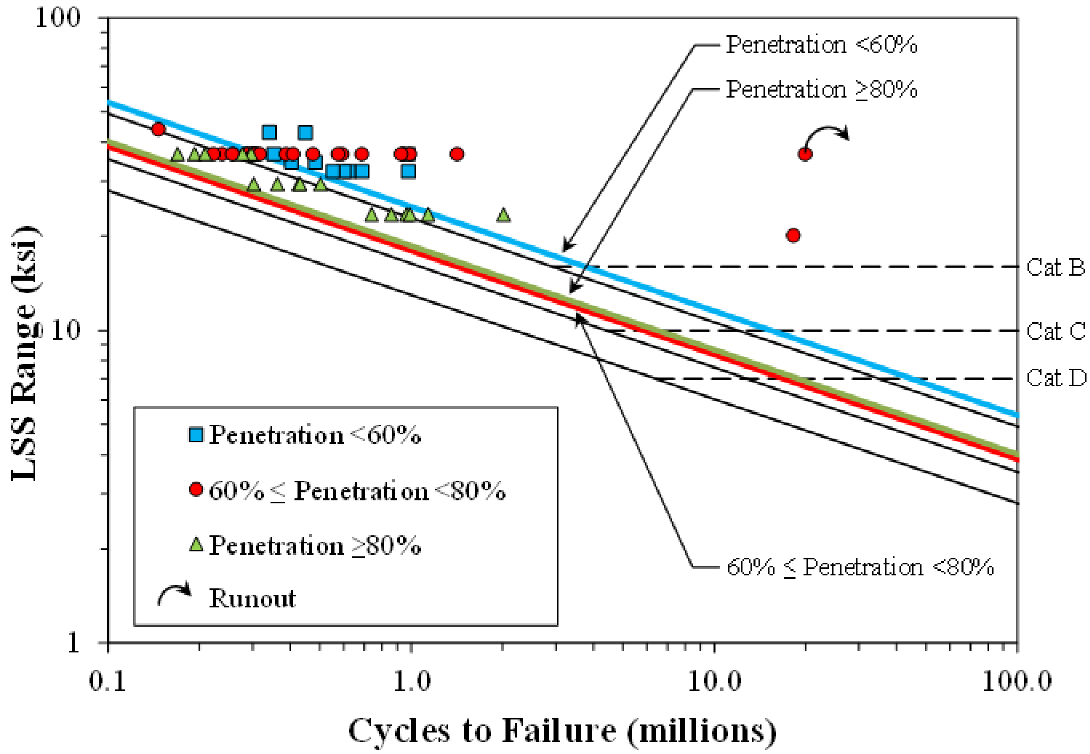


Figure 24. Graph. Plot of all *R* = 0 data sorted by penetration.

The other factor that seemed to influence the fatigue resistance was that the HLAW specimens appeared to have noticeably lower fatigue resistance than all other specimens made with conventional welding processes. This is better shown in figure 25, which divides all of the data into two groups: those that were fabricated with HLAW and those that were fabricated with other weld processes. The lower bound of each group is in between categories B and C, though the HLAW specimens are the lower of the two. There were two visually obvious differences with the HLAW specimens: (1) they consistently attained complete joint penetration welds between the rib and deck plates, and (2) the weld nugget was noticeably smaller than those made with the conventional weld processes. Because of these two observations, it was felt that the weld dimensions likely had an influence on fatigue strength. A first attempt to quantify this is shown figure 26 through figure 33. Each bubble plot presents the relation between two normalized dimension variables and the fatigue strength of individual specimens expressed through the fatigue resistance coefficient, *A*. The bubble plots are stacked upon each other with the top one using $R = -1$ specimens and the bottom one using $R = 0$ specimens. The legends are consistent between the all the plots with the same *R*-ratio. As a point of reference, for a category B detail, $A = 120$ ksi^3 and $A = 250$ ksi^3 for a category A detail. The area of the bubbles is scaled to the fatigue resistance for each data point, so small bubble area have low *A* values, and large bubbles have large *A* values. There are obvious trends in the data as they relate to weld geometry, that is, there is a negative relationship between penetration and deck plate leg length (figure 28) and a positive relationship between penetration and weld throat (figure 32). However, no obvious trend in the bubble diameters can be seen in any of these plots, and a higher level of regression analysis is needed to identify trends between all these various factors of weld geometry, load ratio, weld process, and weld penetration to the fatigue strength. This is more fully described in the next section.

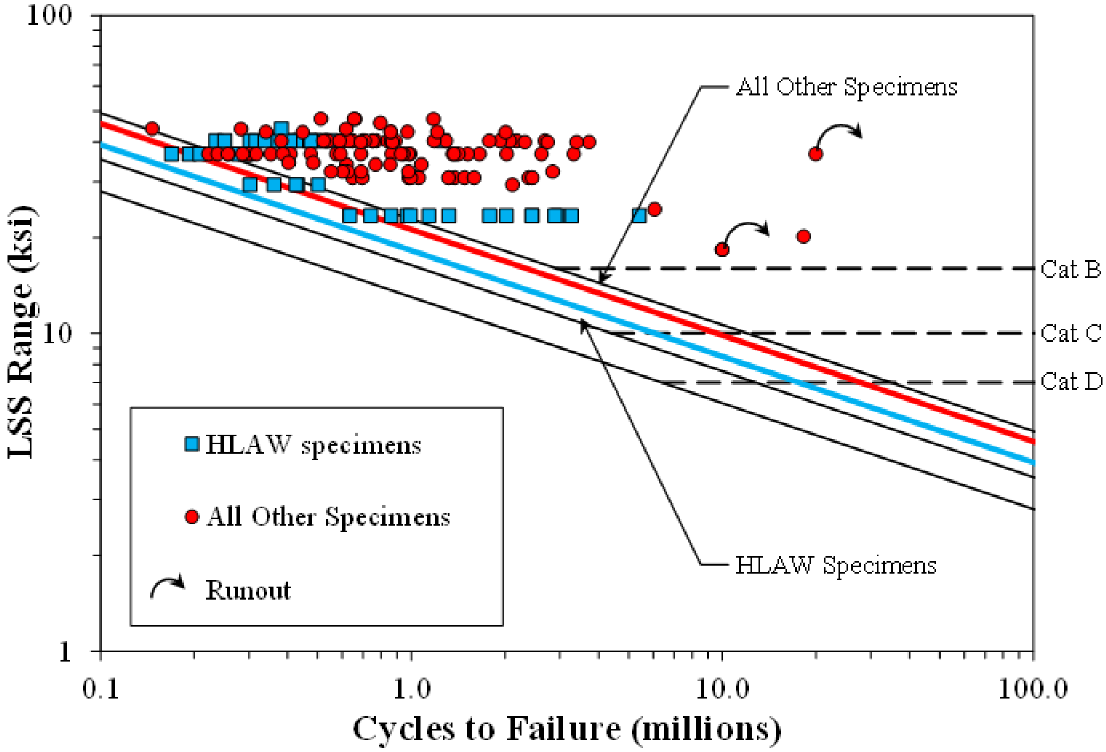


Figure 25. Graph. Plot of all fatigue data differentiated by welding process.

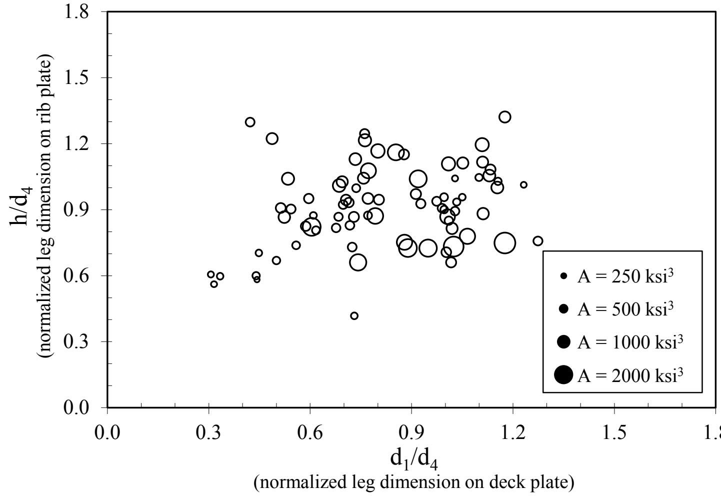


Figure 26. Graph. Relation between rib and deck plate leg sizes at $R = -1$.

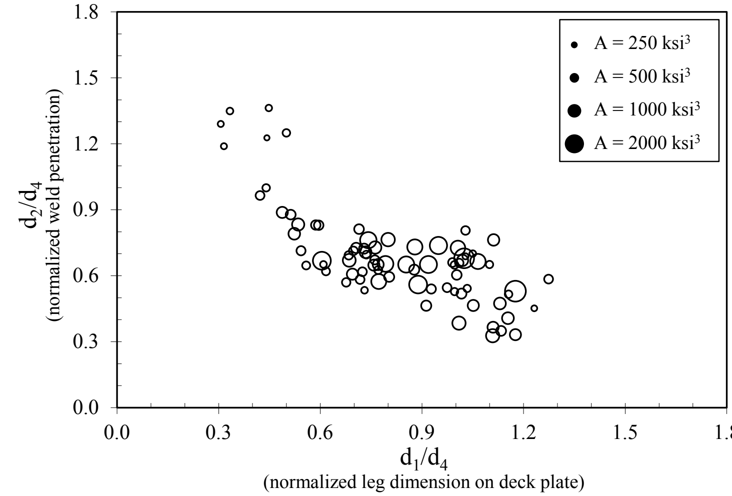


Figure 28. Graph. Relation between weld penetration and deck plate leg size at $R = -1$.

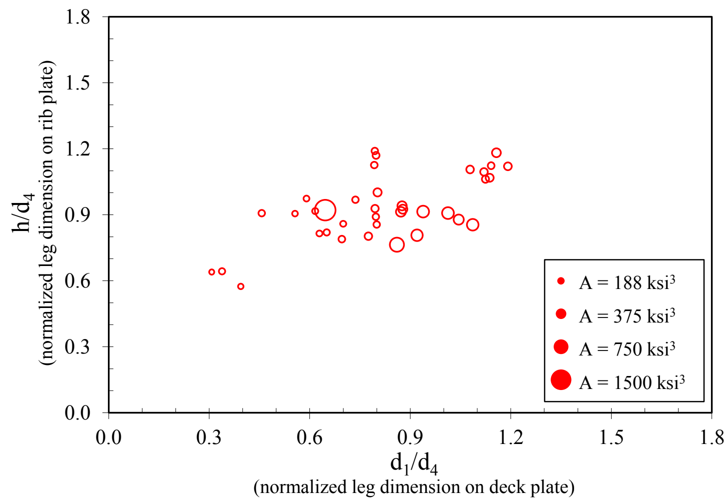


Figure 27. Graph. Relation between rib and deck plate leg sizes at $R = 0$.

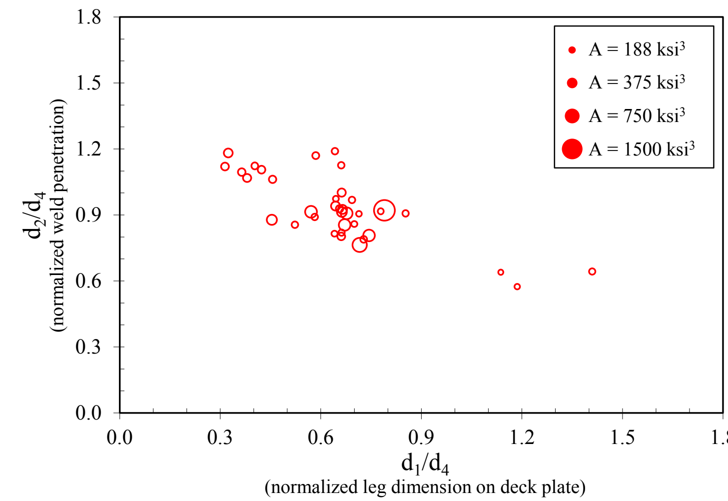


Figure 29. Graph. Relation between weld penetration and deck plate leg size at $R = 0$.

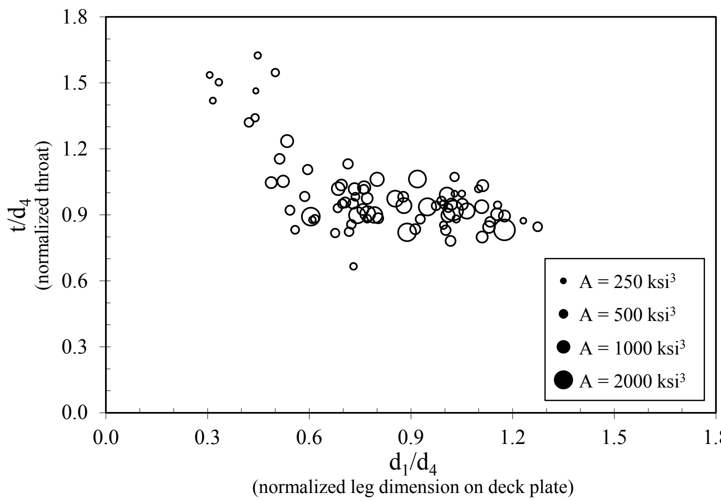


Figure 30. Graph. Relation between throat and deck plate leg sizes at *R* = −1.

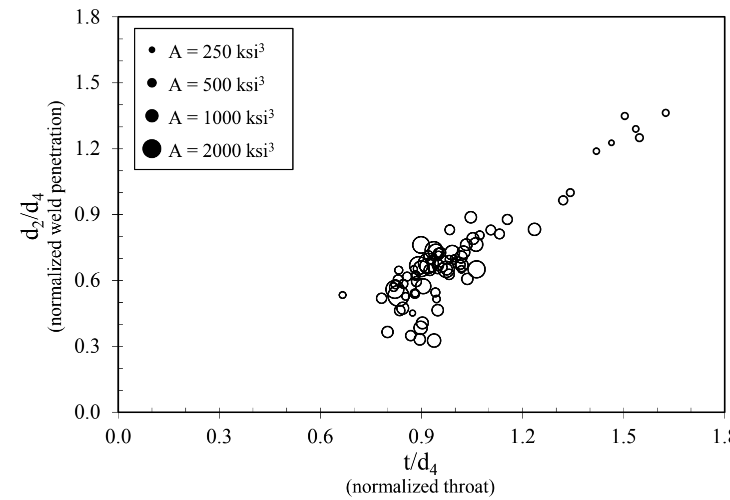


Figure 32. Graph. Relation between weld penetration and throat at *R* = −1.

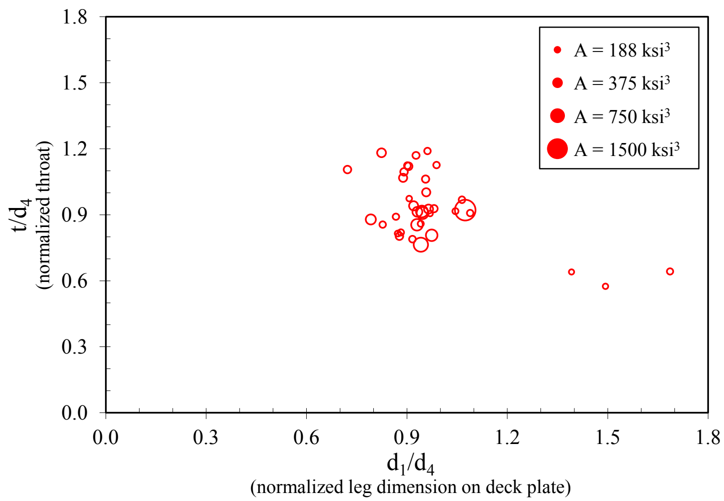


Figure 31. Graph. Relation between throat and deck plate leg sizes at *R* = 0.

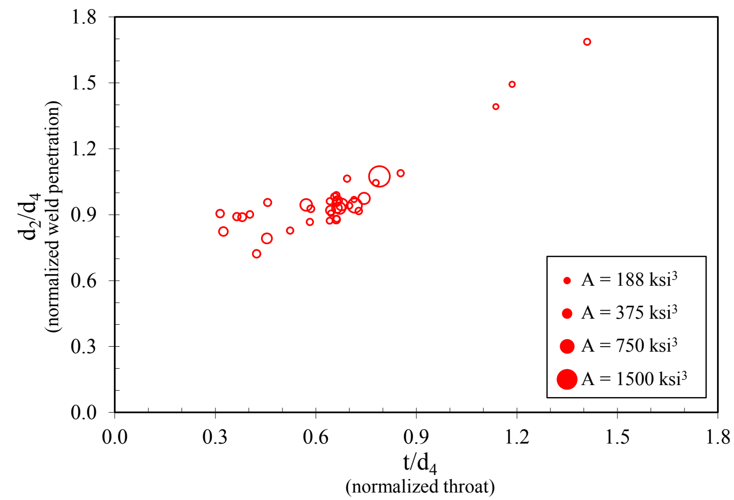


Figure 33. Graph. Relation between weld penetration and throat at *R* = 0.

REGRESSION ANALYSIS OF FATIGUE RESULTS

Fatigue tests were performed on specimens consisting of differing geometries using two different load ratios. Furthermore, specimen weld dimensions varied from test to test. Thus, there were several possible sources of variation in fatigue resistance for the tested specimens. A statistical regression analysis was conducted to determine which factors and quantitative variables best explained the specimen-to-specimen variation in fatigue resistance. The primary objective of the regression analysis was to derive a parametric predictive model that could be used to calculate the fatigue resistance of welded orthotropic details similar to those examined in this study. Determining which test variables are most strongly correlated to fatigue performance allows the possibility of less uncertainty in the classification of the proper fatigue design category for welded orthotropic details. As mentioned previously, the fact that small specimens were used to obtain fatigue resistance data was not considered as part of the analysis. All analysis was conducted using the *R* statistical computing environment.[11]

STATISTICAL DATASET

Table 18 summarizes the observed dataset variables that were considered in the regression analysis. Of the 12 variables, 5 were factor variables (i.e., categorical variables), and 7 were continuous variables. The range column gives the set of possible values for each variable. The meanings of the weld dimension variables are illustrated in appendix B and appendix C.

Table 18. Statistical data variables.

Variable	Type	Range
Load ratio	Factor	{−1, 0}
Failure mode	Factor	{Deck, Rib, Root}
Geometry	Factor	{Type 1, Type 2, Type 3}
Laser welded	Factor	{Laser, Non-Laser}
Root gap opening	Factor	{Open, Closed}
Cycles	Continuous	≥ 0
Stress range	Continuous	≥ 0
d_1	Continuous	≥ 0
d_2	Continuous	[0,1]
d_4	Continuous	≥ 0
h	Continuous	≥ 0
t	Continuous	≥ 0

With the exception of some of the laser-welded specimens, the dataset consisted of complete observations. As shown in appendix C, weld geometry measurements were available for only 10 of the laser welded specimens. One of the primary goals in building a predictive regression model was to uncover possible relationships between weld geometry and fatigue resistance. Thus, the laser-welded specimens without weld measurements were excluded from the regression analysis. While it is possible to impute values for the specimens without measurements in some way using the specimens for which measurements were available, this was avoided so as not to diminish any relationships between geometry and resistance.

The dataset originally consisted of 144 specimens after excluding runouts. Eliminating laser specimens without weld geometry measurements removed 28 specimens from the analysis dataset. In addition, specimens GM8-3 and SA8-9 were removed from the dataset for statistical analysis purposes after data preprocessing, leaving 114 specimens. The fatigue resistance of specimen GM8-3 was significantly higher than for the remaining specimens with the same load ratio. Examination of the data in table 5 shows that this specimen was loaded at 20.16 ksi for 18,253,515 cycles prior to failure. This is the third-lowest stress range amongst all of the specimens tested from that series. The only two specimens with a lower stress range were runout specimens. It is likely that the loading conditions for specimen GM8-3 were within the transition region in going from log-linear S-N behavior to infinite fatigue life behavior. As is the case with the runout specimens, banishing the specimen from the dataset results in more conservative fatigue resistance predictions.

It can be seen in table 6 that specimen SA8-9 had a particularly low fatigue resistance relative to other specimens. Exploratory data analysis revealed that the weld dimension along the rib plate, *h*, was noticeably lower than the measured values for other specimens relative to the specimen rib thickness. It was suspected there may have been a transcription error with this specimen, and it was excluded from the dataset to prevent it from masking relationships. All plots and analysis moving forward in this chapter correspond to the dataset after removal of the aforementioned specimens.

Regression Function

The S-N fatigue life model for welded steel bridge details implicitly assumes that there is a linear relationship in log-log space between the number of cycles to failure and the applied stress range when the stress range is above some specified fatigue threshold. In non-log space, this amounts to saying that the number of cycles to failure for a welded steel bridge detail is proportional to the stress range raised to some power. Thus, fatigue resistance can be thought of as a product of the underlying process parameters in non-log space. The error component in this case can be assumed to be a positive multiplicative value as opposed to additive. With this in mind, the regression function used to model the experimental fatigue resistance coefficients in its most general non-log form is shown in figure 34.

$$A_i = \left(\tilde{A} \prod_{j=1}^{p} {x_{ij}}^{\beta_j} \right) \varepsilon_i$$

Figure 34. Equation. General regression function.

Where:

A_i = Fatigue resistance coefficient of the *i*th test specimen.
$\tilde{A}$ = Base fatigue resistance coefficient (ksi^3).

x_{ij} = Value of the jth predictor variable for the ith test specimen.
β_j = Coefficient corresponding to the jth predictor variable.
ε_i = Random error component (> 0) for the ith test specimen.

Thus, the fatigue resistance coefficient was modeled as the product of some base resistance coefficient and a series of p modifiers that depend on the observed experimental variables. Taking the base 10 log of both sides of the equation given in figure 34 gives the result shown in figure 35.

$$\log_{10} A_i = \log_{10} \tilde{A} + \sum_{j=1}^{p} \beta_j \log_{10} x_{ij} + \log_{10} \varepsilon_i$$

Figure 35. Equation. Linear regression function.

It is seen from the form of this equation that the regression function is a linear model in log-space. The fatigue resistance coefficient for a test specimen was taken as the product of the number of cycles to failure and the cube of the calculated hot spot stress range as is consistent with the fatigue provisions for welded steel bridge details included in AASHTO BDS. Thus, it was implicitly assumed that the number of cycles to failure for a test specimen is inversely proportional to the cube of the corresponding stress range.

It should be noted that the value of the base fatigue resistance coefficient depends on relative factor levels should any factor variables be included as predictors in the model. Non-reference factor variable levels were coded in standard non-log space as either 1 if not applicable or 10 if applicable, corresponding to values of either 0 or 1, respectively, in the additive log-space regression function of figure 35. Thus, the presence of a factor variable in the model amounts to increasing or decreasing the fatigue resistance coefficient by a specified constant multiplicative factor in standard space when applicable. Also, note that if the random error component follows a lognormal distribution, then the value in parentheses of the equation in figure 34 represents the conditional median value of the fatigue resistance coefficient given the specified values of the predictor variables.

Cross-Validation

Regression analysis involves determining the unknown model parameters for the chosen function that minimize some specified error criterion for the dataset that was used in the analysis or the training set. The average error of a fitted regression model corresponding to the training set observations will tend to be lower than the actual error that would be observed when using the model to predict a response for new and unseen observations that were not part of the training set. Thus, a different selection criterion other than training error is necessary to select a model that minimizes prediction error for unseen observations that were not part of the model fitting process.

For the fatigue resistance analysis, repeated tenfold cross-validation was used as a means to select the optimal model that minimizes prediction error. Tenfold cross-validation involves randomly splitting the statistical dataset observations into 10 approximately equally sized subset splits. A candidate regression model is then fit 10 times to the data, leaving a different split out each time. The excluded split is used to estimate the prediction error of the candidate model. The cross-validation errors for the model are then averaged over all splits. The average errors can be used to discriminate between different candidate models that were fit using different model parameters. Five tenfold repetitions were used in calculating cross-validation errors for a total of 50 model fits corresponding to a given candidate regression model. The calculated average error for a specific training/test split was naively assumed to be independent of the average error calculated using some other split. In the case of standard linear regression, different candidate models correspond to models containing different combinations of the predictor variables.

Standard Least Squares Linear Regression

Using standard least squares linear regression, the values of the predictor variable coefficients in the equation of figure 35 are determined by minimizing the sum of the squared model residuals over some training set of observations, given by the equation shown in figure 36.

$$E_{LS} = \sum_{i} \left(\log_{10} A_i - \log_{10} \tilde{A} - \sum_{j=1}^{p} \beta_j \log_{10} x_{ij} \right)^2$$

Figure 36. Equation. Standard least squares regression error function.

The model-tuning parameter to be determined by cross-validation in this case was the number of predictor variables to be included in the regression function. Table 19 lists the predictor variables considered in fitting the least squares model. For factor variables, the reference level used in the regression analysis is listed in parentheses in the "Type" column. The levels for each factor variable were given in table 18. Note that for the factor variable coding scheme used, the number of candidate predictors for a factor variable is always one less than the number of corresponding factor levels; as mentioned previously, the reference level given in parentheses is implicitly included as part of the base fatigue resistance coefficient of the regression function. Weld dimension predictor variables were normalized by the d_4 dimension, which is strongly related to the thickness of the orthotropic rib plate. This was done so that the weld dimension variables would be independent of the overall structural geometry between different specimens. For example, one might expect that a $^1/_4$-inch weld would experience different stress gradients in a structural configuration where the rib plate was 1 inch thick compared to a configuration where the rib plate was only $^1/_2$ inch thick. The d_3 dimension and the d_5 dimension were excluded because they are linear combinations of the weld dimensions that are shown in the table and result in near perfect correlations with the other dimensions even after the log transformation.

Table 19. Standard regression predictor variables.

Variable	Type
Load ratio	Factor (−1)
Failure mode	Factor (Deck)
Geometry	Factor (Type 1)
Laser	Factor (Laser)
Gap	Factor (Closed)
d_1/d_4	Continuous
d_2/d_4	Continuous
h/d_4	Continuous
t/d_4	Continuous
(Failure mode):(d_1/d_4)	Factor-continuous interaction (Deck:d_1/d_4)
(Failure mode):(d_2/d_4)	Factor-continuous interaction (Deck:d_2/d_4)
(Failure mode):(h/d_4)	Factor-continuous interaction (Deck:h/d_4)
(Failure mode):(t/d_4)	Factor-continuous interaction (Deck:t/d_4)
(Load ratio):(d_1/d_4)	Factor-continuous interaction (Load ratio = −1:d_1/d_4)
(Load ratio):(d_2/d_4)	Factor-continuous interaction (Load ratio = −1:d_2/d_4)
(Load ratio):(h/d_4)	Factor-continuous interaction (Load ratio = −1:h/d_4)
(Load ratio):(t/d_4)	Factor-continuous interaction (Load ratio = −1:t/d_4)

Even though deck plate thickness did vary in the testing matrix, this was not exclusively considered in the regression because it was inherently coupled to the stress range calculation.

In addition to the factor variables and normalized weld dimensions, interaction variables between each normalized weld dimension together with the failure mode and load ratio were considered. This was done to account for the possibility that one weld dimension may be of greater importance in the presence of a particular failure mode or load ratio in comparison to other dimensions. Including such an interaction in the model would result in a change of the weld dimension exponent as shown in the equation of figure 34 given the occurrence of the particular failure mode or load ratio under consideration in the interaction.

Forward stepwise selection with a slight modification to satisfy the principle of hierarchy was used to select the best model for each given model size and a given training/test cross-validation split. The principle of hierarchy specifies that when an interaction term is included in a regression model, it should also be the case that the main effects of the interaction are included in the model to preserve the intended meaning of the interaction. Thus, if it were determined by forward selection for a given model size that the best model included an interaction term, a check was made to insure that the main effect terms were already included in the model. If this was not the case, the next best model of the intended size was selected, and the check repeated until the principle of hierarchy was satisfied.

Figure 37 shows a plot of the average cross-validation mean square errors (MSEs) as determined by the model fitting procedure. The error bars in the plot represent one standard error above and below the mean cross-validation error. It is likely that the standard errors shown are larger in reality because of the implicit assumption of independence in the calculation. The zero variable model, or null model, corresponds to the case where only the base fatigue resistance coefficient is included in the regression function. This is equivalent to predicting the value of the fatigue resistance coefficient for a test specimen using the geometric mean of all observed resistance coefficients used to fit the model.

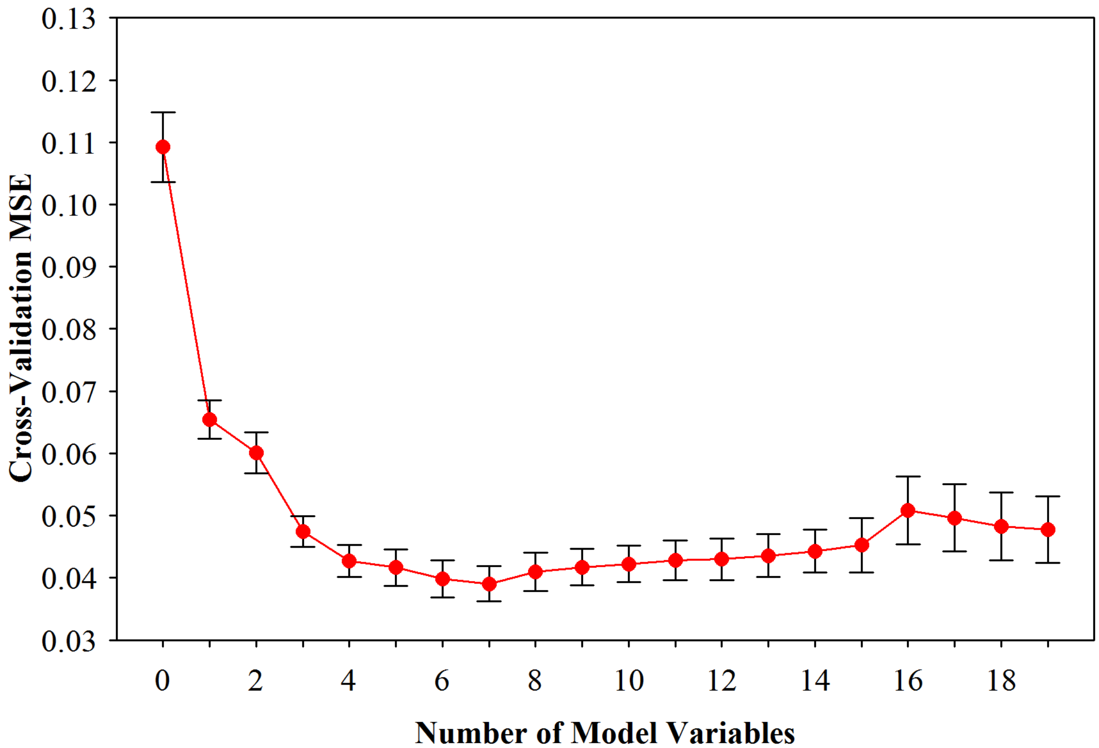


Figure 37. Graph. Standard regression cross-validation error.

The final model predictor variable coefficients in log-space found using the aforementioned forward selection process applied to the full statistical dataset are given in table 20. The lowest cross-validation error occurs when seven predictor variables are included in the model, not including the base fatigue resistance coefficient. Thus only models with seven variables or less are shown in the table. Also shown are the average cross-validation MSEs together with the corresponding standard errors for the given number of variables used. While a model with seven predictor variables results in the lowest cross-validation error, it can be seen that the cross-validation error for a model containing four predictor variables falls within the standard error bounds for the seven variable model. Thus it was decided to use the less complex regression function containing three predictor variables as the final selected predictive model determined using standard regression. As can be seen in table 20, the four most influential predictors ranked in the order that they enter the model are load ratio, weld leg length along the deck plate, weld root failure, and weld penetration. The four-variable model can be expressed as shown in figure 38.

Table 20. Final model regression coefficients by forward selection.

Model Variables	Cross-Validation MSE	Standard Error of MSE	$\tilde{A}$	Load Ratio = 0[a]	d_1/d_4	Weld Root Failure[b]	d_2/d_4	Root Failure: d_1/d_4[b]	Rib Failure	Rib Failure: d_1/d_4[b]
0	0.109	0.00561	10.6	NA	NA	NA	NA	NA	NA	NA
1	0.0654	0.00308	10.7	−0.447	NA	NA	NA	NA	NA	NA
2	0.0601	0.00327	10.8	−0.450	0.661	NA	NA	NA	NA	NA
3	0.0475	0.00247	10.9	−0.524	0.884	−0.356	NA	NA	NA	NA
4	0.0427	0.00247	11.2	−0.513	1.44	−0.414	0.960	NA	NA	NA
5	0.0417	0.00257	11.2	−0.514	1.51	−0.416	1.02	−3.12	NA	NA
6	0.0399	0.00294	11.2	−0.495	1.42	−0.382	0.969	−3.04	0.118	NA
7	0.0390	0.00297	11.2	−0.494	1.476	−0.389	−0.985	−3.09	0.0762	−1.934

[a]$\tilde{A}$ value already includes the reference level of load ratio = −1 as shown in table 19.
[b]$\tilde{A}$ value already includes the reference level of failure mode = deck as shown in table 19.
NA = Not applicable.

$$\log_{10} A = 11.2 - 0.513\alpha_1 + 1.44 \log_{10}\left(\frac{d_1}{d_4}\right) - 0.414\alpha_2 + 0.960 \log_{10}\left(\frac{d_2}{d_4}\right)$$

Figure 38. Equation. Least squares regression final predictive model.

Where:

α_1 = 1 for tension-only loading, 0 for load reversals.
α_2 = 1 for weld root failure, 0 otherwise.

After further simplification, the least squares regression final predictive model is shown in figure 39.

$$A = 1585e8\, ksi^3 \cdot 0.307^{\alpha_1} \cdot 0.385^{\alpha_2} \cdot \left(\frac{d_1}{d_4}\right)^{1.44} \left(\frac{d_2}{d_4}\right)^{0.960}$$

Figure 39. Equation. Simplified least squares regression final predictive model.

The model specifies that full load reversals (load ratio = −1) correspond to fatigue resistances in the test specimens approximately three times greater in an average sense than tension-only specimens (load ratio = 0) assuming that other variables remain constant. It is also seen that there is a reduced fatigue resistance coefficient for weld root failures in comparison to other failure modes. Note that the model as shown is somewhat deceptive in this regard as a result of the fact that weld root failures occurred only in the presence of load reversals, so the two reduction factors in the model do not apply simultaneously for any of the specimens tested. Finally, it can be seen that the fatigue resistance is given as a function of the d_1 weld dimension as well as weld penetration. For both variables, there is positive correlation with fatigue resistance. However, it should be noted that the d_1 dimension has a higher exponent and is generally not restricted to values less than or equal to 1 as is the weld penetration. Thus, for the experimental specimens, the d_1 dimension is a more influential predictor of fatigue resistance than is the weld penetration. Furthermore, as the normalized d_1 dimension increases, the weld penetration generally tends to decrease. Thus, it makes sense to specify design requirements for the weld leg dimension.

A normal probability plot of the deleted residuals for the final model fit is shown in figure 40. The residuals were externally studentized and segregated by load ratio: squares for $R = -1$ and circles for $R = 0$. It can be seen that the residuals for the four-variable model exhibit some right skewness with a mean approximately equal to zero. It is also seen that the tails of the residual distribution are dominated by specimens that were subjected to load reversals. The ramifications of the residual distribution in deriving design guidelines are discussed in the next section.

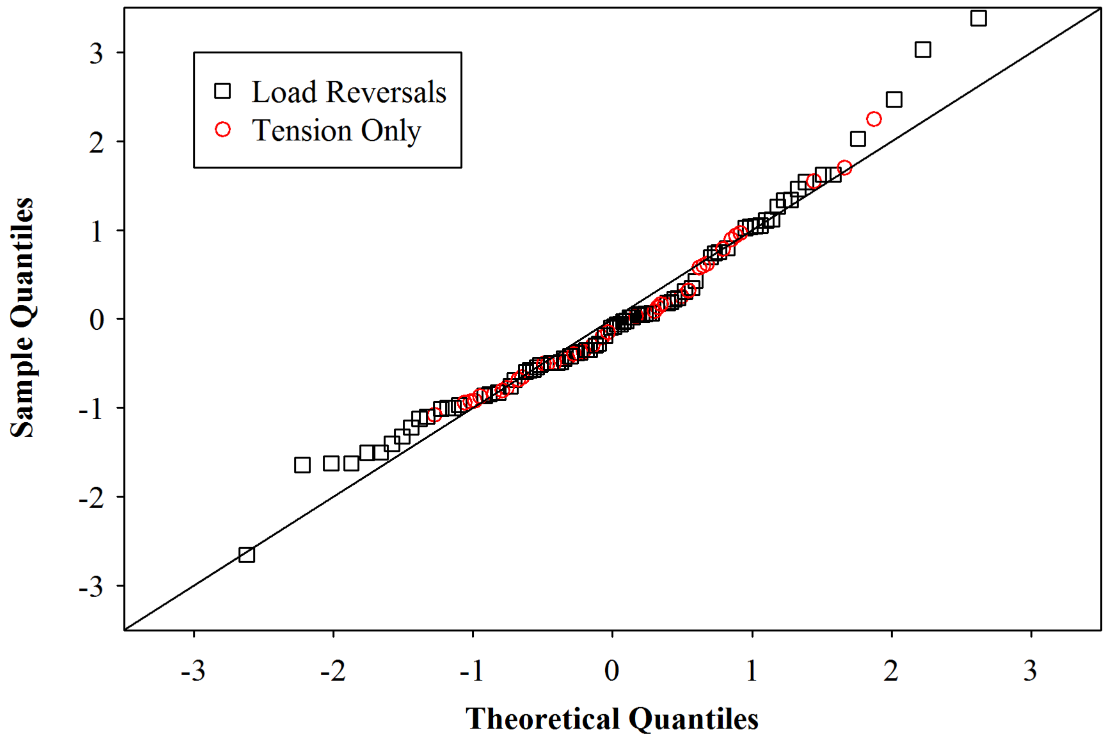


Figure 40. Graph. Normal probability plot of standard regression studentized residuals.

DESIGN RECOMMENDATIONS

It was shown in figure 40 that the standard regression model residuals exhibit right skewness in log-space. Figure 41 shows a histogram of the final fitted model residuals. Also shown on the plot are two different continuous normal distributions. The solid line distribution illustrates a normal distribution with location parameter equal to zero and scale parameter equal to the standard deviation of the fitted model residuals. As mentioned previously, the expected value of the MSE as calculated on the training set potentially gives an overly optimistic estimate for the actual error that would be observed when using the model to predict values for new observations. Thus, for design purposes, it is prudent to use a larger-scale parameter than is given by the standard deviation of the model residuals. The dashed line normal distribution shown in figure 41 is the distribution obtained when using the cross-validation MSE to calculate the scale parameter. The tails of the distribution are larger than in the previous case. While the distribution does not precisely capture the small amount of skewness in the residual distribution, the tails of the distribution should provide a sufficient lower bound estimate for design purposes. Furthermore, if design guidelines are derived assuming a zero load ratio, most of the extreme residuals shown in the histogram become irrelevant, as was illustrated in figure 40. Thus, for design purposes, model predictions were assumed to have a lognormal distribution as represented by the green dashed line curve in figure 41 and a zero load ratio. The assumption of a zero load ratio will become clear in the derivations that follow.

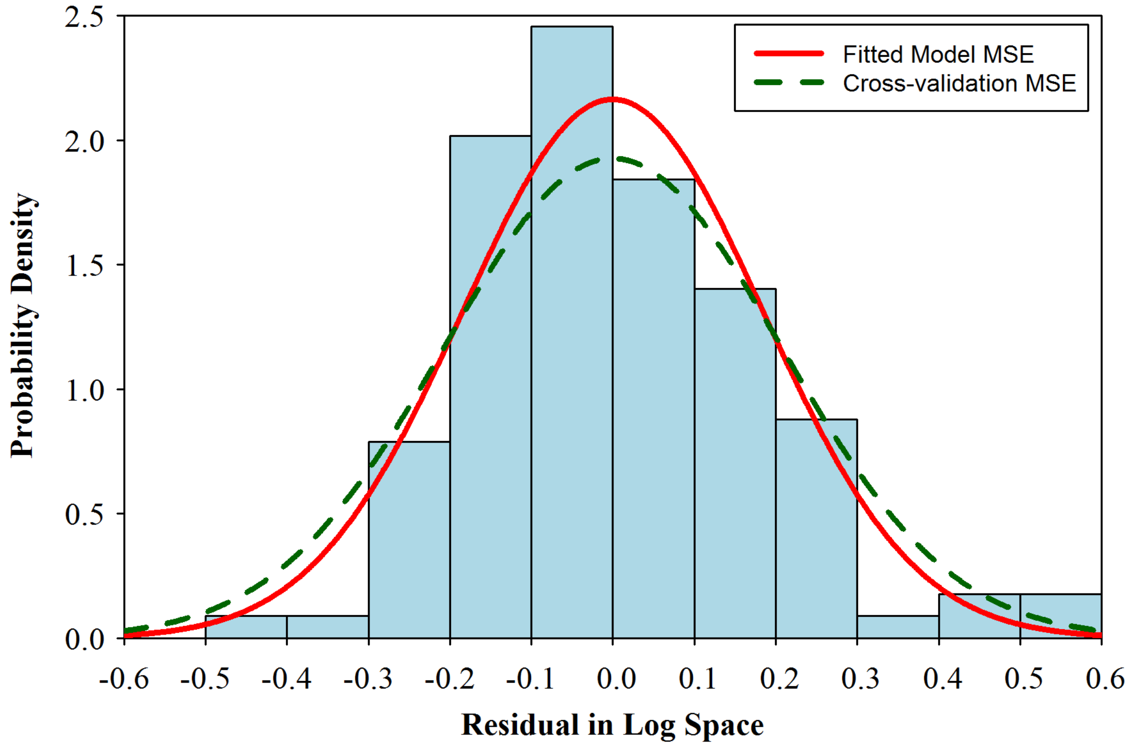


Figure 41. Histogram. Distribution of model residuals.

As is consistent with current fatigue design practice, a lower bound fatigue resistance for the experimental specimens can be expressed as the resistance corresponding to two standard deviations below the mean in log-space. The cross-validation standard deviation estimate (square root of the MSE) for the standard regression model was 0.207 in log-space. Using this as an estimate of the true prediction error of fatigue resistance for the standard regression model gives for a design resistance coefficient as shown in figure 42.

$$\log_{10} A_D \leq 11.2 - 0.513\alpha_1 - 0.414\alpha_2 + 1.44 \log_{10}\left(\frac{d_1}{d_4}\right) + 0.960 \log_{10}\left(\frac{d_2}{d_4}\right) - 2 \cdot 0.207$$

Figure 42. Equation. Design fatigue resistance coefficient.

All variables in the equation are as defined for the equation in figure 38. As mentioned previously, it can be conservatively assumed for design purposes that the load ratio will be equivalent to the worst case, tension-only load ratio loading. Revising the equation to account for this assumption and reverting out of log-space gives the result shown in figure 43.

$$A_D \leq (187e08\ ksi^3) \cdot 0.385^{\alpha_2} \cdot \left(\frac{d_1}{d_4}\right)^{1.44} \left(\frac{d_2}{d_4}\right)^{0.960}$$

Figure 43. Equation. Simplified design fatigue resistance coefficient.

Regarding the occurrence of weld root failures, examination of the statistical dataset shows the following:

- All weld root failures occurred under load reversals ($R = -1$).
- Fourteen of the sixteen weld root failures occurred in conjunction with an open root gap.

Implicit in the inequality is the assumption of a zero load ratio, therefore it would be conservative to simply use the inequality of figure 44 with the weld root term eliminated. The second observation can be used as a basis for a fabrication guideline specifying that rib-to-deck welds be fabricated with closed root gaps in the welded condition. A final design inequality is shown in figure 44.

$$\left(\frac{A_D}{187e08\ ksi^3}\right)^{1.04} \cdot \left(\frac{d_1}{d_4}\right)^{-1.50} \leq \left(\frac{d_2}{d_4}\right)$$

Figure 44. Equation. Design weld-dimension inequality.

There is discretion to choose a value for A_D, though based on the presentation in figure 19 and figure 20, categories B or C would be most prudent. However, as the first term in figure 44 has a denominator of 187e08 ksi^3 indicates the fitted model for design is halfway between category B (120e08 ksi^3) and category A (250e08 ksi^3). For the sake for further presentation of the design inequality, the first term in figure 44 can be represented by a constant, *k*, and results in the equation shown in figure 45.

$$k\left(\frac{d_1}{d_4}\right)^{-1.50} \leq \left(\frac{d_2}{d_4}\right)$$

Figure 45. Equation. Final design weld-dimension inequality.

The value of the constant, *k*, in the inequality is given in table 21 for fatigue design categories A–C.

Table 21. Weld leg design coefficient.

Design Category	*k*
A	1.35
B	0.630
C	0.222

Figure 46 graphically illustrates the experimental data and the derived weld design inequality of figure 45. The data are plotted with the weld penetration (d_2/d_4) on the y-axis, and the normalized d_1-dimension is plotted on the x-axis. The dashed lines represent the boundaries for fatigue design by category as given by the weld design inequality. The sizes of the plotted points are representative of the measured fatigue resistance coefficients as specified in the corresponding legends. As per the equation in figure 39, the fatigue resistances should increase in moving up and to the right of the graph, although the relationship gradients are not shown. It is noted that the inequality lines appear to be conservative as would be expected, considering the manner in which the inequality was derived. It is noted further that had load reversals been considered as part of the derivation, the inequality lines would move down and to the left of the plot. This should be taken into consideration when viewing the open markers that represent the tests where load reversals occurred.

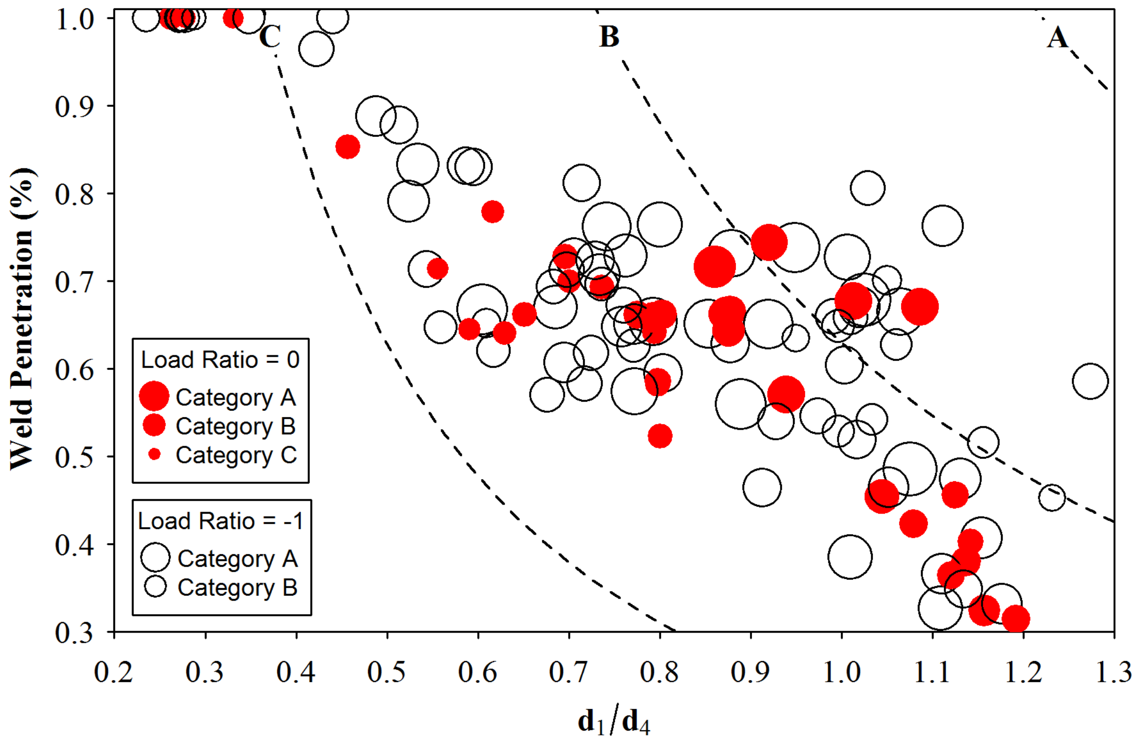


Figure 46. Scatterplot. Weld design inequality.

Because d_1 only defines one dimension of the weld, it is also helpful to understand the range of h dimensions used in the experimental specimen pool to better define further geometric restrictions. Figure 47 shows a histogram of the h-to-d_1 ratios for the experimental specimens tested. As can be seen, the majority of the ratios for the experimental specimens were between 0.5 and 2.0. To insure that the inequality of figure 45 is not used in designing weld geometries that are far removed from the geometries for the specimens from which the inequality was derived, the leg dimension along the rib for new welds should be bounded by these ratios.

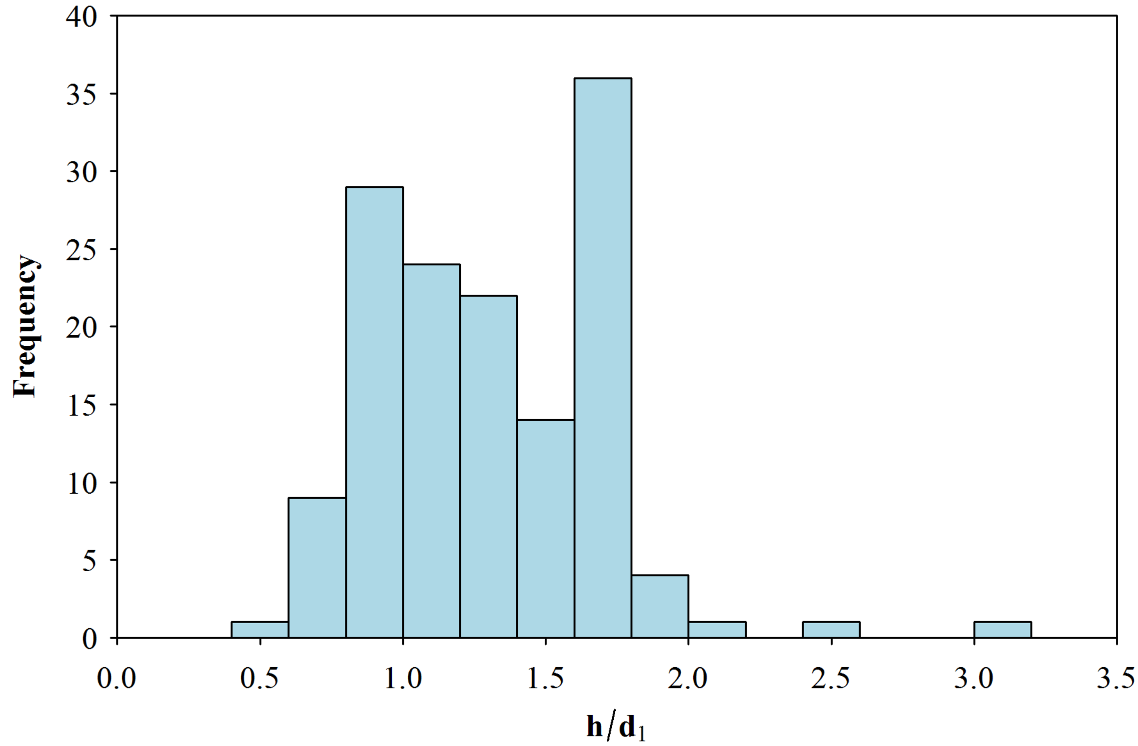


Figure 47. Histogram. Frequency of h-to-d_1 ratio in experimental specimens.

Finally, the design parameter, *k*, used in the previous discussion provides leeway to selection of fatigue resistance to be categories C or B. Selecting one versus the other effectively changes minimum weld size and penetration per the design inequality. Considering the S-N plot shown in figure 22, category C would be a good candidate. Another reason to use category C is to avoid the conundrum of constant amplitude fatigue threshold (CAFT) with LSS analysis as the category C CAFT is 10 ksi. To illustrate the difference, figure 48 shows the variation in required weld sizes when using the category C design versus the category B design using the same rib and deck plate geometries with an assumed 60 percent penetration requirement. The design inequality was used to determine the required minimum d_1 dimension, and then h dimensions of $0.6d_1$ and $2.0d_1$ were drawn to show the bounds. Therefore, the minimum weld is filled with a cross-hatch pattern and the maximum weld with a hatched pattern. While category B design would allow for use of higher stress ranges in the design model, this comes at the expense of a larger weld as shown in figure 48.

From the stance of this research, there should be no problem making the d_1 dimension larger than output from the design inequality, though the largest d_1/d_4 ratio of all the specimens was approximately 1.30. This would be helpful because the minimum diagrammatic welds shown in figure 48 may not be welds that are efficient, or even feasible, and other criteria may control such as maintaining a throat dimension equal to the rib thickness. The design inequality allows the engineer to assume the rib-to-deck plate weld has category C resistance in design and allows them flexible detailing requirements in terms of weld penetration and deck plate leg length to ensure that category C resistance is delivered.

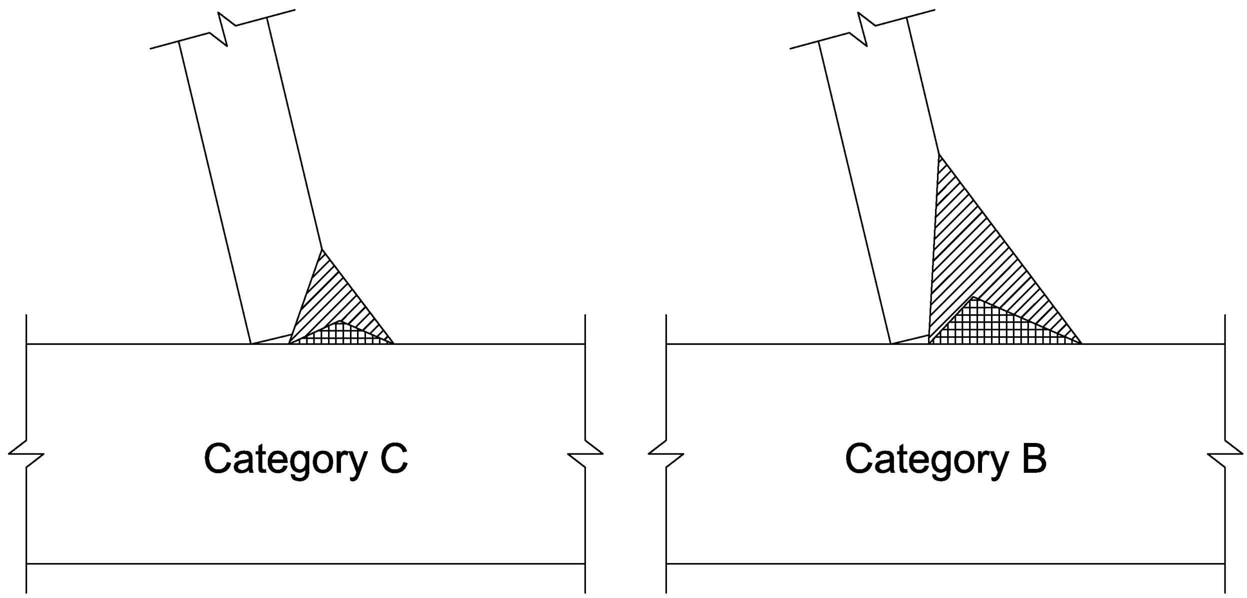


Figure 48. Illustration. Comparison of minimum weld dimensions for categories C or B fatigue design.

CONCLUSIONS AND RECOMMENDATIONS

This research was performed to develop design and detailing recommendations to make the rib-to-deck weld for orthotropic decks more friendly for fabrication. At the time the research began, the current standard for this detail was an 80-percent minimum weld penetration requirement with an initial tight fit and no tolerance for melt- or blow-through in the as-welded condition. As an example, the difference between 80- and 100-percent penetration given a $^{5}/_{16}$-inch rib wall thickness is quite small, and further coupling with a fit-up tolerance not to exceed 0.01 inch makes the weld prohibitively difficult to fabricate. Variations in the fit-up tolerance between the rib and deck can easily result in melt-through or blow-through when attempting to achieve nearly full penetration, especially if the fit-up between the plates is not consistent.

A number of variables were hypothesized to affect the fatigue resistance of this detail, and it was not possible to test a statistically significant population of full-size decks for all of the variables. Therefore, a full-scale, small-specimen fatigue testing protocol was developed to investigate the fatigue resistance of this detail by slicing an individual welded panel into numerous individual specimens. These tests are a cost-effective way to rapidly generate large amounts of data and study the significance of weld procedure variables.

Overall, the study determined that the primary factor in the fatigue resistance of the rib-to-deck weld is its geometry. Welds with larger leg dimensions along the deck plate perform better in fatigue, and, as this leg dimension increases, there is a commensurate decrease in the required penetration. Welds with penetration varying from 40 to 100 percent can be designed assuming a level 3 fatigue analysis with category C fatigue resistance provided the weld leg dimension meets minimum size requirements.

RECOMMENDATIONS

The stress analysis used throughout this report was consistent with a level-3 design procedure. The following recommendations are proposed for consideration and potential adoption into the Federal Highway Administration *Manual for Design, Construction, and Maintenance of Orthotropic Steel Deck Bridges* and the seventh edition of the AASHTO *LRFD Bridge Design Specifications*; however, no consideration of level-1 or level-2 design procedures was considered:[(10,8)]

1. Weld geometry must be made to satisfy the inequality that penetration shall be greater than $0.222(d_1/d_4)^{-1.50}$, where d_1/d_4 is the normalized leg weld dimension along the deck plate. Therefore, two options exist: (1) pick a target penetration value and calculate minimum leg size or (2) select a leg size and calculate a minimum penetration. Either way will produce welds that exceed category C design resistance.

2. The ratio of weld leg dimensions, h-to-d_1, shall be between 0.6 and 2.0, and d_1/d_4 shall be between 0.40 and 1.30. This is to maintain consistency with the specimens tested and reported herein.

3. Qualification shall be performed to ensure welding procedures produce production welds with a closed root condition. The closed root condition is not defined as being fused; it is

merely the notion that the inside rib corner is visibly in close contact with the deck plate. Provided a closed root condition is maintained, root failures should be suppressed.

4. The current pre-welded fit-up gap of 0.020 inch is considered sufficient. For the two panels fabricated with 0.020-inch fit-up gaps, the gap mostly closed across the whole length of panel from weld shrinkage, and there were no weld root failures from these populations of specimens[1]. Some evidence was presented that $^{1}/_{32}$-inch gaps can also close, though they were largely not fatigue tested, and the 0.020-inch recommendation is considered conservative.

FUTURE RESEARCH

The full-scale small-specimen test(s) should be developed into a standardized testing protocol that can evaluate the rib-to-deck weld prior to fabrication. Most bridge owners already require fabricators to produce full-scale mock-ups of rib-to-deck weldments as a qualification test prior to fabrication. It would be relatively inexpensive to section some fatigue test specimens from the mock-ups, and it takes about 1 to 2 d to perform a fatigue test. Such a qualification test can be useful to allow fabricators leeway for efficient design of this weldment.

Currently, the LSS method is limited to weld toes only. The reason is the LSS method assumes that the disparity between the predicted structural stress and the actual stress is uniform throughout all weld toes. Hence, the fatigue resistance for all weld toes follows the same S-N curve. However, this assumption no longer holds for weld roots because the notch effect is much more severe. This is especially true for open root gaps because they create crack-like defects whose fatigue resistance highly depends on the local geometry and is thus difficult to capture by a single S-N curve. A more comprehensive methodology to determine the fatigue resistance from the root of partial penetration welds will be a useful advance in practice.

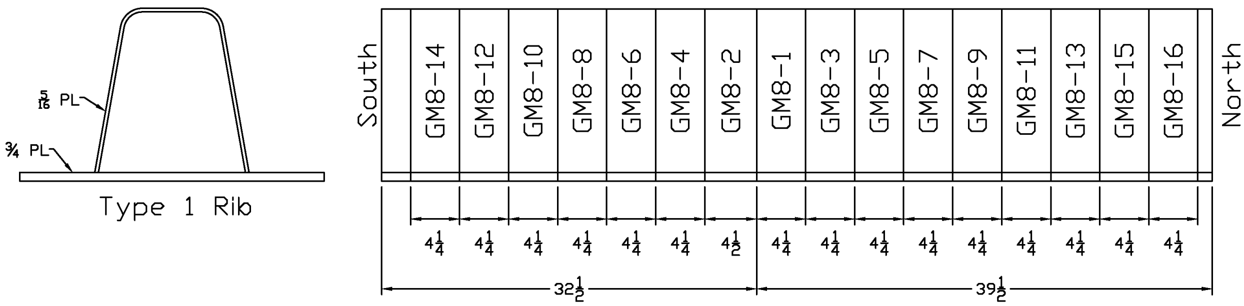
The use of the AASHTO category C resistance curve has been shown to work well with the LSS method in the finite life regime where all stress cycles exceed the fatigue threshold. However, it is unknown if the 10-ksi fatigue threshold for this category applies to the rib-to-deck weld. Additional testing is recommended at lower stress ranges to determine the proper threshold for this weldment. This will enable design of orthotropic decks for infinite fatigue life.

More work is needed to correlate the full-scale small-specimen tests to full-scale testing and in-service performance of orthotropic decks. The full-scale, small specimen tests should be considered to supplement any future tests of orthotropic decks.

There is one exception to this statement. Specimen UB-2 was reported to have a closed root condition and did fail in the weld root under reversal loading. However, a macroetch of that weld was not provided, and it is possible that this may have been reported as a closed condition because that was the intent of the UB panel, but the actual welded condition may have been open.

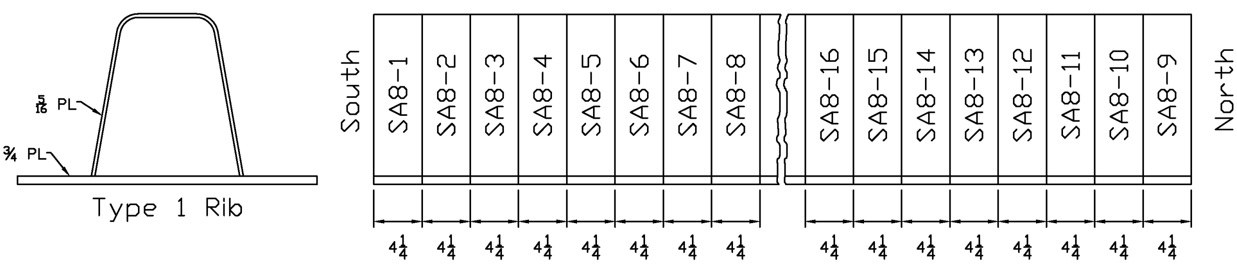
APPENDIX A. SECTIONING OF PANELS INTO SPECIMENS

Figure 49 through figure 62 in this appendix show how individual panels were cut into specimens for the first series of panels that were machined at TFHRC. In the later stages of the project, the fabricator was paid to section the panels with a bandsaw, and it is presumed that specimens were ordered sequentially along the length of the panel.



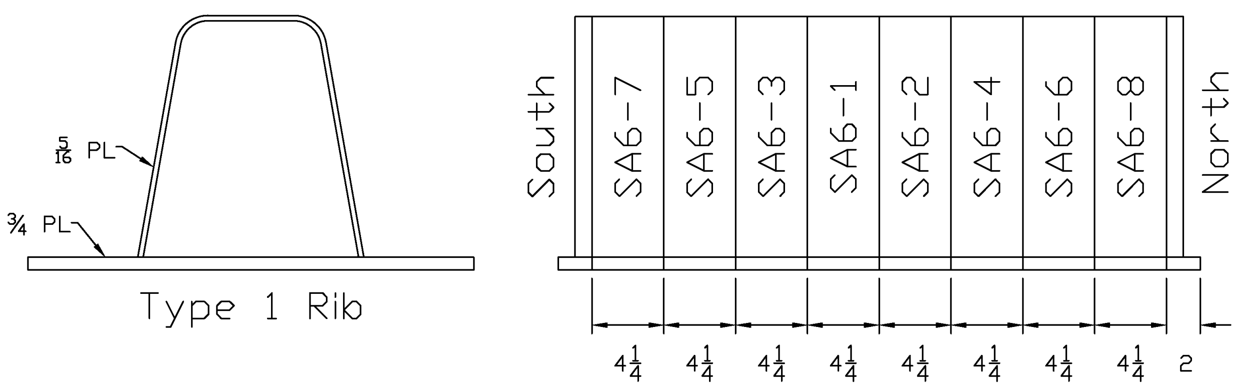
Units = Inches.

Figure 49. Illustration. GM8 series panel.



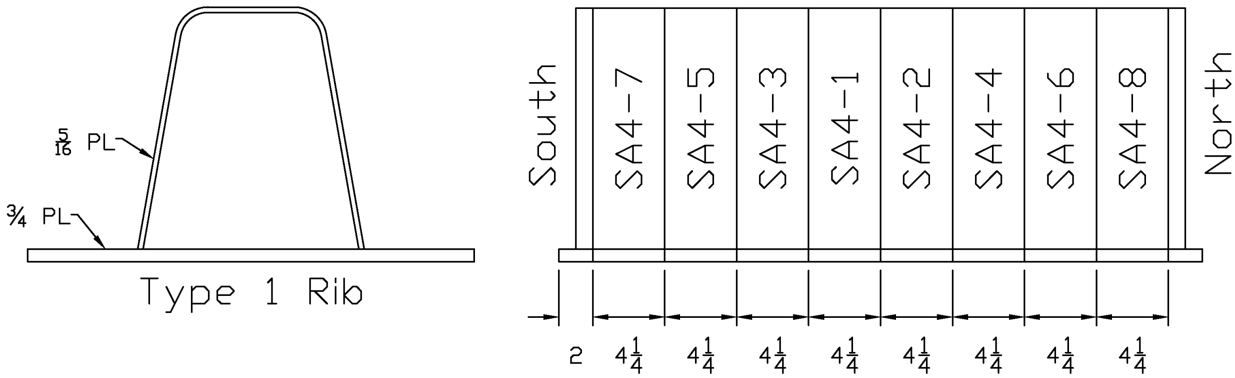
Units = Inches.

Figure 50. Illustration. SA8 series panel.



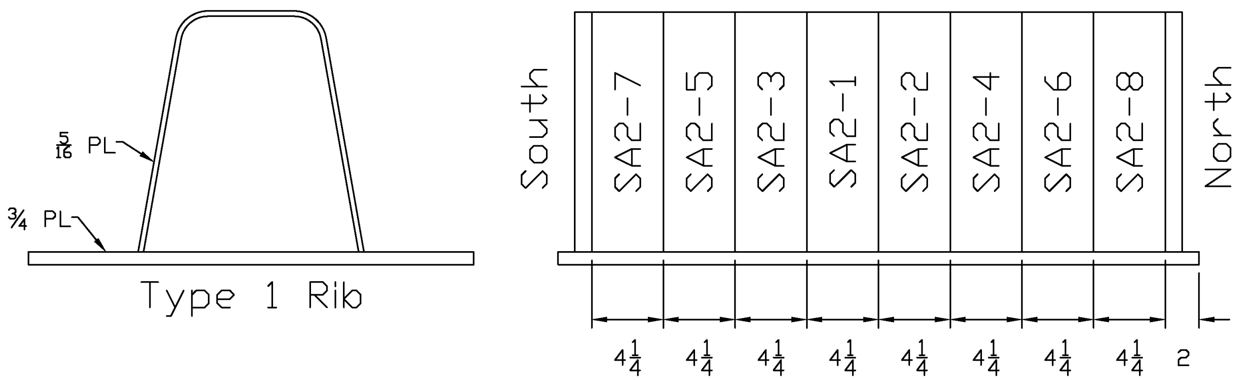
Units = Inches.

Figure 51. Illustration. SA6 series panel.



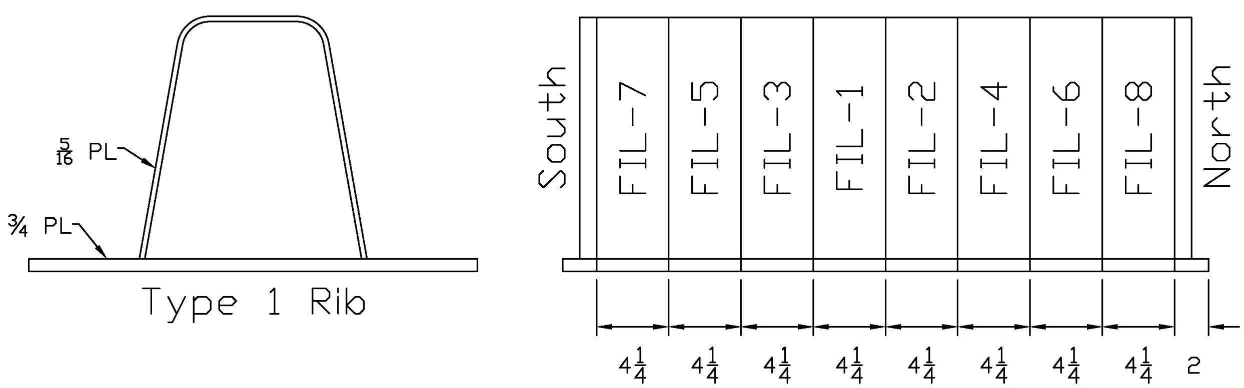
Units = Inches.

Figure 52. Illustration. SA4 series panel.



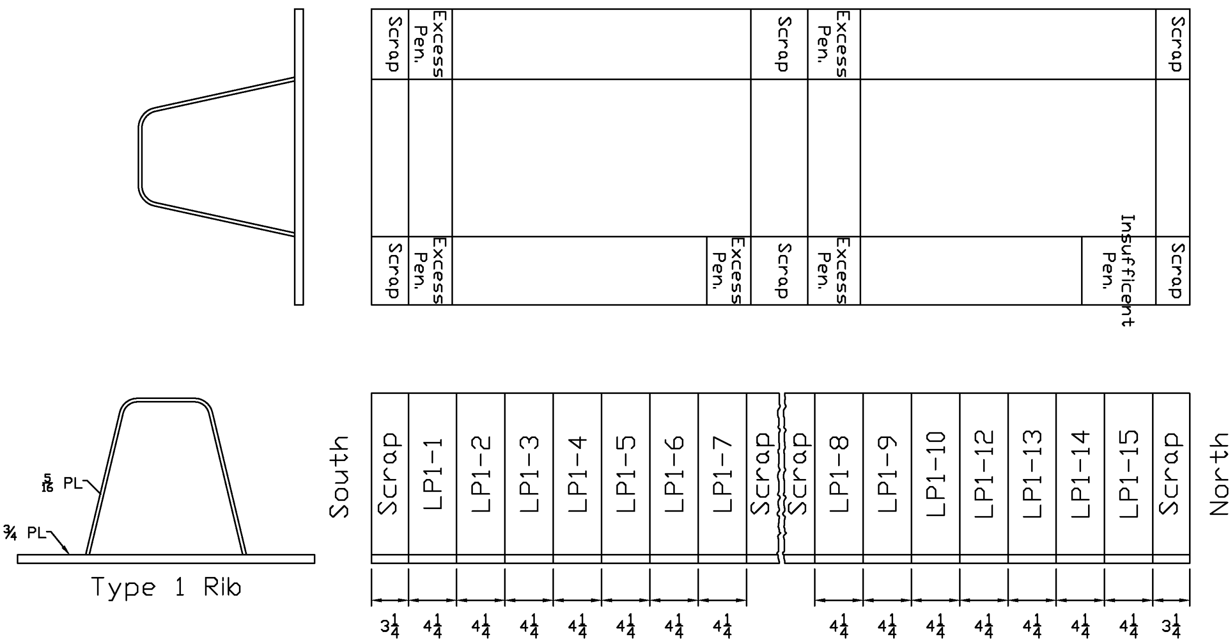
Units = Inches.

Figure 53. Illustration. SA2 series panel.



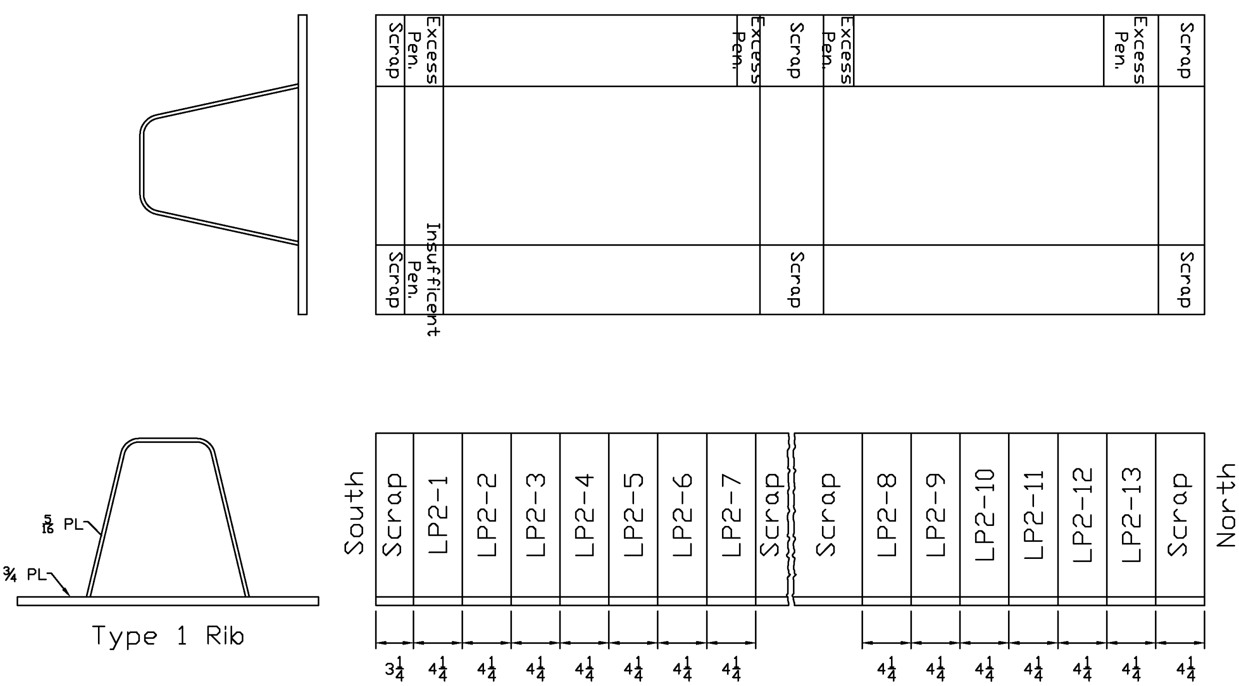
Units = Inches.

Figure 54. Illustration. FIL series panel.



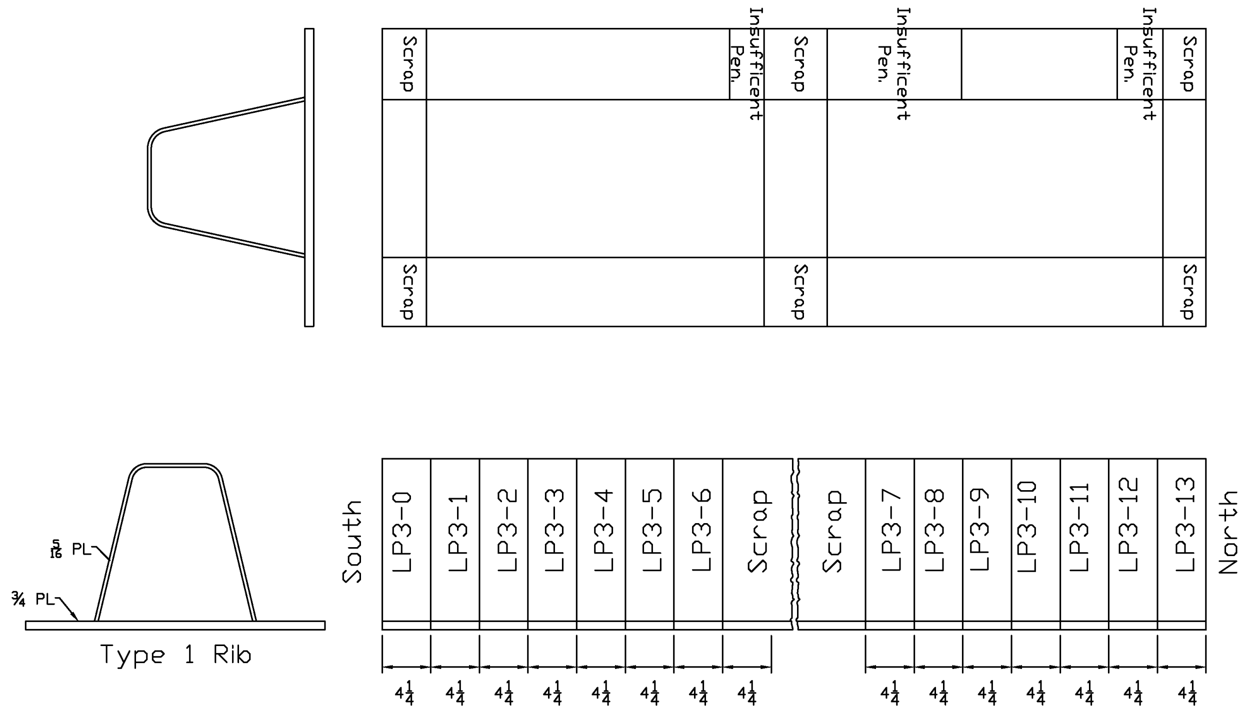
Units = Inches.

Figure 55. Illustration. LP1 series panel.



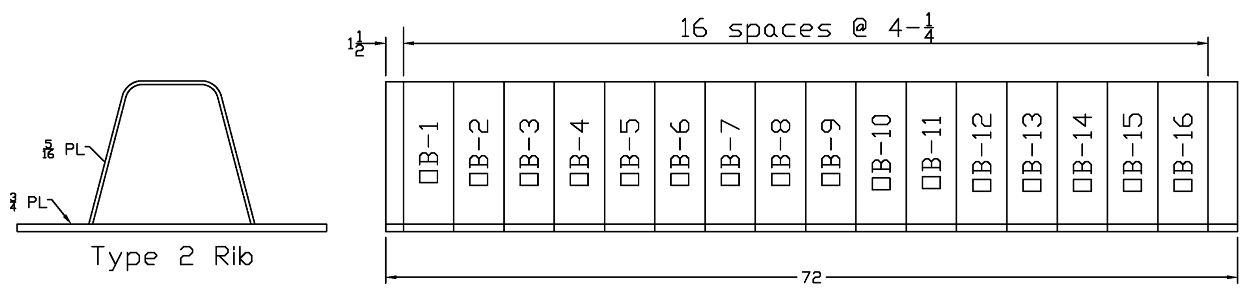
Units = Inches.

Figure 56. Illustration. LP2 series panel.



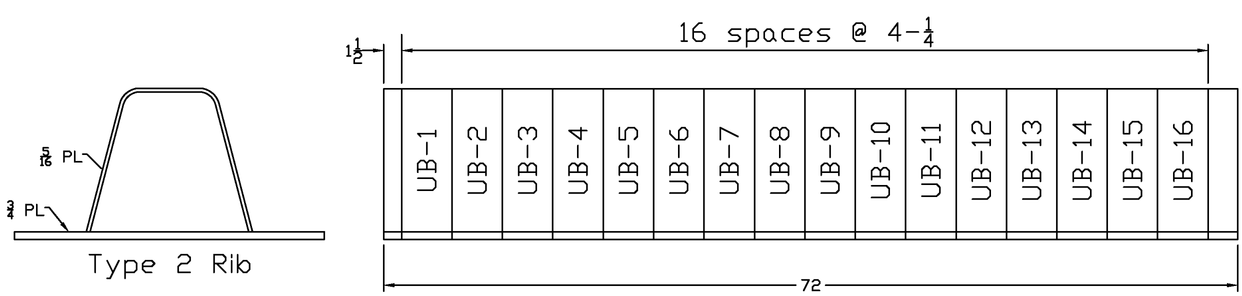
Units = Inches.

Figure 57. Illustration. LP3 series panel.



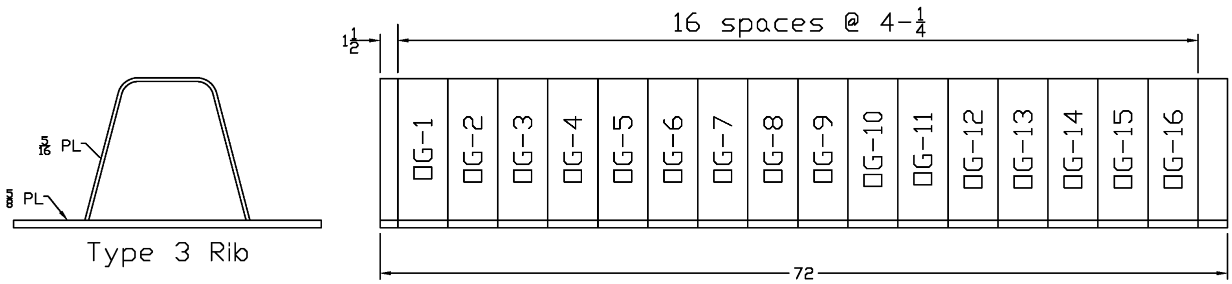
Units = Inches.

Figure 58. Illustration. OB series panel.



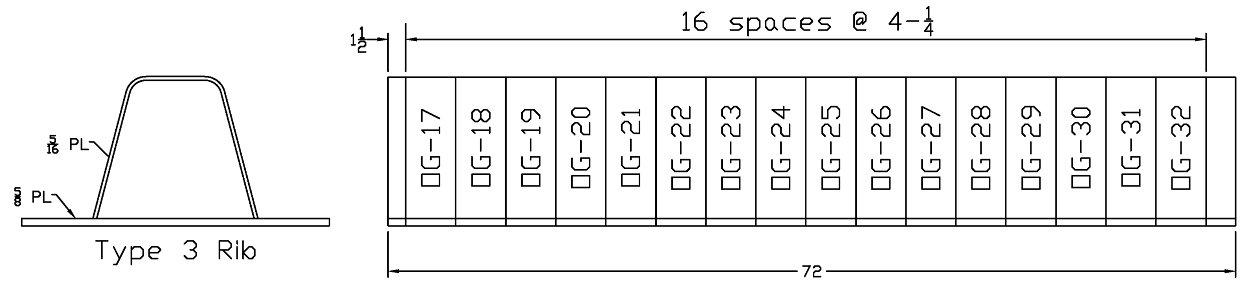
Units = Inches.

Figure 59. Illustration. UB series panel.



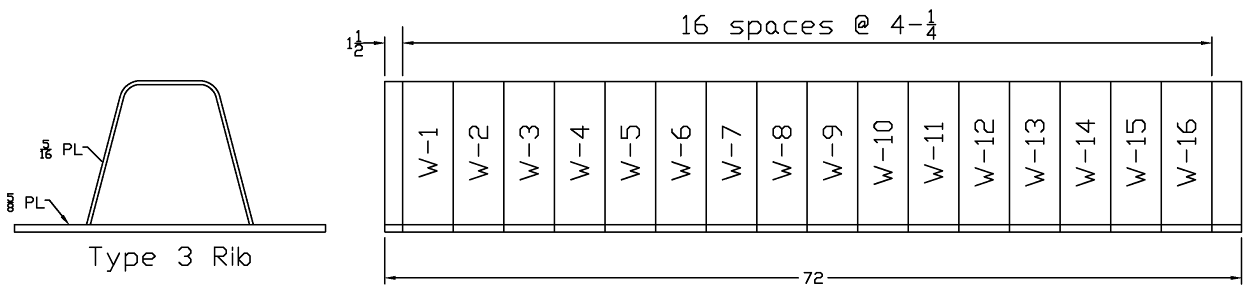
Units = Inches.

Figure 60. Illustration. OG1 series panel.



Units = Inches.

Figure 61. Illustration. OG2 series panel.



Units = Inches.

Figure 62. Illustration. W series panel.

APPENDIX B. WELD DIMENSIONS

This appendix presents the data associated with all measurements taken of weld cross sections from some panel series. These measurements were not taken on any of the OG series panels. Measurements for the laser welded specimens are in appendix C. The weld location syntax used in table 22 through table 30 is shown in figure 63. Weld locations 1 and 2 are on one machined face of the specimen, and locations 3 and 4 are on the opposing machined face. Locations 1 and 3 are on the side with the dominant fatigue crack size because both welds sometimes cracked simultaneously. The exception to this rule is for the W series specimens in table 30, where a table footnote is used to denote the side with the dominant fatigue crack. In addition, the W series specimens were only etched on one face of each specimen in lieu of both sides for the majority of the specimens. This was done to save time because the unetched face of one specimen abuts the etched face of the neighboring specimen. The remaining column headings in this appendix's tables present the measurements recorded as shown in figure 64.

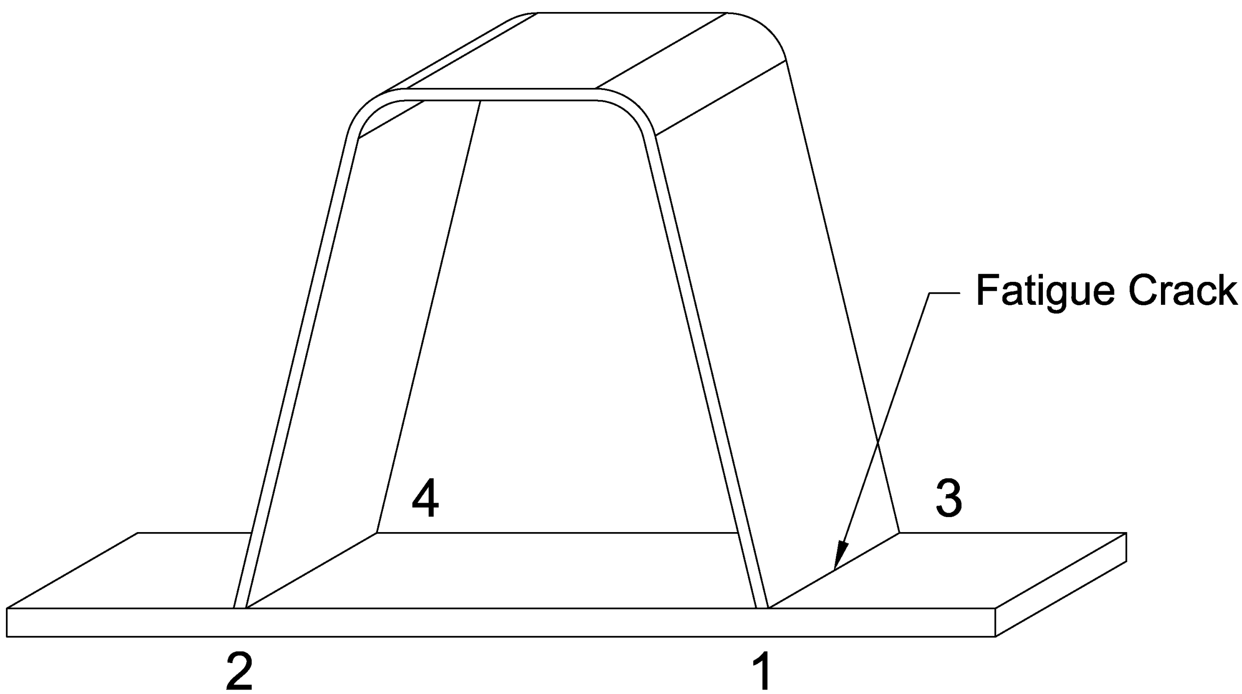


Figure 63. Schematic. Denotation of weld locations.

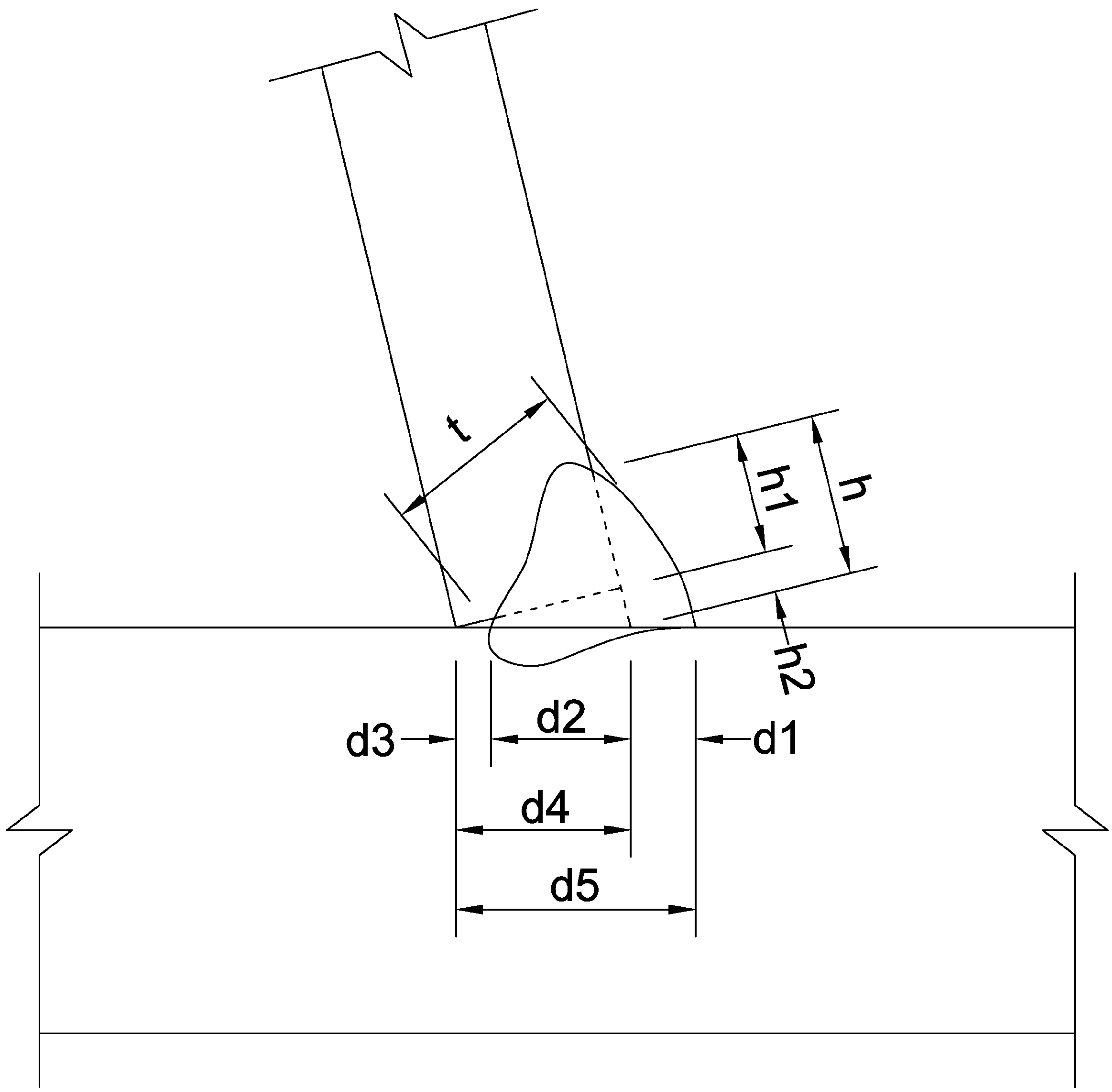


Figure 64. Schematic. Measured dimensions.

Where:

d1 = Weld length along the deck plate.
d2 = Weld penetration along the deck plate.
d3 = Size of the gap behind the weld.
d4 = Projected width of rib on deck plate.
d5 = Length from weld toe to inside edge of rib.
d2/d4 = Percentage of the weld penetration.
h = Total weld length along the rib plate.
h1 = Weld length along the rib plate.
h2 = Face gap.
t = Actual weld throat size, defined as the distance from the weld root to the nearest point on the curved weld surface.

Table 22. Weld dimensions of GM8 series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
GM8-1	1	0.278	0.241	0.105	0.346	0.698	0.624	0.332	0.317	0.059	0.378
	2	0.213	0.262	0.057	0.318	0.822	0.531	0.360	0.330	0.061	0.391
	3	0.197	0.247	0.080	0.327	0.756	0.524	0.309	0.201	0.055	0.256
	4	0.193	0.256	0.067	0.323	0.792	0.516	0.308	0.286	0.061	0.347
	Average 1 and 3	0.237	0.244	0.092	0.336	0.727	0.574	0.321	0.259	0.057	0.317
	Average 2 and 4	0.203	0.259	0.062	0.321	0.807	0.523	0.334	0.308	0.061	0.369
GM8-2	1	0.189	0.251	0.103	0.355	0.709	0.440	0.342	0.227	0.065	0.293
	2	0.255	0.219	0.100	0.319	0.687	0.574	0.342	0.286	0.053	0.338
	3	0.208	0.244	0.078	0.322	0.757	0.530	0.313	0.288	0.065	0.353
	4	0.221	0.252	0.080	0.332	0.759	0.553	0.325	0.255	0.057	0.311
	Average 1 and 3	0.198	0.248	0.091	0.338	0.733	0.485	0.328	0.257	0.065	0.323
	Average 2 and 4	0.238	0.235	0.090	0.325	0.723	0.563	0.333	0.270	0.055	0.325
GM8-3	1	0.194	0.257	0.063	0.320	0.805	0.513	0.357	0.248	0.059	0.307
	2	0.166	0.245	0.074	0.319	0.768	0.485	0.310	0.190	0.061	0.252
	3	0.220	0.249	0.072	0.321	0.775	0.541	0.332	0.227	0.052	0.282
	4	0.180	0.256	0.073	0.329	0.778	0.509	0.333	0.223	0.065	0.288
	Average 1 and 3	0.207	0.253	0.067	0.321	0.790	0.527	0.344	0.238	0.056	0.295
	Average 2 and 4	0.173	0.250	0.073	0.324	0.773	0.497	0.322	0.206	0.063	0.270
GM8-4	1	0.220	0.226	0.097	0.322	0.700	0.542	0.336	0.295	0.039	0.334
	2	0.167	0.225	0.105	0.330	0.681	0.497	0.336	0.252	0.069	0.321
	3	0.220	0.205	0.115	0.320	0.640	0.540	0.317	0.275	0.038	0.313
	4	0.168	0.273	0.046	0.318	0.857	0.486	0.363	0.254	0.066	0.320

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.220	0.215	0.106	0.321	0.670	0.541	0.327	0.285	0.039	0.324
	Average 2 and 4	0.168	0.249	0.075	0.324	0.769	0.492	0.349	0.253	0.067	0.320
GM8-5	1	0.217	0.252	0.053	0.305	0.828	0.522	0.347	0.222	0.052	0.275
	2	0.154	0.274	0.043	0.317	0.863	0.471	0.348	0.226	0.061	0.286
	3	0.220	0.246	0.063	0.309	0.797	0.529	0.347	0.245	0.052	0.297
	4	0.170	0.248	0.065	0.313	0.792	0.483	0.327	0.206	0.061	0.267
	Average 1 and 3	0.219	0.249	0.058	0.307	0.812	0.526	0.347	0.234	0.052	0.286
	Average 2 and 4	0.162	0.261	0.054	0.315	0.827	0.477	0.337	0.216	0.061	0.276
GM8-6	1	0.162	0.265	0.061	0.325	0.814	0.487	0.350	0.224	0.063	0.286
	2	0.157	0.254	0.076	0.330	0.770	0.411	0.352	0.256	0.055	0.311
	3	0.185	0.262	0.079	0.340	0.768	0.526	0.350	0.222	0.068	0.290
	4	0.216	0.195	0.135	0.330	0.592	0.545	0.304	0.230	0.056	0.286
	Average 1 and 3	0.174	0.263	0.070	0.333	0.791	0.507	0.350	0.223	0.065	0.288
	Average 2 and 4	0.187	0.224	0.105	0.330	0.681	0.478	0.328	0.243	0.056	0.299
GM8-7	1	0.181	0.268	0.047	0.315	0.851	0.496	0.357	0.251	0.056	0.308
	2	0.196	0.256	0.055	0.312	0.822	0.508	0.332	0.206	0.063	0.269
	3	0.195	0.255	0.060	0.316	0.809	0.511	0.341	0.235	0.057	0.292
	4	0.165	0.267	0.054	0.321	0.831	0.486	0.334	0.222	0.062	0.284
	Average 1 and 3	0.188	0.262	0.054	0.315	0.830	0.503	0.349	0.243	0.056	0.300
	Average 2 and 4	0.181	0.261	0.055	0.316	0.827	0.497	0.333	0.214	0.062	0.276
GM8-8	1	0.244	0.219	0.106	0.325	0.674	0.569	0.338	0.243	0.054	0.297
	2	0.174	0.255	0.072	0.326	0.780	0.500	0.339	0.241	0.062	0.303
	3	0.233	0.229	0.093	0.322	0.711	0.554	0.351	0.274	0.055	0.329

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.141	0.276	0.051	0.327	0.844	0.468	0.350	0.218	0.062	0.280
	Average 1 and 3	0.238	0.224	0.099	0.323	0.693	0.562	0.344	0.259	0.054	0.313
	Average 2 and 4	0.157	0.265	0.061	0.327	0.812	0.484	0.344	0.230	0.062	0.292
GM8-9	1	0.171	0.253	0.059	0.312	0.810	0.483	0.309	0.308	0.046	0.354
	2	0.157	0.314	0.014	0.328	0.957	0.485	0.320	0.285	0.070	0.355
	3	0.182	0.271	0.040	0.311	0.871	0.494	0.308	0.351	0.048	0.399
	4	0.192	0.253	0.055	0.308	0.822	0.501	0.302	0.289	0.059	0.349
	Average 1 and 3	0.176	0.262	0.050	0.312	0.841	0.488	0.308	0.329	0.047	0.376
	Average 2 and 4	0.175	0.284	0.035	0.318	0.889	0.493	0.311	0.287	0.065	0.352
GM8-10	1	0.151	0.272	0.065	0.336	0.808	0.487	0.347	0.225	0.066	0.291
	2	0.207	0.255	0.076	0.331	0.770	0.538	0.363	0.272	0.055	0.327
	3	0.151	0.292	0.034	0.326	0.897	0.477	0.372	0.244	0.065	0.308
	4	0.213	0.214	0.107	0.321	0.666	0.535	0.323	0.244	0.053	0.296
	Average 1 and 3	0.151	0.282	0.049	0.331	0.853	0.482	0.360	0.234	0.065	0.300
	Average 2 and 4	0.210	0.234	0.092	0.326	0.718	0.536	0.343	0.258	0.054	0.312
GM8-11	1	0.149	0.303	0.019	0.322	0.940	0.471	0.316	0.312	0.062	0.374
	2	0.161	0.262	0.076	0.337	0.776	0.498	0.347	0.316	0.068	0.384
	3	0.166	0.270	0.053	0.323	0.836	0.488	0.359	0.357	0.058	0.415
	4	0.188	0.259	0.075	0.334	0.776	0.522	0.368	0.307	0.063	0.370
	Average 1 and 3	0.157	0.286	0.036	0.322	0.888	0.480	0.337	0.335	0.060	0.394
	Average 2 and 4	0.175	0.260	0.075	0.335	0.776	0.510	0.357	0.311	0.066	0.377
GM8-12	1	0.168	0.298	0.042	0.340	0.878	0.507	0.392	0.262	0.064	0.326
	2	0.201	0.262	0.062	0.325	0.808	0.525	0.375	0.262	0.055	0.316

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	3	0.180	0.298	0.042	0.340	0.878	0.507	0.392	0.232	0.059	0.291
	4	0.229	0.241	0.085	0.326	0.738	0.554	0.349	0.276	0.050	0.326
	Average 1 and 3	0.174	0.298	0.042	0.340	0.878	0.507	0.392	0.247	0.061	0.308
	Average 2 and 4	0.215	0.252	0.074	0.325	0.773	0.540	0.362	0.269	0.052	0.321
GM8-13	1	0.134	0.308	0.000	0.308	1.000	0.458	0.425	0.346	0.053	0.399
	2	0.148	0.278	0.045	0.323	0.861	0.472	0.355	0.275	0.067	0.342
	3	0.169	0.283	0.035	0.317	0.890	0.486	0.368	0.268	0.055	0.323
	4	0.167	0.264	0.056	0.319	0.825	0.487	0.335	0.285	0.067	0.356
	Average 1 and 3	0.151	0.295	0.017	0.313	0.945	0.472	0.396	0.307	0.054	0.361
	Average 2 and 4	0.158	0.271	0.050	0.321	0.843	0.479	0.345	0.280	0.067	0.349
GM8-14	1	0.221	0.220	0.103	0.323	0.682	0.544	0.293	0.190	0.061	0.251
	2	0.176	0.273	0.053	0.326	0.837	0.502	0.364	0.250	0.054	0.304
	3	0.172	0.277	0.039	0.317	0.876	0.489	0.376	0.276	0.058	0.334
	4	0.196	0.277	0.058	0.335	0.826	0.531	0.376	0.274	0.058	0.332
	Average 1 and 3	0.197	0.249	0.071	0.320	0.779	0.516	0.334	0.233	0.060	0.293
	Average 2 and 4	0.186	0.275	0.056	0.331	0.832	0.516	0.370	0.262	0.056	0.318
GM8-15	1	0.132	0.315	0.000	0.315	1.000	0.454	0.434	0.355	0.061	0.416
	2	0.153	0.265	0.061	0.326	0.814	0.479	0.336	0.310	0.067	0.377
	3	0.134	0.293	0.022	0.315	0.930	0.449	0.399	0.348	0.054	0.402
	4	0.159	0.266	0.055	0.321	0.827	0.480	0.352	0.226	0.066	0.292
	Average 1 and 3	0.133	0.304	0.011	0.315	0.965	0.452	0.416	0.352	0.057	0.409
	Average 2 and 4	0.156	0.265	0.058	0.323	0.821	0.479	0.344	0.268	0.066	0.334
GM8-16	1	0.187	0.244	0.075	0.318	0.765	0.505	0.347	0.242	0.055	0.297

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	2	0.154	0.243	0.082	0.325	0.748	0.479	0.316	0.216	0.063	0.279
	3	0.153	0.286	0.031	0.317	0.901	0.470	0.440	0.309	0.056	0.364
	4	0.140	0.257	0.067	0.325	0.793	0.464	0.373	0.231	0.063	0.294
	Average 1 and 3	0.170	0.265	0.053	0.318	0.833	0.488	0.393	0.275	0.055	0.331
	Average 2 and 4	0.147	0.250	0.075	0.325	0.770	0.472	0.344	0.223	0.063	0.286
Average	1 and 3	0.187	0.262	0.060	0.323	0.814	0.507	0.353	0.269	0.056	0.326
	2 and 4	0.181	0.256	0.068	0.324	0.790	0.502	0.341	0.256	0.061	0.317
	All	0.184	0.259	0.064	0.323	0.802	0.505	0.347	0.263	0.059	0.322
Standard Deviation	1 and 3	0.035	0.028	0.031	0.011	0.092	0.039	0.036	0.048	0.007	0.046
	2 and 4	0.028	0.022	0.022	0.007	0.068	0.033	0.021	0.035	0.005	0.036
	All	0.031	0.025	0.027	0.009	0.081	0.036	0.030	0.042	0.007	0.042

Table 23. Weld dimensions of SA8 series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
SA8-1	1	0.374	0.167	0.153	0.320	0.521	0.693	0.263	0.193	0.059	0.252
	2	0.083	0.139	0.166	0.305	0.456	0.387	0.154	0.066	0.000	0.066
	3	0.436	0.205	0.111	0.315	0.650	0.752	0.275	0.166	0.064	0.231
	4	0.348	0.159	0.102	0.261	0.609	0.609	0.278	0.235	0.003	0.238
	Average 1 and 3	0.405	0.186	0.132	0.318	0.585	0.723	0.269	0.180	0.062	0.241
	Average 2 and 4	0.215	0.149	0.134	0.283	0.532	0.498	0.216	0.151	0.001	0.152
SA8-3	1	0.359	0.201	0.135	0.336	0.598	0.694	0.296	0.195	0.064	0.260
	2	0.290	0.216	0.112	0.329	0.658	0.619	0.277	0.167	0.058	0.226
	3	0.351	0.119	0.206	0.325	0.365	0.676	0.207	0.132	0.060	0.192
	4	0.299	0.219	0.097	0.316	0.692	0.615	0.282	0.181	0.062	0.242
	Average 1 and 3	0.355	0.160	0.171	0.330	0.484	0.685	0.251	0.164	0.062	0.226
	Average 2 and 4	0.295	0.218	0.105	0.322	0.675	0.617	0.280	0.174	0.060	0.234
SA8-4	1	0.245	0.266	0.074	0.340	0.784	0.585	0.305	0.142	0.063	0.206
	2	0.312	0.216	0.106	0.321	0.672	0.633	0.295	0.198	0.058	0.256
	3	0.265	0.258	0.091	0.349	0.739	0.614	0.313	0.183	0.066	0.249
	4	0.337	0.254	0.068	0.323	0.788	0.660	0.328	0.200	0.061	0.261
	Average 1 and 3	0.255	0.262	0.082	0.345	0.762	0.599	0.309	0.163	0.065	0.227
	Average 2 and 4	0.324	0.235	0.087	0.322	0.730	0.646	0.311	0.199	0.059	0.258
SA8-5	1	0.289	0.263	0.056	0.319	0.823	0.608	0.325	0.187	0.059	0.246
	2	0.312	0.283	0.064	0.347	0.815	0.659	0.339	0.184	0.068	0.252
	3	0.322	0.213	0.113	0.326	0.653	0.648	0.279	0.164	0.058	0.222
	4	0.321	0.212	0.119	0.331	0.641	0.657	0.284	0.178	0.065	0.243

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.306	0.238	0.085	0.322	0.738	0.628	0.302	0.175	0.059	0.234
	Average 2 and 4	0.317	0.247	0.091	0.339	0.728	0.658	0.311	0.181	0.066	0.247
SA8-6	1	0.319	0.234	0.109	0.343	0.683	0.662	0.303	0.176	0.069	0.245
	2	0.297	0.220	0.110	0.330	0.668	0.627	0.306	0.198	0.059	0.257
	3	0.389	0.208	0.114	0.322	0.646	0.711	0.307	0.211	0.061	0.273
	4	0.253	0.226	0.106	0.332	0.679	0.585	0.289	0.170	0.061	0.231
	Average 1 and 3	0.354	0.221	0.111	0.332	0.665	0.686	0.305	0.194	0.065	0.259
	Average 2 and 4	0.275	0.223	0.108	0.331	0.674	0.606	0.298	0.184	0.060	0.244
SA8-7	1	0.313	0.263	0.075	0.338	0.777	0.651	0.326	0.186	0.068	0.254
	2	0.322	0.238	0.088	0.325	0.730	0.648	0.313	0.192	0.055	0.247
	3	0.375	0.193	0.139	0.331	0.582	0.706	0.292	0.177	0.063	0.239
	4	0.275	0.252	0.078	0.331	0.762	0.607	0.310	0.171	0.061	0.232
	Average 1 and 3	0.344	0.228	0.107	0.335	0.679	0.679	0.309	0.181	0.065	0.246
	Average 2 and 4	0.299	0.245	0.083	0.328	0.746	0.627	0.311	0.182	0.058	0.240
SA8-8	1	0.324	0.195	0.139	0.334	0.584	0.658	0.290	0.205	0.059	0.264
	2	0.348	0.203	0.134	0.337	0.601	0.685	0.289	0.196	0.066	0.262
	3	0.276	0.183	0.159	0.342	0.535	0.618	0.263	0.163	0.062	0.225
	4	0.331	0.236	0.096	0.332	0.710	0.663	0.293	0.161	0.067	0.228
	Average 1 and 3	0.300	0.189	0.149	0.338	0.560	0.638	0.277	0.184	0.061	0.245
	Average 2 and 4	0.340	0.219	0.115	0.335	0.656	0.674	0.291	0.179	0.067	0.245
SA8-9	1	0.311	0.209	0.122	0.331	0.633	0.641	0.282	0.117	0.067	0.184
	2	0.377	0.202	0.136	0.339	0.596	0.716	0.282	0.202	0.071	0.273
	3	0.166	0.139	0.179	0.319	0.435	0.485	0.151	0.032	0.056	0.088

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.405	0.064	0.260	0.323	0.198	0.728	0.219	0.214	0.066	0.280
	Average 1 and 3	0.238	0.174	0.150	0.325	0.534	0.563	0.217	0.074	0.062	0.136
	Average 2 and 4	0.391	0.133	0.198	0.331	0.397	0.722	0.250	0.208	0.069	0.277
SA8-10	1	0.330	0.168	0.169	0.337	0.499	0.667	0.253	0.162	0.065	0.226
	2	0.366	0.217	0.111	0.328	0.661	0.695	0.306	0.226	0.068	0.294
	3	0.344	0.176	0.151	0.327	0.539	0.670	0.265	0.151	0.062	0.212
	4	0.350	0.162	0.171	0.333	0.487	0.683	0.259	0.177	0.069	0.247
	Average 1 and 3	0.337	0.172	0.160	0.332	0.519	0.669	0.259	0.156	0.063	0.219
	Average 2 and 4	0.358	0.189	0.141	0.330	0.574	0.689	0.282	0.202	0.069	0.271
SA8-11	1	0.315	0.220	0.113	0.333	0.660	0.648	0.291	0.178	0.061	0.240
	2	0.375	0.209	0.123	0.332	0.629	0.704	0.305	0.224	0.069	0.293
	3	0.349	0.180	0.148	0.327	0.549	0.676	0.259	0.168	0.060	0.228
	4	0.313	0.215	0.121	0.336	0.640	0.649	0.296	0.190	0.070	0.259
	Average 1 and 3	0.332	0.200	0.130	0.330	0.604	0.662	0.275	0.173	0.061	0.234
	Average 2 and 4	0.344	0.212	0.122	0.334	0.634	0.677	0.301	0.207	0.070	0.276
SA8-12	1	0.280	0.266	0.064	0.330	0.807	0.610	0.333	0.195	0.061	0.256
	2	0.354	0.220	0.117	0.337	0.652	0.691	0.315	0.226	0.069	0.295
	3	0.302	0.218	0.115	0.333	0.655	0.635	0.291	0.182	0.061	0.243
	4	0.304	0.216	0.116	0.332	0.652	0.636	0.302	0.202	0.069	0.271
	Average 1 and 3	0.291	0.242	0.089	0.331	0.731	0.622	0.312	0.189	0.061	0.249
	Average 2 and 4	0.329	0.218	0.117	0.335	0.652	0.663	0.308	0.214	0.069	0.283
SA8-13	1	0.305	0.250	0.082	0.332	0.752	0.637	0.338	0.226	0.069	0.295
	2	0.270	0.265	0.062	0.327	0.810	0.596	0.333	0.196	0.060	0.255

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	3	0.364	0.235	0.099	0.334	0.703	0.698	0.321	0.215	0.067	0.282
	4	0.283	0.277	0.056	0.333	0.832	0.616	0.338	0.191	0.060	0.250
	Average 1 and 3	0.335	0.242	0.091	0.333	0.727	0.668	0.330	0.221	0.068	0.289
	Average 2 and 4	0.276	0.271	0.059	0.330	0.821	0.606	0.335	0.193	0.060	0.253
SA8-14	1	0.306	0.223	0.107	0.330	0.676	0.636	0.299	0.189	0.061	0.250
	2	0.349	0.217	0.112	0.329	0.659	0.678	0.300	0.191	0.065	0.256
	3	0.265	0.252	0.081	0.334	0.756	0.599	0.326	0.197	0.061	0.259
	4	0.354	0.202	0.133	0.335	0.603	0.690	0.302	0.228	0.066	0.294
	Average 1 and 3	0.286	0.238	0.094	0.332	0.716	0.618	0.313	0.193	0.061	0.254
	Average 2 and 4	0.352	0.209	0.123	0.332	0.631	0.684	0.301	0.209	0.066	0.275
SA8-15	1	0.354	0.209	0.119	0.329	0.636	0.684	0.295	0.195	0.065	0.260
	2	0.315	0.246	0.085	0.331	0.742	0.647	0.338	0.221	0.062	0.283
	3	0.367	0.237	0.098	0.336	0.706	0.702	0.323	0.243	0.067	0.309
	4	0.311	0.235	0.104	0.339	0.693	0.650	0.317	0.199	0.061	0.260
	Average 1 and 3	0.361	0.223	0.108	0.333	0.671	0.693	0.309	0.219	0.066	0.284
	Average 2 and 4	0.313	0.240	0.095	0.335	0.718	0.648	0.327	0.210	0.061	0.271
SA8-16	1	0.282	0.274	0.061	0.336	0.817	0.617	0.342	0.222	0.060	0.282
	2	0.325	0.232	0.093	0.325	0.714	0.650	0.313	0.198	0.063	0.260
	3	0.334	0.225	0.110	0.335	0.671	0.669	0.309	0.197	0.061	0.258
	4	0.343	0.237	0.097	0.334	0.709	0.677	0.318	0.209	0.064	0.274
	Average 1 and 3	0.308	0.249	0.086	0.335	0.744	0.643	0.326	0.209	0.060	0.270
	Average 2 and 4	0.334	0.235	0.095	0.330	0.712	0.664	0.315	0.204	0.064	0.267
Average	1 and 3	0.320	0.215	0.116	0.331	0.651	0.652	0.291	0.178	0.063	0.241

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	2 and 4	0.317	0.216	0.111	0.328	0.659	0.645	0.296	0.193	0.060	0.253
	All	0.319	0.216	0.114	0.330	0.655	0.648	0.293	0.186	0.061	0.247
Standard Deviation	1 and 3	0.043	0.032	0.030	0.006	0.087	0.041	0.032	0.035	0.003	0.036
	2 and 4	0.042	0.036	0.032	0.013	0.101	0.052	0.030	0.018	0.017	0.032
	All	0.042	0.034	0.031	0.010	0.093	0.046	0.031	0.028	0.012	0.034

Table 24. Weld dimensions of SA6 series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
SA6-1	1	0.227	0.261	0.091	0.353	0.741	0.579	0.320	0.185	0.065	0.250
	2	0.256	0.229	0.098	0.328	0.700	0.584	0.310	0.199	0.068	0.267
	3	0.253	0.241	0.096	0.337	0.716	0.590	0.313	0.232	0.061	0.293
	4	0.226	0.240	0.095	0.336	0.716	0.561	0.310	0.223	0.069	0.292
	Average 1 and 3	0.240	0.251	0.093	0.345	0.728	0.584	0.316	0.209	0.063	0.272
	Average 2 and 4	0.241	0.235	0.097	0.332	0.708	0.572	0.310	0.211	0.069	0.280
SA6-2	1	0.235	0.236	0.083	0.319	0.740	0.554	0.314	0.226	0.056	0.282
	2	0.185	0.253	0.069	0.321	0.786	0.506	0.319	0.220	0.067	0.287
	3	0.222	0.222	0.114	0.337	0.660	0.559	0.302	0.220	0.059	0.279
	4	0.256	0.225	0.106	0.331	0.680	0.587	0.307	0.211	0.069	0.280
	Average 1 and 3	0.229	0.229	0.099	0.328	0.700	0.557	0.308	0.223	0.057	0.281
	Average 2 and 4	0.221	0.239	0.087	0.326	0.733	0.547	0.313	0.216	0.068	0.283
SA6-3	1	0.241	0.229	0.135	0.363	0.630	0.604	0.321	0.240	0.066	0.306
	2	0.245	0.260	0.077	0.337	0.771	0.582	0.320	0.206	0.059	0.265
	3	0.220	0.242	0.107	0.349	0.694	0.569	0.305	0.199	0.077	0.275
	4	0.219	0.249	0.081	0.329	0.755	0.549	0.315	0.193	0.058	0.252
	Average 1 and 3	0.231	0.235	0.121	0.356	0.662	0.586	0.313	0.219	0.071	0.291
	Average 2 and 4	0.232	0.254	0.079	0.333	0.763	0.565	0.318	0.200	0.059	0.258
SA6-4	1	0.229	0.224	0.102	0.326	0.686	0.554	0.302	0.254	0.057	0.312
	2	0.247	0.227	0.094	0.321	0.708	0.568	0.284	0.157	0.067	0.223
	3	0.223	0.238	0.084	0.321	0.740	0.545	0.315	0.230	0.057	0.286
	4	0.171	0.257	0.059	0.315	0.814	0.486	0.311	0.172	0.064	0.237

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.226	0.231	0.093	0.324	0.713	0.549	0.308	0.242	0.057	0.299
	Average 2 and 4	0.209	0.242	0.076	0.318	0.761	0.527	0.297	0.164	0.066	0.230
SA6-5	1	0.279	0.202	0.123	0.325	0.621	0.605	0.280	0.219	0.064	0.284
	2	0.416	0.021	0.297	0.318	0.065	0.734	0.185	0.430	0.051	0.480
	3	0.236	0.224	0.102	0.326	0.687	0.562	0.306	0.219	0.066	0.285
	4	0.222	0.205	0.121	0.326	0.628	0.548	0.274	0.184	0.056	0.240
	Average 1 and 3	0.258	0.213	0.113	0.326	0.654	0.583	0.293	0.219	0.065	0.284
	Average 2 and 4	0.319	0.113	0.209	0.322	0.347	0.641	0.230	0.307	0.054	0.360
SA6-6	1	0.243	0.230	0.093	0.323	0.713	0.566	0.303	0.205	0.056	0.262
	2	0.236	0.249	0.070	0.319	0.780	0.555	0.309	0.246	0.066	0.312
	3	0.231	0.241	0.088	0.329	0.733	0.560	0.316	0.246	0.057	0.303
	4	0.235	0.223	0.098	0.321	0.696	0.556	0.297	0.202	0.066	0.268
	Average 1 and 3	0.237	0.235	0.090	0.326	0.723	0.563	0.309	0.226	0.057	0.282
	Average 2 and 4	0.236	0.236	0.084	0.320	0.738	0.556	0.303	0.224	0.066	0.290
SA6-7	1	0.231	0.228	0.092	0.320	0.712	0.552	0.301	0.230	0.055	0.285
	2	0.251	0.232	0.090	0.322	0.721	0.572	0.314	0.228	0.065	0.293
	3	0.206	0.217	0.105	0.321	0.674	0.527	0.296	0.216	0.055	0.270
	4	0.268	0.214	0.105	0.319	0.671	0.587	0.307	0.221	0.062	0.283
	Average 1 and 3	0.219	0.222	0.099	0.321	0.693	0.540	0.298	0.223	0.055	0.278
	Average 2 and 4	0.259	0.223	0.097	0.320	0.696	0.580	0.310	0.225	0.064	0.288
SA6-8	1	0.219	0.250	0.167	0.417	0.600	0.636	0.324	0.227	0.056	0.283
	2	0.297	0.175	0.152	0.327	0.535	0.624	0.250	0.256	0.067	0.325
	3	0.196	0.233	0.103	0.335	0.694	0.532	0.296	0.209	0.059	0.268

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.214	0.226	0.143	0.369	0.613	0.583	0.287	0.251	0.066	0.317
	Average 1 and 3	0.208	0.241	0.135	0.376	0.647	0.584	0.310	0.218	0.057	0.275
	Average 2 and 4	0.256	0.201	0.147	0.348	0.574	0.603	0.268	0.253	0.067	0.321
Average	1 and 3	0.231	0.232	0.105	0.338	0.690	0.568	0.307	0.222	0.060	0.283
	2 and 4	0.246	0.218	0.110	0.327	0.665	0.574	0.294	0.225	0.064	0.289
	All	0.239	0.225	0.107	0.332	0.677	0.571	0.300	0.224	0.062	0.286
Standard Deviation	1 and 3	0.019	0.014	0.022	0.025	0.044	0.028	0.012	0.018	0.006	0.016
	2 and 4	0.054	0.057	0.056	0.013	0.175	0.054	0.035	0.061	0.005	0.059
	All	0.041	0.041	0.042	0.020	0.126	0.042	0.026	0.044	0.006	0.042

Table 25. Weld dimensions of SA4 series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
SA4-1	1	0.248	0.199	0.170	0.369	0.540	0.617	0.290	0.224	0.056	0.280
	2	0.152	0.333	0.000	0.333	1.000	0.485	0.374	0.226	0.065	0.292
	3	0.253	0.209	0.125	0.335	0.626	0.587	0.285	0.242	0.057	0.299
	4	0.266	0.236	0.138	0.374	0.630	0.640	0.304	0.211	0.062	0.273
	Average 1 and 3	0.251	0.204	0.148	0.352	0.583	0.602	0.288	0.233	0.057	0.290
	Average 2 and 4	0.209	0.284	0.069	0.353	0.815	0.562	0.339	0.219	0.063	0.282
SA4-2	1	0.258	0.195	0.133	0.328	0.593	0.586	0.282	0.223	0.058	0.280
	2	0.219	0.333	0.000	0.333	1.000	0.552	0.358	0.150	0.067	0.218
	3	0.253	0.219	0.114	0.333	0.658	0.585	0.301	0.238	0.060	0.298
	4	0.191	0.290	0.058	0.348	0.834	0.539	0.316	0.130	0.073	0.203
	Average 1 and 3	0.255	0.207	0.124	0.330	0.626	0.586	0.292	0.230	0.059	0.289
	Average 2 and 4	0.205	0.312	0.029	0.340	0.917	0.546	0.337	0.140	0.070	0.210
SA4-3	1	0.226	0.190	0.185	0.375	0.506	0.601	0.281	0.234	0.057	0.292
	2	0.196	0.320	0.000	0.320	1.000	0.516	0.372	0.272	0.059	0.331
	3	0.244	0.207	0.120	0.326	0.634	0.570	0.286	0.221	0.056	0.277
	4	0.182	0.323	0.000	0.323	1.000	0.505	0.377	0.426	0.061	0.487
	Average 1 and 3	0.235	0.198	0.152	0.351	0.570	0.585	0.284	0.227	0.057	0.284
	Average 2 and 4	0.189	0.321	0.000	0.321	1.000	0.510	0.374	0.349	0.060	0.409
SA4-4	1	0.255	0.200	0.142	0.342	0.586	0.597	0.290	0.256	0.058	0.314
	2	0.210	0.276	0.050	0.326	0.846	0.536	0.323	0.207	0.064	0.271
	3	0.277	0.193	0.127	0.321	0.603	0.598	0.297	0.255	0.056	0.312
	4	0.197	0.200	0.123	0.323	0.618	0.520	0.256	0.193	0.064	0.257

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.266	0.197	0.134	0.331	0.595	0.598	0.293	0.256	0.057	0.313
	Average 2 and 4	0.204	0.238	0.087	0.325	0.732	0.528	0.289	0.200	0.064	0.264
SA4-5	1	0.256	0.194	0.127	0.321	0.605	0.576	0.284	0.193	0.055	0.248
	2	0.234	0.284	0.053	0.336	0.844	0.571	0.306	0.191	0.067	0.189
	3	0.222	0.213	0.125	0.339	0.630	0.560	0.281	0.171	0.063	0.234
	4	0.205	0.284	0.075	0.359	0.792	0.564	0.349	0.302	0.061	0.363
	Average 1 and 3	0.239	0.204	0.126	0.330	0.618	0.568	0.283	0.182	0.059	0.241
	Average 2 and 4	0.220	0.284	0.064	0.347	0.818	0.567	0.328	0.247	0.064	0.276
SA4-6	1	0.261	0.200	0.135	0.334	0.597	0.596	0.290	0.230	0.058	0.288
	2	0.202	0.221	0.102	0.323	0.684	0.525	0.267	0.186	0.064	0.250
	3	0.265	0.185	0.141	0.326	0.568	0.591	0.282	0.241	0.059	0.300
	4	0.251	0.177	0.150	0.327	0.542	0.578	0.238	0.166	0.064	0.230
	Average 1 and 3	0.263	0.192	0.138	0.330	0.582	0.593	0.286	0.236	0.058	0.294
	Average 2 and 4	0.226	0.199	0.126	0.325	0.613	0.552	0.253	0.176	0.064	0.240
SA4-7	1	0.278	0.143	0.180	0.324	0.443	0.601	0.251	0.213	0.052	0.265
	2	0.362	0.085	0.246	0.331	0.255	0.693	0.222	0.187	0.067	0.254
	3	0.242	0.196	0.129	0.324	0.604	0.567	0.286	0.237	0.054	0.291
	4	0.211	0.256	0.081	0.337	0.759	0.548	0.296	0.176	0.068	0.244
	Average 1 and 3	0.260	0.170	0.154	0.324	0.523	0.584	0.269	0.225	0.053	0.278
	Average 2 and 4	0.287	0.170	0.164	0.334	0.507	0.620	0.259	0.181	0.068	0.249
SA4-8	1	0.245	0.231	0.115	0.346	0.667	0.591	0.304	0.229	0.063	0.291
	2	0.278	0.153	0.181	0.334	0.459	0.612	0.253	0.229	0.058	0.287
	3	0.271	0.210	0.111	0.320	0.655	0.591	0.280	0.178	0.065	0.244

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.250	0.218	0.113	0.331	0.658	0.581	0.294	0.209	0.061	0.270
	Average 1 and 3	0.258	0.220	0.113	0.333	0.661	0.591	0.292	0.203	0.064	0.267
	Average 2 and 4	0.264	0.185	0.147	0.332	0.559	0.597	0.273	0.219	0.059	0.278
Average	1 and 3	0.253	0.199	0.136	0.335	0.595	0.588	0.286	0.224	0.058	0.282
	2 and 4	0.226	0.249	0.086	0.335	0.745	0.560	0.307	0.216	0.064	0.276
	All	0.239	0.224	0.111	0.335	0.670	0.574	0.296	0.220	0.061	0.279
Standard Deviation	1 and 3	0.016	0.019	0.023	0.016	0.059	0.015	0.012	0.025	0.004	0.024
	2 and 4	0.049	0.071	0.072	0.014	0.215	0.053	0.050	0.070	0.004	0.071
	All	0.038	0.057	0.058	0.015	0.173	0.041	0.037	0.052	0.005	0.052

Table 26. Weld dimensions of SA2 series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
SA2-1	1	0.196	0.289	0.035	0.324	0.891	0.520	0.332	0.179	0.063	0.242
	2	0.200	0.210	0.116	0.326	0.643	0.526	0.289	0.217	0.065	0.282
	3	0.188	0.255	0.076	0.331	0.771	0.519	0.311	0.232	0.066	0.298
	4	0.197	0.206	0.120	0.326	0.632	0.523	0.292	0.223	0.063	0.287
	Average 1 and 3	0.192	0.272	0.056	0.327	0.831	0.519	0.322	0.206	0.065	0.270
	Average 2 and 4	0.198	0.208	0.118	0.326	0.637	0.524	0.290	0.220	0.064	0.284
SA2-2	1	0.196	0.217	0.114	0.332	0.654	0.527	0.294	0.204	0.066	0.270
	2	0.173	0.279	0.053	0.332	0.840	0.505	0.330	0.325	0.064	0.389
	3	0.205	0.224	0.105	0.329	0.681	0.535	0.296	0.206	0.067	0.273
	4	0.264	0.202	0.147	0.349	0.580	0.613	0.320	0.475	0.068	0.543
	Average 1 and 3	0.200	0.221	0.109	0.331	0.668	0.531	0.295	0.205	0.067	0.272
	Average 2 and 4	0.219	0.240	0.100	0.340	0.710	0.559	0.325	0.400	0.066	0.466
SA2-3	1	0.194	0.269	0.061	0.330	0.814	0.524	0.317	0.190	0.064	0.253
	2	0.182	0.210	0.120	0.331	0.636	0.513	0.283	0.216	0.066	0.282
	3	0.167	0.208	0.131	0.339	0.614	0.506	0.297	0.280	0.069	0.349
	4	0.202	0.206	0.118	0.324	0.636	0.526	0.302	0.269	0.063	0.332
	Average 1 and 3	0.181	0.238	0.096	0.334	0.714	0.515	0.307	0.235	0.066	0.301
	Average 2 and 4	0.192	0.208	0.119	0.327	0.636	0.519	0.292	0.243	0.064	0.307
SA2-4	1	0.212	0.208	0.116	0.323	0.643	0.535	0.287	0.237	0.064	0.301
	2	0.333	0.194	0.125	0.319	0.609	0.652	0.340	0.443	0.058	0.501
	3	0.188	0.221	0.114	0.334	0.661	0.522	0.288	0.205	0.068	0.274
	4	0.182	0.242	0.082	0.324	0.747	0.506	0.292	0.212	0.060	0.273

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.200	0.214	0.115	0.329	0.652	0.529	0.288	0.221	0.066	0.287
	Average 2 and 4	0.257	0.218	0.103	0.322	0.678	0.579	0.316	0.328	0.059	0.387
SA2-5	1	0.224	0.193	0.137	0.331	0.585	0.555	0.284	0.184	0.066	0.251
	2	0.174	0.264	0.068	0.332	0.796	0.507	0.320	0.193	0.063	0.256
	3	0.187	0.219	0.115	0.334	0.656	0.521	0.302	0.219	0.066	0.286
	4	0.211	0.183	0.140	0.323	0.566	0.535	0.274	0.243	0.063	0.306
	Average 1 and 3	0.205	0.206	0.126	0.332	0.620	0.538	0.293	0.202	0.066	0.268
	Average 2 and 4	0.193	0.224	0.104	0.328	0.681	0.521	0.297	0.218	0.063	0.281
SA2-6	1	0.227	0.212	0.115	0.327	0.649	0.552	0.287	0.204	0.064	0.268
	2	0.195	0.268	0.058	0.326	0.823	0.521	0.313	0.202	0.062	0.265
	3	0.186	0.208	0.121	0.329	0.634	0.514	0.285	0.200	0.065	0.265
	4	0.224	0.216	0.111	0.327	0.662	0.551	0.271	0.171	0.063	0.234
	Average 1 and 3	0.206	0.210	0.118	0.328	0.641	0.533	0.286	0.202	0.064	0.267
	Average 2 and 4	0.210	0.242	0.084	0.327	0.743	0.536	0.292	0.187	0.063	0.250
SA2-7	1	0.193	0.235	0.098	0.333	0.707	0.526	0.310	0.210	0.065	0.275
	2	0.202	0.199	0.144	0.343	0.582	0.545	0.281	0.236	0.067	0.303
	3	0.173	0.235	0.091	0.326	0.722	0.499	0.328	0.260	0.061	0.322
	4	0.266	0.150	0.177	0.327	0.459	0.593	0.239	0.160	0.062	0.221
	Average 1 and 3	0.183	0.235	0.094	0.329	0.714	0.512	0.319	0.235	0.063	0.298
	Average 2 and 4	0.234	0.175	0.160	0.335	0.520	0.569	0.260	0.198	0.064	0.262
SA2-8	1	0.182	0.231	0.097	0.328	0.704	0.510	0.311	0.246	0.064	0.309
	2	0.225	0.260	0.073	0.336	0.773	0.561	0.314	0.205	0.064	0.269
	3	0.207	0.192	0.136	0.328	0.586	0.535	0.286	0.267	0.063	0.330

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.356	0.283	0.043	0.326	0.869	0.682	0.369	0.256	0.060	0.316
	Average 1 and 3	0.194	0.212	0.117	0.328	0.645	0.523	0.298	0.256	0.064	0.320
	Average 2 and 4	0.291	0.272	0.058	0.331	0.821	0.622	0.341	0.231	0.062	0.292
Average	1 and 3	0.195	0.226	0.104	0.330	0.686	0.525	0.301	0.220	0.065	0.285
	2 and 4	0.224	0.223	0.106	0.329	0.678	0.554	0.302	0.253	0.063	0.316
	All	0.210	0.225	0.105	0.330	0.682	0.539	0.301	0.237	0.064	0.301
Standard Deviation	1 and 3	0.017	0.026	0.027	0.004	0.082	0.015	0.016	0.030	0.002	0.030
	2 and 4	0.054	0.038	0.039	0.008	0.116	0.054	0.031	0.090	0.003	0.090
	All	0.042	0.032	0.033	0.006	0.099	0.042	0.024	0.068	0.003	0.068

Table 27. Weld dimensions of FIL series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
FIL-1	1	0.241	0.248	0.076	0.324	0.767	0.565	0.353	0.290	0.067	0.356
	2	0.259	0.226	0.108	0.335	0.675	0.594	0.312	0.230	0.063	0.293
	3	0.278	0.184	0.148	0.332	0.555	0.610	0.293	0.310	0.070	0.380
	4	0.248	0.218	0.097	0.315	0.691	0.563	0.319	0.316	0.056	0.372
	Average 1 and 3	0.259	0.216	0.112	0.328	0.661	0.587	0.323	0.300	0.068	0.368
	Average 2 and 4	0.254	0.222	0.103	0.325	0.683	0.579	0.316	0.273	0.059	0.332
FIL-2	1	0.269	0.172	0.154	0.326	0.528	0.594	0.300	0.334	0.060	0.334
	2	0.262	0.202	0.130	0.332	0.608	0.594	0.314	0.298	0.069	0.366
	3	0.263	0.218	0.122	0.340	0.642	0.602	0.318	0.378	0.068	0.445
	4	0.240	0.222	0.099	0.321	0.690	0.561	0.310	0.256	0.065	0.321
	Average 1 and 3	0.266	0.195	0.138	0.333	0.585	0.598	0.309	0.356	0.064	0.390
	Average 2 and 4	0.251	0.212	0.115	0.326	0.649	0.577	0.312	0.277	0.067	0.344
FIL-3	1	0.267	0.206	0.119	0.324	0.634	0.591	0.316	0.333	0.060	0.393
	2	0.205	0.272	0.044	0.316	0.860	0.521	0.357	0.328	0.065	0.392
	3	0.255	0.216	0.116	0.332	0.650	0.587	0.316	0.328	0.060	0.388
	4	0.268	0.150	0.181	0.331	0.453	0.599	0.301	0.292	0.070	0.362
	Average 1 and 3	0.261	0.211	0.118	0.328	0.642	0.589	0.316	0.331	0.060	0.391
	Average 2 and 4	0.237	0.211	0.113	0.324	0.656	0.560	0.329	0.310	0.067	0.377
FIL-4	1	0.261	0.225	0.105	0.329	0.682	0.591	0.335	0.336	0.060	0.396
	2	0.241	0.211	0.116	0.327	0.646	0.568	0.320	0.301	0.067	0.368
	3	0.235	0.213	0.110	0.323	0.661	0.558	0.327	0.355	0.061	0.416
	4	0.264	0.334	0.000	0.334	1.000	0.598	0.293	0.246	0.070	0.317

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.248	0.219	0.107	0.326	0.672	0.574	0.331	0.345	0.061	0.406
	Average 2 and 4	0.253	0.272	0.058	0.330	0.823	0.583	0.307	0.274	0.069	0.342
FIL-5	1	0.269	0.233	0.092	0.325	0.718	0.594	0.328	0.298	0.067	0.365
	2	0.284	0.151	0.165	0.315	0.478	0.600	0.273	0.256	0.054	0.311
	3	0.301	0.175	0.151	0.326	0.538	0.631	0.310	0.317	0.066	0.384
	4	0.275	0.180	0.137	0.316	0.569	0.591	0.289	0.275	0.057	0.331
	Average 1 and 3	0.285	0.204	0.121	0.325	0.628	0.612	0.319	0.308	0.067	0.374
	Average 2 and 4	0.280	0.165	0.151	0.316	0.524	0.595	0.281	0.266	0.056	0.321
FIL-6	1	0.270	0.208	0.117	0.326	0.640	0.596	0.314	0.304	0.060	0.364
	2	0.196	0.265	0.058	0.323	0.821	0.519	0.353	0.286	0.066	0.353
	3	0.285	0.215	0.109	0.325	0.663	0.610	0.319	0.331	0.061	0.392
	4	0.271	0.164	0.160	0.324	0.507	0.595	0.289	0.267	0.065	0.332
	Average 1 and 3	0.278	0.212	0.113	0.325	0.651	0.603	0.317	0.317	0.060	0.378
	Average 2 and 4	0.234	0.215	0.109	0.324	0.664	0.557	0.321	0.277	0.065	0.342
FIL-7	1	0.324	0.079	0.253	0.332	0.239	0.657	0.235	0.252	0.067	0.318
	2	0.326	0.082	0.249	0.331	0.249	0.658	0.244	0.255	0.060	0.315
	3	0.265	0.221	0.100	0.321	0.689	0.585	0.304	0.245	0.065	0.310
	4	0.286	0.206	0.120	0.326	0.633	0.612	0.300	0.242	0.059	0.301
	Average 1 and 3	0.295	0.150	0.176	0.326	0.464	0.621	0.270	0.248	0.066	0.314
	Average 2 and 4	0.306	0.144	0.184	0.329	0.441	0.635	0.272	0.248	0.060	0.308
FIL-8	1	0.232	0.232	0.091	0.323	0.720	0.555	0.345	0.253	0.065	0.318
	2	0.245	0.194	0.135	0.328	0.589	0.573	0.311	0.278	0.059	0.337
	3	0.246	0.220	0.107	0.327	0.672	0.574	0.292	0.265	0.066	0.330

Specimen	**Weld Location**	d_1 **(inches)**	d_2 **(inches)**	d_3 **(inches)**	d_4 **(inches)**	d_2/d_4	d_5 **(inches)**	t **(inches)**	h_1 **(inches)**	h_2 **(inches)**	h **(inches)**
	4	0.286	0.161	0.156	0.317	0.507	0.603	0.265	0.257	0.055	0.312
	Average 1 and 3	0.239	0.226	0.099	0.325	0.696	0.564	0.319	0.259	0.065	0.324
	Average 2 and 4	0.265	0.177	0.146	0.323	0.548	0.588	0.288	0.267	0.057	0.324
Average	1 and 3	0.266	0.204	0.123	0.327	0.625	0.594	0.313	0.308	0.064	0.368
	2 and 4	0.260	0.202	0.122	0.325	0.624	0.584	0.303	0.274	0.062	0.336
	All	0.263	0.203	0.123	0.326	0.624	0.589	0.308	0.291	0.063	0.352
Standard Deviation	1 and 3	0.024	0.039	0.041	0.005	0.122	0.026	0.027	0.039	0.004	0.038
	2 and 4	0.032	0.058	0.058	0.007	0.177	0.034	0.029	0.028	0.005	0.029
	All	0.028	0.049	0.049	0.006	0.150	0.030	0.028	0.037	0.005	0.037

Table 28. Weld dimensions of OB series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
OB-1	1	0.448	0.094	0.234	0.328	0.288	0.776	0.262	0.254	0.074	0.328
	2	0.213	0.241	0.088	0.329	0.732	0.542	0.342	0.255	0.085	0.341
	3	0.364	0.204	0.127	0.331	0.616	0.695	0.314	0.265	0.075	0.341
	4	0.238	0.215	0.126	0.341	0.630	0.579	0.312	0.200	0.090	0.290
	Average 1 and 3	0.406	0.149	0.180	0.330	0.452	0.736	0.288	0.259	0.075	0.334
	Average 2 and 4	0.225	0.228	0.107	0.335	0.681	0.560	0.327	0.227	0.088	0.315
OB-2	1	0.361	0.220	0.117	0.337	0.652	0.697	0.329	0.246	0.076	0.321
	2	0.264	0.240	0.088	0.329	0.731	0.593	0.337	0.224	0.087	0.311
	3	0.345	0.199	0.130	0.329	0.604	0.067	0.325	0.277	0.074	0.351
	4	0.267	0.200	0.129	0.329	0.609	0.596	0.320	0.225	0.086	0.311
	Average 1 and 3	0.353	0.209	0.124	0.333	0.628	0.382	0.327	0.261	0.075	0.336
	Average 2 and 4	0.266	0.220	0.108	0.329	0.670	0.594	0.329	0.225	0.086	0.311
OB-3	1	0.356	0.228	0.120	0.348	0.656	0.704	0.322	0.195	0.074	0.269
	2	0.285	0.242	0.071	0.313	0.774	0.598	0.348	0.241	0.061	0.302
	3	0.332	0.224	0.103	0.327	0.684	0.661	0.319	0.212	0.069	0.281
	4	0.310	0.199	0.108	0.307	0.647	0.617	0.314	0.227	0.061	0.287
	Average 1 and 3	0.344	0.226	0.111	0.337	0.670	0.682	0.320	0.203	0.072	0.275
	Average 2 and 4	0.298	0.220	0.090	0.310	0.711	0.608	0.331	0.234	0.061	0.295
OB-4	1	0.306	0.304	0.015	0.319	0.954	0.625	0.356	0.192	0.062	0.254
	2	0.307	0.226	0.100	0.327	0.691	0.634	0.324	0.238	0.082	0.320
	3	0.349	0.209	0.109	0.318	0.657	0.668	0.328	0.255	0.061	0.316
	4	0.253	0.240	0.114	0.354	0.677	0.636	0.326	0.235	0.095	0.330

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.328	0.257	0.062	0.318	0.806	0.646	0.342	0.223	0.061	0.285
	Average 2 and 4	0.280	0.233	0.107	0.341	0.684	0.635	0.325	0.236	0.088	0.325
OB-5	1	0.296	0.222	0.116	0.337	0.659	0.633	0.320	0.224	0.092	0.316
	2	0.338	0.220	0.121	0.341	0.646	0.679	0.323	0.241	0.078	0.319
	3	0.290	0.222	0.109	0.332	0.670	0.622	0.324	0.214	0.089	0.303
	4	0.332	0.204	0.131	0.335	0.610	0.667	0.313	0.250	0.079	0.329
	Average 1 and 3	0.293	0.222	0.113	0.334	0.665	0.628	0.322	0.219	0.090	0.309
	Average 2 and 4	0.335	0.212	0.126	0.338	0.628	0.673	0.318	0.245	0.078	0.324
OB-6	1	0.305	0.221	0.108	0.330	0.672	0.634	0.305	0.210	0.089	0.299
	2	0.326	0.203	0.133	0.336	0.605	0.662	0.307	0.230	0.076	0.306
	3	0.288	0.228	0.120	0.348	0.655	0.636	0.327	0.225	0.095	0.320
	4	0.351	0.185	0.161	0.345	0.535	0.696	0.306	0.249	0.077	0.327
	Average 1 and 3	0.296	0.225	0.114	0.339	0.663	0.635	0.316	0.218	0.092	0.310
	Average 2 and 4	0.338	0.194	0.147	0.341	0.570	0.679	0.306	0.240	0.077	0.316
OB-7	1	0.339	0.202	0.142	0.344	0.587	0.683	0.307	0.226	0.077	0.303
	2	0.293	0.225	0.103	0.328	0.685	0.621	0.310	0.194	0.087	0.281
	3	0.328	0.243	0.088	0.331	0.733	0.659	0.341	0.236	0.072	0.308
	4	0.310	0.271	0.074	0.345	0.785	0.655	0.338	0.195	0.090	0.285
	Average 1 and 3	0.333	0.222	0.115	0.338	0.660	0.671	0.324	0.231	0.075	0.305
	Average 2 and 4	0.301	0.248	0.089	0.337	0.735	0.638	0.324	0.195	0.089	0.283
OB-8	1	0.332	0.235	0.097	0.332	0.708	0.664	0.333	0.229	0.074	0.303
	2	0.313	0.207	0.125	0.332	0.624	0.645	0.299	0.190	0.086	0.276
	3	0.366	0.230	0.101	0.332	0.694	0.698	0.329	0.261	0.073	0.333

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.340	0.204	0.126	0.330	0.618	0.671	0.307	0.232	0.086	0.318
	Average 1 and 3	0.349	0.233	0.099	0.332	0.701	0.681	0.331	0.245	0.074	0.318
	Average 2 and 4	0.327	0.206	0.125	0.331	0.621	0.658	0.303	0.211	0.086	0.297
OB-9	1	0.338	0.252	0.066	0.319	0.792	0.656	0.328	0.202	0.062	0.264
	2	0.311	0.205	0.127	0.332	0.618	0.644	0.345	0.228	0.062	0.320
	3	0.371	0.233	0.085	0.318	0.733	0.689	0.329	0.238	0.059	0.297
	4	0.327	0.174	0.146	0.320	0.545	0.647	0.282	0.244	0.063	0.307
	Average 1 and 3	0.354	0.243	0.076	0.318	0.763	0.673	0.329	0.220	0.061	0.281
	Average 2 and 4	0.319	0.190	0.136	0.326	0.581	0.645	0.313	0.236	0.062	0.313
OB-10	1	0.339	0.176	0.166	0.341	0.515	0.680	0.278	0.220	0.083	0.303
	2	0.309	0.242	0.072	0.314	0.772	0.622	0.346	0.246	0.072	0.317
	3	0.329	0.178	0.151	0.329	0.541	0.657	0.293	0.218	0.084	0.302
	4	0.308	0.241	0.096	0.337	0.715	0.645	0.340	0.238	0.079	0.317
	Average 1 and 3	0.334	0.177	0.158	0.335	0.528	0.668	0.286	0.219	0.083	0.302
	Average 2 and 4	0.309	0.241	0.084	0.325	0.743	0.634	0.343	0.242	0.075	0.317
OB-11	1	0.350	0.149	0.193	0.342	0.436	0.692	0.279	0.228	0.083	0.310
	2	0.290	0.176	0.147	0.323	0.546	0.613	0.295	0.221	0.077	0.298
	3	0.345	0.215	0.116	0.331	0.649	0.675	0.313	0.235	0.083	0.318
	4	0.299	0.220	0.112	0.332	0.664	0.630	0.326	0.236	0.079	0.314
	Average 1 and 3	0.347	0.182	0.154	0.336	0.542	0.683	0.296	0.231	0.083	0.314
	Average 2 and 4	0.294	0.198	0.129	0.327	0.605	0.622	0.310	0.228	0.078	0.306
OB-12	1	0.341	0.233	0.121	0.355	0.658	0.696	0.321	0.198	0.089	0.286
	2	0.339	0.200	0.131	0.331	0.604	0.671	0.309	0.233	0.078	0.311

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	3	0.354	0.219	0.114	0.333	0.659	0.686	0.319	0.214	0.084	0.298
	4	0.323	0.231	0.098	0.329	0.701	0.652	0.325	0.225	0.077	0.302
	Average 1 and 3	0.347	0.226	0.117	0.344	0.658	0.691	0.320	0.206	0.086	0.292
	Average 2 and 4	0.331	0.215	0.115	0.330	0.652	0.661	0.317	0.229	0.078	0.307
OB-13	1	0.345	0.242	0.095	0.336	0.719	0.681	0.323	0.211	0.090	0.301
	2	0.327	0.202	0.127	0.329	0.614	0.656	0.301	0.217	0.076	0.292
	3	0.331	0.211	0.121	0.332	0.635	0.663	0.310	0.218	0.088	0.306
	4	0.346	0.141	0.200	0.342	0.413	0.688	0.279	0.216	0.082	0.298
	Average 1 and 3	0.338	0.226	0.108	0.334	0.677	0.672	0.316	0.214	0.089	0.303
	Average 2 and 4	0.337	0.172	0.164	0.335	0.514	0.672	0.290	0.217	0.079	0.295
OB-14	1	0.339	0.167	0.166	0.333	0.501	0.672	0.300	0.228	0.077	0.305
	2	0.339	0.188	0.143	0.331	0.568	0.670	0.299	0.204	0.087	0.290
	3	0.290	0.216	0.121	0.337	0.641	0.626	0.332	0.229	0.079	0.307
	4	0.335	0.201	0.137	0.338	0.595	0.673	0.308	0.228	0.087	0.314
	Average 1 and 3	0.314	0.191	0.144	0.335	0.571	0.649	0.316	0.228	0.078	0.306
	Average 2 and 4	0.337	0.194	0.140	0.334	0.582	0.672	0.303	0.216	0.087	0.302
OB-15	1	0.257	0.213	0.129	0.342	0.624	0.599	0.315	0.242	0.075	0.317
	2	0.325	0.192	0.134	0.327	0.588	0.651	0.297	0.223	0.085	0.308
	3	0.253	0.223	0.109	0.332	0.672	0.585	0.307	0.307	0.078	0.385
	4	0.318	0.222	0.108	0.330	0.674	0.648	0.315	0.230	0.087	0.317
	Average 1 and 3	0.255	0.218	0.119	0.337	0.648	0.592	0.311	0.274	0.077	0.351
	Average 2 and 4	0.321	0.207	0.121	0.328	0.631	0.650	0.306	0.227	0.086	0.313
OB-16	1	0.376	0.172	0.160	0.332	0.517	0.708	0.291	0.220	0.082	0.302

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	2	0.213	0.216	0.109	0.326	0.665	0.539	0.353	0.279	0.073	0.351
	3	0.391	0.171	0.160	0.331	0.516	0.722	0.336	0.295	0.084	0.379
	4	0.248	0.212	0.118	0.329	0.643	0.577	0.319	0.220	0.075	0.295
	Average 1 and 3	0.383	0.171	0.160	0.332	0.516	0.715	0.313	0.257	0.083	0.341
	Average 2 and 4	0.231	0.214	0.113	0.327	0.654	0.558	0.336	0.249	0.074	0.323
Average	1 and 3	0.336	0.211	0.122	0.333	0.636	0.650	0.316	0.232	0.078	0.310
	2 and 4	0.303	0.212	0.119	0.331	0.641	0.635	0.318	0.229	0.079	0.309
	All	0.319	0.212	0.120	0.332	0.639	0.643	0.317	0.230	0.079	0.309
Standard Deviation	1 and 3	0.035	0.029	0.031	0.007	0.092	0.079	0.015	0.021	0.009	0.022
	2 and 4	0.036	0.020	0.022	0.008	0.063	0.038	0.014	0.014	0.009	0.012
	All	0.039	0.024	0.027	0.007	0.078	0.062	0.014	0.018	0.009	0.017

Table 29. Weld dimensions of UB series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
UB-1	1	0.251	0.223	0.113	0.335	0.664	0.587	0.332	0.235	0.087	0.322
	2	0.345	0.166	0.166	0.333	0.500	0.678	0.280	0.218	0.083	0.301
	3	0.262	0.211	0.120	0.331	0.637	0.593	0.318	0.230	0.082	0.312
	4	0.347	0.203	0.129	0.332	0.612	0.679	0.303	0.218	0.079	0.294
	Average 1 and 3	0.257	0.217	0.116	0.333	0.651	0.590	0.325	0.232	0.085	0.317
	Average 2 and 4	0.346	0.185	0.148	0.332	0.556	0.678	0.291	0.218	0.081	0.297
UB-2	1	0.322	0.183	0.151	0.334	0.549	0.656	0.293	0.267	0.078	0.345
	2	0.261	0.224	0.110	0.334	0.669	0.595	0.327	0.282	0.083	0.371
	3	0.311	0.241	0.094	0.334	0.720	0.645	0.321	0.215	0.083	0.298
	4	0.270	0.250	0.086	0.336	0.744	0.606	0.336	0.223	0.080	0.302
	Average 1 and 3	0.317	0.212	0.122	0.334	0.635	0.651	0.307	0.241	0.080	0.321
	Average 2 and 4	0.266	0.237	0.098	0.335	0.707	0.600	0.332	0.252	0.081	0.336
UB-3	1	0.281	0.226	0.080	0.306	0.740	0.587	0.344	0.263	0.063	0.326
	2	0.367	0.177	0.157	0.334	0.529	0.701	0.286	0.216	0.081	0.296
	3	0.280	0.172	0.134	0.306	0.563	0.586	0.307	0.248	0.063	0.311
	4	0.337	0.148	0.183	0.332	0.447	0.669	0.275	0.240	0.078	0.318
	Average 1 and 3	0.281	0.199	0.107	0.306	0.651	0.587	0.325	0.256	0.063	0.318
	Average 2 and 4	0.352	0.163	0.170	0.333	0.488	0.685	0.280	0.228	0.079	0.307
UB-4	1	0.254	0.214	0.117	0.331	0.647	0.585	0.323	0.231	0.082	0.313
	2	0.344	0.144	0.169	0.312	0.459	0.656	0.276	0.234	0.077	0.311
	3	0.206	0.189	0.144	0.333	0.567	0.539	0.363	0.286	0.081	0.366
	4	0.370	0.156	0.176	0.332	0.469	0.702	0.285	0.232	0.083	0.315

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	Average 1 and 3	0.230	0.201	0.130	0.332	0.607	0.562	0.343	0.258	0.081	0.340
	Average 2 and 4	0.357	0.150	0.173	0.322	0.464	0.679	0.281	0.233	0.080	0.313
UB-5	1	0.279	0.240	0.103	0.343	0.699	0.622	0.337	0.230	0.085	0.315
	2	0.333	0.137	0.192	0.329	0.417	0.662	0.264	0.207	0.083	0.290
	3	0.258	0.204	0.129	0.333	0.613	0.591	0.328	0.229	0.084	0.313
	4	0.329	0.202	0.129	0.331	0.609	0.660	0.297	0.220	0.080	0.300
	Average 1 and 3	0.269	0.222	0.116	0.338	0.656	0.607	0.332	0.229	0.085	0.314
	Average 2 and 4	0.331	0.170	0.161	0.330	0.513	0.661	0.281	0.213	0.081	0.295
UB-6	1	0.262	0.251	0.089	0.342	0.732	0.604	0.346	0.304	0.088	0.392
	2	0.356	0.175	0.154	0.330	0.532	0.686	0.283	0.214	0.082	0.296
	3	0.287	0.201	0.138	0.340	0.593	0.626	0.309	0.209	0.083	0.293
	4	0.337	0.193	0.140	0.333	0.580	0.670	0.298	0.222	0.081	0.303
	Average 1 and 3	0.274	0.226	0.114	0.341	0.662	0.615	0.327	0.257	0.085	0.342
	Average 2 and 4	0.346	0.184	0.147	0.331	0.556	0.678	0.290	0.218	0.081	0.299
UB-7	1	0.265	0.241	0.094	0.335	0.719	0.600	0.337	0.315	0.085	0.400
	2	0.327	0.191	0.142	0.333	0.573	0.660	0.287	0.205	0.086	0.291
	3	0.245	0.247	0.087	0.334	0.739	0.580	0.349	0.329	0.085	0.414
	4	0.321	0.179	0.152	0.331	0.541	0.653	0.287	0.225	0.080	0.304
	Average 1 and 3	0.255	0.244	0.091	0.335	0.729	0.590	0.343	0.322	0.085	0.407
	Average 2 and 4	0.324	0.185	0.147	0.332	0.557	0.657	0.287	0.215	0.083	0.297
UB-8	1	0.247	0.224	0.115	0.338	0.661	0.585	0.342	0.277	0.082	0.359
	2	0.326	0.191	0.140	0.331	0.577	0.657	0.286	0.258	0.083	0.343
	3	0.248	0.254	0.083	0.338	0.753	0.586	0.345	0.321	0.084	0.404

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	4	0.305	0.200	0.135	0.335	0.597	0.640	0.295	0.279	0.085	0.365
	Average 1 and 3	0.248	0.239	0.099	0.338	0.707	0.586	0.344	0.299	0.083	0.382
	Average 2 and 4	0.316	0.195	0.138	0.333	0.587	0.648	0.291	0.269	0.084	0.354
UB-9	1	0.280	0.249	0.084	0.333	0.747	0.613	0.341	0.316	0.079	0.394
	2	0.281	0.205	0.119	0.324	0.633	0.603	0.314	0.288	0.084	0.372
	3	0.251	0.259	0.072	0.331	0.782	0.058	0.366	0.303	0.080	0.383
	4	0.305	0.198	0.137	0.335	0.590	0.640	0.296	0.219	0.083	0.302
	Average 1 and 3	0.266	0.254	0.078	0.332	0.764	0.336	0.353	0.309	0.079	0.388
	Average 2 and 4	0.293	0.202	0.128	0.330	0.611	0.622	0.305	0.254	0.084	0.337
UB-10	1	0.273	0.244	0.088	0.332	0.734	0.605	0.332	0.285	0.084	0.370
	2	0.274	0.227	0.103	0.329	0.688	0.604	0.322	0.231	0.078	0.309
	3	0.262	0.221	0.113	0.334	0.662	0.595	0.317	0.228	0.086	0.315
	4	0.308	0.225	0.108	0.333	0.677	0.641	0.349	0.280	0.074	0.354
	Average 1 and 3	0.267	0.232	0.100	0.333	0.698	0.600	0.325	0.257	0.085	0.342
	Average 2 and 4	0.291	0.226	0.105	0.331	0.682	0.622	0.335	0.256	0.076	0.332
UB-11	1	0.298	0.187	0.141	0.328	0.571	0.626	0.298	0.243	0.072	0.315
	2	0.276	0.211	0.126	0.337	0.626	0.613	0.311	0.225	0.087	0.312
	3	0.348	0.175	0.161	0.336	0.521	0.684	0.327	0.231	0.077	0.307
	4	0.270	0.203	0.128	0.331	0.614	0.602	0.311	0.239	0.083	0.322
	Average 1 and 3	0.323	0.181	0.151	0.332	0.546	0.655	0.312	0.237	0.075	0.311
	Average 2 and 4	0.273	0.207	0.127	0.334	0.620	0.607	0.311	0.232	0.085	0.317
UB-12	1	0.340	0.176	0.160	0.336	0.523	0.676	0.302	0.271	0.074	0.345
	2	0.295	0.193	0.140	0.333	0.581	0.628	0.292	0.205	0.085	0.290

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h_1 (inches)	h_2 (inches)	h (inches)
	3	0.291	0.192	0.154	0.346	0.556	0.637	0.297	0.206	0.081	0.286
	4	0.263	0.157	0.169	0.326	0.482	0.589	0.283	0.225	0.082	0.307
	Average 1 and 3	0.316	0.184	0.157	0.341	0.540	0.657	0.300	0.238	0.077	0.316
	Average 2 and 4	0.279	0.175	0.154	0.329	0.531	0.608	0.288	0.215	0.083	0.298
UB-13	1	0.343	0.148	0.186	0.334	0.444	0.677	0.270	0.212	0.070	0.282
	2	0.300	0.228	0.107	0.335	0.679	0.635	0.326	0.234	0.085	0.319
	3	0.361	0.157	0.181	0.338	0.465	0.699	0.264	0.237	0.073	0.310
	4	0.311	0.205	0.126	0.331	0.620	0.642	0.300	0.214	0.083	0.296
	Average 1 and 3	0.352	0.153	0.183	0.336	0.454	0.688	0.267	0.224	0.072	0.296
	Average 2 and 4	0.305	0.216	0.117	0.333	0.650	0.638	0.313	0.224	0.084	0.308
UB-14	1	0.307	0.218	0.120	0.338	0.644	0.645	0.306	0.222	0.094	0.315
	2	0.342	0.215	0.122	0.336	0.638	0.678	0.304	0.207	0.078	0.285
	3	0.282	0.216	0.120	0.336	0.643	0.618	0.315	0.233	0.086	0.319
	4	0.342	0.187	0.143	0.330	0.567	0.672	0.292	0.225	0.077	0.302
	Average 1 and 3	0.295	0.217	0.120	0.337	0.644	0.632	0.310	0.227	0.090	0.317
	Average 2 and 4	0.342	0.201	0.132	0.333	0.603	0.675	0.298	0.216	0.078	0.294
UB-15	1	0.318	0.243	0.089	0.333	0.731	0.650	0.339	0.267	0.076	0.343
	2	0.275	0.198	0.146	0.344	0.577	0.619	0.316	0.227	0.087	0.314
	3	0.343	0.187	0.143	0.330	0.567	0.673	0.290	0.213	0.077	0.290
	4	0.295	0.204	0.132	0.336	0.607	0.631	0.310	0.243	0.081	0.324
	Average 1 and 3	0.330	0.215	0.116	0.331	0.649	0.662	0.314	0.240	0.077	0.317
	Average 2 and 4	0.285	0.201	0.139	0.340	0.592	0.625	0.313	0.235	0.084	0.319
UB-16	1	0.268	0.188	0.148	0.336	0.559	0.604	0.315	0.252	0.083	0.335

Specimen	**Weld Location**	***d_1* (inches)**	***d_2* (inches)**	***d_3* (inches)**	***d_4* (inches)**	***d_2/d_4***	***d_5* (inches)**	***t* (inches)**	***h_1* (inches)**	***h_2* (inches)**	***h* (inches)**
	2	0.311	0.165	0.176	0.341	0.485	0.652	0.299	0.220	0.080	0.300
	3	0.254	0.199	0.139	0.339	0.588	0.593	0.298	0.310	0.083	0.393
	4	0.420	0.168	0.176	0.344	0.489	0.764	0.316	0.295	0.082	0.377
	Average 1 and 3	0.261	0.194	0.144	0.337	0.574	0.599	0.306	0.281	0.083	0.364
	Average 2 and 4	0.365	0.167	0.176	0.342	0.487	0.708	0.307	0.257	0.081	0.339
Average	1 and 3	0.284	0.212	0.122	0.334	0.639	0.601	0.321	0.257	0.080	0.337
	2 and 4	0.317	0.191	0.141	0.333	0.575	0.649	0.300	0.233	0.082	0.315
	All	0.300	0.202	0.131	0.333	0.607	0.625	0.311	0.245	0.081	0.326
Standard Deviation	1 and 3	0.034	0.026	0.027	0.008	0.079	0.079	0.021	0.030	0.007	0.032
	2 and 4	0.033	0.024	0.023	0.004	0.070	0.033	0.017	0.018	0.003	0.019
	All	0.037	0.027	0.026	0.006	0.080	0.064	0.022	0.027	0.005	0.028

Table 30. Weld dimensions of W series.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h (inches)
W-1	1	0.432	0.092	0.232	0.325	0.283	0.757	0.220	0.319
	2	0.318	0.122	0.197	0.319	0.382	0.637	0.304	0.382
	3	0.401	0.106	0.219	0.324	0.327	0.725	0.285	0.382
	4	0.394	0.087	0.233	0.320	0.272	0.714	0.298	0.385
	Average 1 and 3	0.417	0.099	0.226	0.325	0.305	0.741	0.253	0.351
	Average 2 and 4[a]	0.356	0.105	0.215	0.320	0.327	0.676	0.301	0.384
W-2	1	0.401	0.106	0.219	0.324	0.327	0.725	0.285	0.382
	2	0.394	0.087	0.233	0.320	0.272	0.714	0.298	0.385
	3	0.348	0.104	0.221	0.325	0.320	0.673	0.248	0.384
	4	0.388	0.125	0.197	0.323	0.387	0.711	0.291	0.331
	Average 1 and 3[a]	0.375	0.105	0.220	0.325	0.324	0.699	0.267	0.383
	Average 2 and 4	0.391	0.106	0.215	0.322	0.330	0.713	0.295	0.358
W-3	1	0.348	0.104	0.221	0.325	0.320	0.673	0.248	0.384
	2	0.388	0.125	0.197	0.323	0.387	0.711	0.291	0.331
	3	0.363	0.141	0.200	0.341	0.413	0.704	0.255	0.418
	4	0.365	0.141	0.189	0.330	0.427	0.694	0.298	0.323
	Average 1 and 3	0.356	0.123	0.211	0.333	0.367	0.689	0.252	0.401
	Average 2 and 4[a]	0.377	0.133	0.193	0.327	0.407	0.703	0.295	0.327
W-4	1	0.363	0.141	0.200	0.341	0.413	0.704	0.255	0.418
	2	0.365	0.141	0.189	0.330	0.427	0.694	0.298	0.323
	3	0.351	0.139	0.183	0.322	0.432	0.673	0.222	0.313
	4	0.386	0.101	0.205	0.306	0.330	0.692	0.263	0.452

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h (inches)
	Average 1 and 3[a]	0.357	0.140	0.192	0.332	0.423	0.689	0.239	0.366
	Average 2 and 4	0.376	0.121	0.197	0.318	0.379	0.693	0.281	0.388
W-5	1	0.351	0.139	0.183	0.322	0.432	0.673	0.222	0.313
	2	0.386	0.101	0.205	0.306	0.330	0.692	0.263	0.452
	3	0.361	0.122	0.206	0.328	0.372	0.689	0.225	0.334
	4	0.358	0.109	0.216	0.326	0.334	0.684	0.303	0.384
	Average 1 and 3	0.356	0.131	0.195	0.325	0.402	0.681	0.224	0.324
	Average 2 and 4[a]	0.372	0.105	0.211	0.316	0.332	0.688	0.283	0.418
W-6	1	0.361	0.122	0.206	0.328	0.372	0.689	0.225	0.334
	2	0.358	0.109	0.216	0.326	0.334	0.684	0.303	0.384
	3	0.344	0.131	0.192	0.323	0.406	0.344	0.235	0.346
	4	0.401	0.144	0.194	0.339	0.425	0.740	0.290	0.330
	Average 1 and 3	0.353	0.127	0.199	0.326	0.389	0.517	0.230	0.340
	Average 2 and 4[a]	0.380	0.127	0.205	0.333	0.380	0.712	0.297	0.357
W-7	1	0.344	0.131	0.192	0.323	0.406	0.344	0.235	0.346
	2	0.401	0.144	0.194	0.339	0.425	0.740	0.290	0.330
	3	0.375	0.171	0.145	0.316	0.541	0.691	0.303	0.325
	4	0.363	0.150	0.162	0.313	0.479	0.676	0.316	0.345
	Average 1 and 3[a]	0.360	0.151	0.169	0.320	0.474	0.518	0.269	0.336
	Average 2 and 4	0.382	0.147	0.178	0.326	0.452	0.708	0.303	0.338
W-8	1	0.375	0.171	0.145	0.316	0.541	0.691	0.303	0.325
	2	0.363	0.150	0.162	0.313	0.479	0.676	0.316	0.345
	3	0.358	0.130	0.206	0.335	0.388	0.693	0.236	0.363

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h (inches)
	4	0.357	0.141	0.186	0.326	0.433	0.683	0.296	0.335
	Average 1 and 3	0.367	0.151	0.176	0.326	0.465	0.692	0.270	0.344
	Average 2 and 4[a]	0.360	0.146	0.174	0.320	0.456	0.680	0.306	0.340
W-9	1	0.358	0.130	0.206	0.335	0.388	0.693	0.236	0.363
	2	0.357	0.141	0.186	0.326	0.433	0.683	0.296	0.335
	3	0.369	0.110	0.210	0.320	0.344	0.690	0.288	0.369
	4	0.359	0.137	0.188	0.326	0.420	0.685	0.290	0.339
	Average 1 and 3[a]	0.364	0.120	0.208	0.328	0.366	0.692	0.262	0.366
	Average 2 and 4	0.358	0.139	0.187	0.326	0.427	0.684	0.293	0.337
W-10	1	0.369	0.110	0.210	0.320	0.344	0.690	0.288	0.369
	2	0.359	0.137	0.188	0.326	0.420	0.685	0.290	0.339
	3	0.344	0.122	0.196	0.318	0.384	0.663	0.279	0.329
	4	0.381	0.149	0.192	0.341	0.437	0.721	0.302	0.355
	Average 1 and 3[a]	0.357	0.116	0.203	0.319	0.364	0.677	0.284	0.349
	Average 2 and 4	0.370	0.143	0.190	0.334	0.429	0.703	0.296	0.347
W-11	1	0.344	0.122	0.196	0.318	0.384	0.663	0.279	0.329
	2	0.381	0.149	0.192	0.341	0.437	0.721	0.302	0.355
	3	0.361	0.130	0.198	0.329	0.395	0.690	0.288	0.342
	4	0.379	0.084	0.237	0.322	0.261	0.701	0.280	0.371
	Average 1 and 3	0.353	0.126	0.197	0.324	0.390	0.677	0.284	0.336
	Average 2 and 4[a]	0.380	0.117	0.215	0.332	0.349	0.711	0.291	0.363
W-12	1	0.361	0.130	0.198	0.329	0.395	0.690	0.288	0.342
	2	0.379	0.084	0.237	0.322	0.261	0.701	0.280	0.371

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h (inches)
	3	0.381	0.132	0.189	0.322	0.410	0.702	0.298	0.387
	4	0.330	0.174	0.150	0.324	0.537	0.654	0.311	0.347
	Average 1 and 3[a]	0.371	0.131	0.194	0.326	0.403	0.696	0.293	0.365
	Average 2 and 4	0.355	0.129	0.194	0.323	0.399	0.678	0.296	0.359
W-13	1	0.381	0.132	0.189	0.322	0.410	0.702	0.298	0.387
	2	0.330	0.174	0.150	0.324	0.537	0.654	0.311	0.347
	3	0.396	0.096	0.228	0.324	0.296	0.720	0.301	0.386
	4	0.361	0.132	0.203	0.336	0.393	0.697	0.312	0.385
	Average 1 and 3	0.389	0.114	0.209	0.323	0.353	0.711	0.300	0.387
	Average 2 and 4[a]	0.346	0.153	0.177	0.330	0.465	0.676	0.312	0.366
W-14	1	0.396	0.096	0.228	0.324	0.296	0.720	0.301	0.386
	2	0.361	0.132	0.203	0.336	0.393	0.697	0.312	0.385
	3	0.378	0.108	0.217	0.325	0.332	0.704	0.287	0.341
	4	0.292	0.119	0.202	0.322	0.370	0.614	0.297	0.376
	Average 1 and 3[a]	0.387	0.102	0.223	0.325	0.314	0.712	0.294	0.364
	Average 2 and 4	0.327	0.126	0.203	0.329	0.382	0.656	0.305	0.381
W-15	1	0.378	0.108	0.217	0.325	0.332	0.704	0.287	0.341
	2	0.292	0.119	0.202	0.322	0.370	0.614	0.297	0.376
	3	0.362	0.072	0.236	0.307	.235	0.670	0.268	0.355
	4	0.357	0.128	0.192	0.320	0.400	0.677	0.280	0.338
	Average 1 and 3	0.370	0.090	0.227	0.316	0.284	0.687	0.278	0.348
	Average 2 and 4[a]	0.325	0.124	0.197	0.321	0.385	0.646	0.289	0.357
W-16	1	0.362	0.072	0.236	0.307	.235	0.670	0.268	0.355

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_3 (inches)	d_4 (inches)	d_2/d_4	d_5 (inches)	t (inches)	h (inches)
	2	0.357	0.128	0.192	0.320	0.400	0.677	0.280	0.338
Average	1 and 3	0.368	0.120	0.204	0.324	0.370	0.672	0.266	0.357
	2 and 4	0.363	0.128	0.196	0.325	0.393	0.688	0.295	0.360
	All	0.366	0.124	0.200	0.324	0.382	0.680	0.281	0.359
Standard Deviation	1 and 3	0.021	0.023	0.022	0.008	0.070	0.090	0.029	0.029
	2 and 4	0.028	0.024	0.022	0.009	0.071	0.030	0.013	0.033
	All	0.024	0.024	0.022	0.008	0.071	0.067	0.027	0.031

[a]Used to denote side the fatigue failure occurred on.

APPENDIX C. LASER WELD DIMENSIONS

This appendix presents the data associated with measurements of some of the laser panel specimens. The original intent of etching the welds was to confirm the weld penetration, and, after etching so many laser welded specimens, it was clear that it consistently attained 100 percent or more penetration, and further documentation of weld cross sections ceased. Later in the research program, it was found the dimensions of the weld were relevant to fatigue life; however, only a few of the weld cross sections were photo documented, and the data in this appendix may appear incomplete. Only one face of the laser panel specimens was etched. The weld location syntax used in table 31 is shown in figure 65. Location 1 represents the side with the dominant fatigue crack size because sometimes both welds cracked simultaneously. The remaining column headings in table 31 present the measurements recorded as shown in figure 66.

Because the laser was able to achieve full penetration, there is no definition for the weld throat as there was for the conventional weld processes. To be able to introduce the weld throat dimension in the multiple linear regression statistical analysis, a throat dimension had to be defined for the laser specimens. For this work and for just the laser specimens, the actual throat dimension was taken from the toe of the root reinforcement to the outside of the face weld in a direction aligned with the thickness direction of the rib wall.

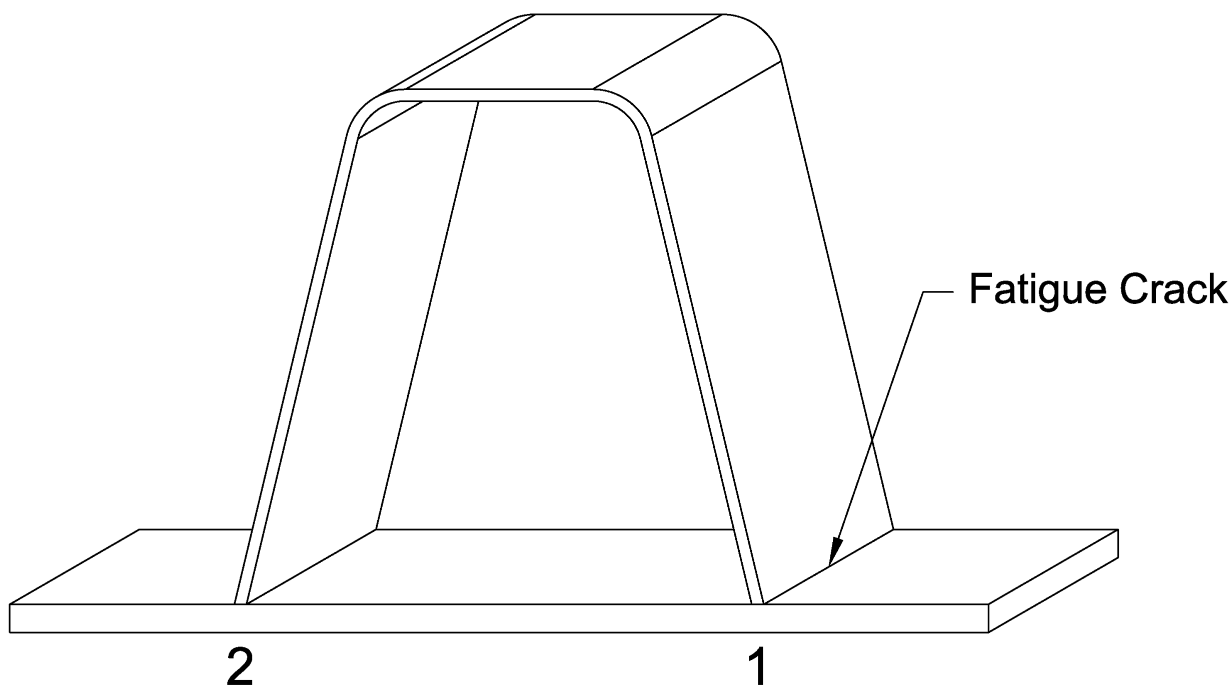


Figure 65. Schematic. Denotation of weld locations for laser panel specimens.

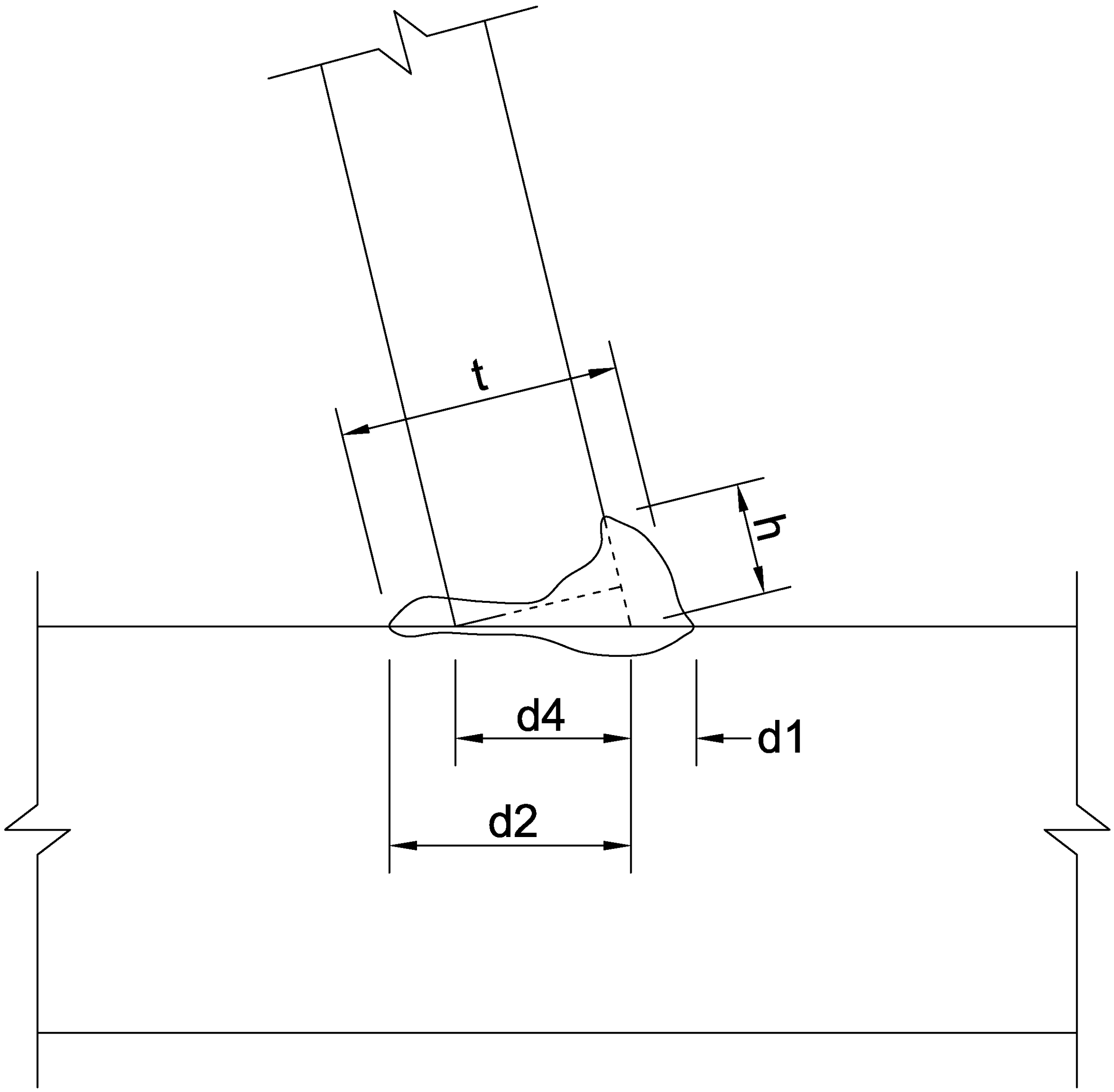


Figure 66. Schematic. Measured dimensions for laser panel specimens.

Where:

d1 = Weld length along the deck plate.
d2 = Weld penetration.
d4 = Projected width of rib on deck plate.
d2/d4 = Percentage of the weld penetration.
t = Actual weld throat measured from the toe of the root reinforcement to the face of the weld aligned in the thickness direction of the rib wall.
h = Weld length along the rib plate.

Table 31. Weld dimensions of some LP series specimens.

Specimen	Weld Location	d_1 (inches)	d_2 (inches)	d_4 (inches)	d_2/d_4	t (inches)	h (inches)
LP1-1	1	0.109	0.454	0.322	1.410	0.543	0.207
	2	0.112	0.392	0.323	1.214	0.450	0.199
LP1-2	1	0.099	0.366	0.322	1.137	0.448	0.206
	2	0.120	0.424	0.322	1.317	0.495	0.174
LP1-3	1	0.100	0.377	0.317	1.189	0.450	0.178
	2	0.119	0.433	0.323	1.341	0.471	0.164
LP1-4	1	0.142	0.394	0.321	1.227	0.470	0.187
	2	0.091	0.419	0.324	1.293	0.485	0.192
LP1-5	1	0.097	0.409	0.317	1.290	0.487	0.192
	2	0.110	0.476	0.320	1.488	0.539	0.200
LP1-6	1	0.142	0.432	0.317	1.363	0.515	0.223
	2	0.107	0.467	0.317	1.473	0.519	0.215
LP1-7	1	0.106	0.429	0.318	1.349	0.478	0.190
	2	0.128	0.432	0.322	1.342	0.494	0.192
LP3-1	1	0.143	0.325	0.325	1.000	0.436	0.195
	2	0.138	0.315	0.315	1.000	0.427	0.211
LP3-2	1	0.127	0.382	0.322	1.186	0.481	0.185
	2	0.135	0.409	0.320	1.278	0.502	0.198
LP3-6	1	0.160	0.400	0.320	1.250	0.495	0.214
	2	0.120	0.404	0.320	1.263	0.497	0.203

REFERENCES

1. Sedlacek, G. (1992). “Orthotropic Plate Bridge Decks,” *Constructional Steel Design—An International Guide*, Chapter 2.10, edited by Dowling, P.J., Harding, J.E., and Björhovde, R., pp. 227–245, Elsevier, Essex, England.

2. Mehue, P. (1981). “Steel Decks in Road Bridges,” *International Symposium on the Management of Civil Structures: Surveillance, Maintenance and Repair of Road and Railway Bridges* (translated), pp. 609–612, Paris, France.

3. Mehue, P. (1990). “Cracks in Steel Orthotropic Decks,” *Proceedings of the International Conference on Bridge Management*, pp. 633–642, Surrey, United Kingdom.

4. Mehue, P. (1992). “Repair Procedures for Cracks in Steel Orthotropic Decks,” *Proceedings of the 3rd International Workshop on Bridge Rehabilitation*, pp. 159–163, Darmstadt, Germany.

5. Burdekin, F.M. (1981). “Fatigue Cracks in Some Steel Bridges,” *International Symposium on the Management of Civil Structures: Surveillance, Maintenance and Repair of Road and Railway Bridges* (translated), pp. 163–167, Paris, France.

6. Leendertz, J.S. and Jong de, F.B.P. (2003). “Fatigue Aspects of Orthotropic Steel Decks,” *Proceedings of the Lightweight Bridge Decks: European Bridge Engineering Conference*, pp. 1–13, Rotterdam, The Netherlands.

7. AASHTO. (2007). *AASHTO LRFD Bridge Design Specifications*, Fourth Edition, American Association of State Highway and Transportation Officials, Washington, DC.

8. AASHTO. (2014). *AASHTO LRFD Bridge Design Specifications*, Seventh Edition, American Association of State Highway and Transportation Officials, Washington, DC.

9. Hobbacher, A. (2008). *Recommendations for Fatigue Design of Welded Joints and Components*, IIW Document IIW-1823-07, International Institute of Welding, Paris, France.

10. Connor, R.J. et al. (2012). *Manual for Design, Construction, and Maintenance of Orthotropic Steel Deck Bridges*, Report No. FHWA-IF-12-027, Federal Highway Administration. Washington, DC.

11. R Core Team. (2014). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, obtained from: http://www.R-project.org, last accessed June 1, 2016.

HRDI-40/02-17(WEB)E