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TEST TO DETERMINE MARGIN-TO-FAILURE FOR HY-100 STEEL WITH UNDERMATCHED WELDS

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ABSTRACT

This test program was undertaken to determine the flaw tolerance and to quantify the strength margin-to-failure of high yield strength steel fillet welded specimens. The tests demonstrate adequate margin-to-failure for HY-100 specimens fabricated with matched welding systems.

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SUMMARY

In the use of high yield (HY) steel materials in designs required to accommodate rapidly applied dynamic loads, the concern was raised where the possibility of decreased flaw tolerance and premature failure by unstable ductile tearing could limit their use. Tests were developed and conducted to demonstrate adequate margin-to-failure in HY-100 fillet and partial penetration welded structures. In addition, inelastic analytical predictions were performed to assess the accuracy of such predictive tools compared to actual test data. Results showed that adequate margin-to-failure exists when using matched welding systems.

INTRODUCTION

The objective of this test was to demonstrate adequate margin-to-failure in HY-100 fillet and partial penetration welded structures. This test was proposed to address the concern of premature structural failures in these types of materials due to ductile tearing instability or inadequate flaw tolerance. It was to ensure adequacy for structures fabricated from high yield (HY) strength materials containing these types of weld joints when elastic stress criteria limits for general membrane stress of $1.0 S_u$ and membrane-plus-bending stress limits of $2.0 S_u$ are applied. The S_u value used in determining the criteria limits is the minimum ultimate tensile stress. Adequate margin in HY-100 automatically qualifies lower strength carbon steel materials.

Fillet and partial penetration weld joints are considered most susceptible to the types of premature failures considered by this test, due to inherent lack of fusion provided by the nature of the weld joint. Unstable ductile tearing is a material failure in a ductile manner that occurs at lower than expected strain levels. Certain types of metal are known to be susceptible to this phenomena. However, HY steel is not considered susceptible to this type of failure. The test was performed, as a safeguard, to document that premature ductile tearing would not occur due to the high yield strength and low ultimate-to-yield strength ratio of all types of HY material.

Premature failure in fillet welded joints due to inadequate flaw tolerance (i.e., the presence of an inherent discontinuity in the weld joint) was also investigated. To ensure that the stress concentration in the structural joint due to a lack of weld fusion would be present in some of the test specimens, half of the test samples had purposely induced flaws at the root of the fillet weld. Thus, if all specimens were tested to failure, and the strain level at which failure occurred is higher than the applicable acceptance criteria level, adequacy would be demonstrated.

Strength and toughness for HY-100 weldments are controllable, to an extent, by both the type of welding process used and the welding parameters specified. Production welding of HY-100 fillet and partial penetration joints generally utilize either of two processes; gas metal arc welding (GMAW) (wire) or shielded metal arc welding (SMAW) (electrode). Welding procedures for HY-100 steel are engineered to result in acceptable weld metal tensile and toughness properties. Using the lower ends of the preheat temperature and welding heat input ranges specified in a given procedure tends to maximize the weld metal yield strength. Similarly, using the upper ends of the preheat temperature and heat input ranges tends to minimize the weldment yield strength. In addition, vendor certification reports were examined to identify filler wire and electrode lots which possessed rich and lean chemical compositions; rich or lean being defined, respectively, as the highest or lowest concentration of major alloying elements. For HY-100 weld metal, there is no clear correlation between weld metal toughness and welding procedure variables within the range specified in typical welding procedures. It was, however, desired to minimize the weld metal toughness as much as possible while staying within the limits of the existing typical welding procedures. In addition, it was desired to deposit weld metal with yield strengths at the extremes of that expected to be produced using existing procedures. This resulted in the selection of fabricated test specimens per the test matrix shown in Table 1.

Static testing presents a conservative, lower bound load application for assessing the structural effects of dynamic loading conditions. Static test loads were applied to all specimens to induce a combined axial plus bending stress in each test specimen. The combined loading was a result of the built-in offset of the test specimen load pin locations, as described further in this report, combined with the direct load itself. The targeted ratio of half bending, half axial load in the test specimen mid-plate location produced the worst case allowable stress condition on both the outer fiber ($2.0 S_u$) and mid plane ($1.0 S_u$). This is based on the stress criteria limits where S_u is the ultimate stress value for the material. Test specimens were designed such that the maximum stress occurred at the fillet weld, since induced flaws were located at the weld root. Testing four specimens for each condition was considered to be adequate since the intent of the test was to establish proof-of-principle, not to provide a statistical sample to form a design basis.

The margin-to-failure values, as documented in this report, were determined by dividing the measured maximum strain by the measured strain at the design load of 108.1 kips. This design load was associated with the

largest stress allowable permitted by the above stated elastic criteria. A detailed description of the derivation of this design load is provided in the following sections of this report.

TABLE 1 Test Assembly Fabrication

WELD PROCESS	ELECTRODE CHEMISTRY	WELDING POSITION	HEAT INPUT, PREHEAT	DESIRED STRENGTH
SGMAW	LEAN	HORIZ FILLET	HIGH	LOW
PGMAW	RICH	VERT	LOW	HIGH
SMAW	LEAN	HORIZ FILLET	HIGH	LOW
SMAW	RICH	HORIZ FILLET	LOW	HIGH

Where: SGMAW - Gas metal arc welding process - spray
PGMAW - Gas metal arc welding process - pulse
SMAW - Shielded metal arc welding process

METHODS, ASSUMPTIONS AND PROCEDURES

Specimen Fabrication

Two sets of test assemblies were fabricated. One set of plates was welded with a matched system, where the weld metal was of comparable strength to the base plate material. The other was welded with an undermatched system, where the weld metal was of a lesser strength than the base plate material. The set of matched yield strength (100 ksi minimum) assemblies used MIL-120S-1 filler wire and MIL-12018-M2 electrode. The set of undermatched yield strength (82 ksi minimum) assemblies used MIL-100S-1 filler wire and MIL-11018-M electrode. For each of the two sets, four test assemblies were welded in accordance with the matrix presented in Table 1. This resulted in a total of eight assemblies representing eight unique test conditions.

The test assembly was fabricated as follows. A 1.00 inch thick plate (30 inches x 8 inches) was partially machined to the required 0.80 inch thickness. A portion of the plate was left at the full thickness with the edge beveled for a full penetration weld. This plate was fillet welded to a 2.00 inch base plate, as illustrated in Figure 1, to form the assembly.

FIGURE 1 Test Plate Assemblies

Eight test assemblies were produced for the four sets of welding parameters from Table 1 for both matched and undermatched welding processes. Test specimens, 1.5 inches in width, were next cut ("sliced") from sections of

each assembly in a manner to avoid welding end effects (i.e., the ends of the test plate were cut off and discarded). In order to provide a weld surface in the as-deposited condition and minimize overwelding, the next-to-last weld layer was ground back prior to the final weld pass, when required. Maintaining an as-deposited weld surface finish allowed any effects from surface irregularities, that could exist in production, to participate in the outcome of the test. Minimizing overwelding provided a weld as close to 100 percent efficient as possible and eliminated any reserve strength that overwelding would provide.

Weld metal tensile specimens per ASTM E8, Small-Size (0.113 inch nominal diameter), were taken from each of the fillet welds. These were tested to determine as-deposited mechanical properties of the fillet welds. Results of these all-weld-metal tensile tests are included in Appendix 1.

Ten test specimens were cut from each of the eight test assemblies. Five were from the area of the test assembly where it was purposely attempted to produce lack-of-penetration at the root, and five were from the area where normal welding techniques were used. Each specimen was machined to the final 1.5 inch width. Both faces transverse to the weld were polished, etched, and examined for root penetration and the presence of defects. Selected test specimen examination photographs are included in Appendix 2. For each test assembly, two specimens with zero or minimal lack-of-penetration or other defects were selected, and two specimens with lack-of-penetration/defects were selected. In the latter case, specimens with the largest visible deficiencies were selected.

For the GMAW process, spray transfer (SGMAW) was used in the horizontal fillet position at the high end of both the preheat and heat input ranges (slow cooling rates) specified in the applicable welding procedure to produce weld metal with the minimum expected yield strength for the subject joint. Horizontal position spray GMAW was chosen over vertical position pulsed GMAW (PGMAW) because extensive experience has consistently shown that horizontal SGMAW produces weld metal with lower toughness than vertical position PGMAW when using slow cooling rate welding conditions. MIL-120S-1 and MIL-100S-1 filler wire vendor certification reports were examined to locate and use the heats with the leanest (lowest concentration of major alloying elements) chemical compositions among the heats in stock. This tends to minimize strength as much as possible. Of the heats examined, filler wire carbon content was the major difference in alloy content between rich and lean heats of a given electrode type. Considering the normal variations in chemical analysis results encountered when determining electrode composition over a large heat size, the differences between the heats selected as rich and lean were minimal.

Pulsed GMAW (PGMAW) was selected for use in the vertical position using low heat input/low preheat (fast cooling rate) conditions within the applicable welding procedure in combination with filler wire with a rich chemical composition to maximize the yield strength. Vertical PGMAW was selected over horizontal SGMAW to minimize the weld metal toughness. This was based on extensive characterization of gas metal arc weld metal properties performed to date.

For the shielded metal arc welding (SMAW) process, 0.1563 inch diameter electrodes were used in the horizontal fillet position to deposit welds using fast and slow cooling rate conditions within the applicable welding procedures. For MIL-12018 electrode, only the 0.1563 inch diameter size is qualified for thicknesses below 1.0 inch in existing weld procedures. In addition, 0.1563 inch diameter MIL-12018 electrodes are qualified only for use in the flat or horizontal positions. Therefore, the choice for electrode diameter and position was limited. As was done for the assemblies welded using the gas metal arc process, lean chemical composition electrode lots were coupled with the slow cooling rate welds in an attempt to minimize weld metal yield strengths. Rich chemical composition electrodes lots were therefore used with the fast cooling rate assemblies to maximize the weld metal yield strength as much as possible. As reported by the electrode manufacturers, the rich lot of MIL-12018-M2 electrodes had slightly higher carbon, manganese, and nickel compared to the lean lot. The rich lot of MIL-11018-M electrodes was slightly higher in carbon. In both cases, the reported differences were minimal. Table 2 summarizes the test assemblies fabricated and the nominal conditions used.

Welding was accomplished to induce incomplete penetration at the root area over half the length of each test weld. This was done by using unconventional electrode and torch angles, by increasing the arc length, and by directing the arc against the root to reduce the chances for full root fusion. Over the other half of the assembly, normal welding was accomplished on the root pass. Fillet welds of approximately 0.5625 inch were produced. Considering that two different root pass techniques were used on each assembly, a total of sixteen different test conditions were available for evaluation.

A test member thickness of 0.80 inches results in the weld being 100 percent efficient for the matched welding condition. As a precaution, to ensure maximum stress at the fillet weld, the plate member at the upper full penetration weld was tapered to 1.00 inch thick. Top and bottom lug plates were then welded to the flawed and unflawed specimens selected for testing, as illustrated in Figure 2.

A 200K Tinius-Olsen Universal testing machine was used in all testing. Since this test machine is not capable of handling any loading that is not axial, the load was applied to the test specimen with a clevis-pin arrangement. This connection design maintained an axial load on the specimen while allowing specimen rotation as a result of the specimen centerline offset with respect to the load. In order to enable free rotation, the pin was fitted within the test specimen lug with a 0.004 - 0.008 inch clearance on the radius. This tight fit reduced the point loading that may locally deform the lug hole and provided increased bearing surface for a high bearing capacity (500 ksi) molybdenum disulfide lubricant to act. A 63 root-mean-squared minimum surface finish on both the pin and lug hole minimized the asperate protrusion through the lubricant film. A pretest analytical study was performed to ensure that free pin rotation under load would occur.

TABLE 2 Specimen Type and Identification Number

MATERIAL	MARK NUMBER	WELD ELECTRODE	WELD PROCESS	WELDING POSITION	PRE / INT TEMP (°F)	HEAT INPUT (kJ/in)
HY-100	PD20719	MIL-120S-1	SGMAW	HORIZ FILLET	250 / 275	51.2
HY-100	PD20741	MIL-120S-1	PGMAW	VERT	225 / 250	33.0
HY-100	PD20743	MIL-12018	SMAW	HORIZ FILLET	275 / 300	44.3
HY-100	PD20745	MIL-12018	SMAW	HORIZ FILLET	225 / 225	30.7
HY-100 (u)	PD20720	MIL-100S-1	SGMAW	HORIZ FILLET	250 / 275	54.9
HY-100 (u)	PD20734	MIL-100S-1	PGMAW	VERT	150 / 175	26.3
HY-100 (u)	PD20744	MIL-11018	SMAW	HORIZ FILLET	275 / 300	53.5
HY-100 (u)	PD20746	MIL-11018	SMAW	HORIZ FILLET	225 / 225	30.0

Where:

MATERIAL - Plate, weld material type

HY-100 - HY-100 base plate welded with HY-100 weld metal

HY-100 (u) - HY-100 base plate welded with HY-80 (undermatched) weld metal

MARK NUMBER - Test plate identification number, stamped on each specimen

WELD ELECTRODE - Welding electrode type

WELD PROCESS

SGMAW - Spray gas metal arc welding process

PGMAW - Pulse gas metal arc welding process

SMAW - Shielded metal arc welding process

WELDING POSITION - Related to the orientation of the welding torch or rod and specimen

PRE/INT - Preheat and interpass temperature

HEAT INPUT - Nominal heat input - kJ/in

Test Procedure

Prior to testing, a procedure was determined to ensure that all testing was performed in a similar manner. It required that pretest measurements were recorded and that low level loading was applied to the specimen to verify proper working of the sensors and recording instrumentation.

The following sequence applied for all testing:

1. Measure and record the overall length and the as-fabricated dimensions of the test specimen.
2. Secure the ends of the test specimen with the clevis pins. Attach instrumentation to strain and displacement gages.
3. Load the test specimen to 40,000 lb (60 percent yield) three times, and unload.
4. Apply continuous load at a rate of approximately 0.025 in/in/min until failure of the specimen. Sample and record data at a rate of four readings per second.

FIGURE 2 Test Specimen Setup

Instrumentation

A digital data recording system was used to record load, strain, and displacement data. The data was recorded on the system hard drive and transferred to a floppy disk upon conclusion of the test. Strains were measured by high elongation strain gages with a range for static loading of 0-15 percent. Gages were type EP-08-050SB-120 manufactured by Micro Measurement. The Tinius-Olsen machine is equipped with a torque bar weighing system to measure all loads. Load was recorded on a strip chart produced by the test machine and by the data recorder used during the test.

Two different types of potentiometers were used to measure displacement. During initial testing, a Celesco Position/Displacement Transducer ("Yo-Yo" pot) was used but was found to provide inadequate readings for low values of displacement, such as that occurring for the elastic portion of specimen displacement. Displacement data obtained by this sensor for the test portion where significant plastic deformation occurred was acceptable. The "Yo-Yo" pot potentiometer (See Figure 3) consists of a cable which, when extended, produces a change in signal which can be calibrated to measure distance. In use, the potentiometer is attached to one end of the specimen and the extendible cable is attached to the other end by a small machine screw. All the specimens were tested utilizing this approach. Upon completion of the first eight specimens and subsequent data review, it was noted that there were anomalies in the displacement data at very low values (less than 0.05 inches) for some of the specimens. Since the design displacement which produces the targeted membrane-bending ratio (0.027 inches) is in this range, an additional method of measuring the relative displacement was added to the remaining test specimens.

A Kaman sensor was added to the opposite side of the test specimen as shown in Figure 3. This sensor measures the change in the field strength between the aluminum brackets shown, and converts this value to a

change in displacement reading as the brackets are separated. While providing a more sensitive means of measuring the relative displacement across the specimen, the use of the Kaman sensor was not without problems. When the specimen rotated, it caused the brackets to rotate resulting in a non-constant variation in the gap across the field. While this rotation was very small, the effects on measuring the change in displacements at low values (less than 0.05 inches) was significant enough to cause variation in the recorded data. Both measuring devices were utilized, however, for the remaining specimens in order that displacement data above 0.05 inches could be accurately recorded. A reliable means of measuring the pure vertical motion of the specimen at values less than 0.05 inches was not found.

FIGURE 3 Potentiometer Setup

Two initial test specimens (one matched, one undermatched) without induced flaws, were fully instrumented with 11 strain gages as shown in Figure 4. This level of instrumentation was selected to ensure that sufficient information was available for the initial part of the test sequence to verify test parameters, methods, and specimen design. The remaining specimens were instrumented with four strain gages as shown in Figure 5. This level of instrumentation was sufficient to monitor the balance of axial versus bending load as well as any load imbalances, such as strong axis bending of the specimen, while reducing testing costs. The 11 gage specimens permitted direct calculation of margins-to-failure near the weld location as well as at the mid-plate locations. For the remaining specimens, direct calculation of the margin-to-failure values were limited to the mid-plate area. Extrapolation of test results to the weld area was possible for these specimens.

The Tinius-Olsen test machine was periodically calibrated and certified. Calibration was in accordance with ASTM E4. Verification of certifying devices complied with ASTM E74. Certification of other instrumentation used in the test was maintained by the testing laboratory. All certifying devices were traceable to the National Institute of Standards and Technology.

FIGURE 4 Strain Gage Setup - 11 Gage Setup

FIGURE 5 Strain Gage Setup - 4 Gage Setup

ANALYTICAL MODEL AND DETERMINATION OF STRAIN AT DESIGN LOAD LIMIT

Finite Element Model Development

In order to determine the design strain condition, a finite element model of the HY-100 ductile tear specimen was constructed. The model, Figure 6, consisted of the 8.0 inch long test specimen, test fillet weld and top and bottom lug plates that were used to transfer the loading to the specimen. A clevis lubricated pin connection, not explicitly modeled, was used to connect the lug plates to the Tinius-Olsen test machine. The model utilized eight node incompatible mode solid elements to model the specimen and weld. This formulation eliminated the parasitic shear stress normally associated with lower order solid elements that are too stiff in bending. The incompatible mode elements are as capable in modeling bending response as higher-order 20 node quadratic elements, but can do so at reduced cost. Portions of the top and bottom lugs were modeled with solids and then transitioned to shell elements away from the areas of concern. Appropriate Multipoint Constraint (MPC) equations were used to connect the solid elements to the shell elements.

FIGURE 6 Finite Element Model of HY-100 Ductile Tear Specimen

The model was loaded with a parabolic load distribution applied at the top and bottom pin hole locations. An elastic analysis, using Reference (a), was performed to determine the relative displacement across the 8.0 inch test specimen for the design stress condition of $2.0 S_u$. This relative displacement was determined in order that the strain associated with this pseudo-elastic design condition could be obtained from actual test data or inelastic finite element analyses. The latter was simply accomplished by including nonlinear material properties as determined in Reference (b) in the model, and repeating the loading analysis to a level that caused a relative displacement across the specimen equal to that of the elastic analysis. To obtain test design strains, continuous measurements of relative displacement and strain were recorded. The test relative displacement that matched the elastic displacement determined the design strain value.

Calculation Procedure for Margin-to-Failure

The margin-to-failure for the tested specimens was calculated as follows :

1. To determine the strain at the design load, an elastic finite element model was loaded such that the membrane plus bending stress at the extreme fiber of the mid-plate height was at the previously stated elastic criteria limit of $2.0 S_u$. In addition, the specimen's 0.13 inch offset was such that the membrane stress was at the criteria limit of $1.0 S_u$, resulting in a nominal 50 percent bending, 50 percent membrane loading condition. The relative displacement (δ) across the 8.0 inch test specimen was determined to be 0.027 inches.
2. A nonlinear finite element model with as-tested base metal material properties was loaded to attain the relative displacement (δ) determined from the elastic model. The applied load (P) for a 0.027 inch relative displacement was 108.1 kips. Associated mid-plate axial design strain (ϵ_{md}) was 0.49 percent with strain at the weld strain gage location (ϵ_{wd}) determined to be 0.69 percent. Reported strains are from the tension side of the test specimen.
3. Each test specimen was loaded to failure. The resulting relative displacement (δ), load (P) and measured strains at the specimen mid-plate height (ϵ_{mt}) and near the weld location (ϵ_w) were recorded, when available.
4. The margin-to-failure was determined by dividing the maximum test strain prior to failure (ϵ_{mf}) by the design strain at the specimen mid-plate height on the tension side of the member. The tension side of the specimen is the side of maximum stress. Two of the specimens had additional instrumentation near the fillet weld connection. For these specimens, additional margin-to-failure ratios based on the strains near the welds were also calculated. For all specimens, several approaches were used to determine the design strain as listed below;

APPROACH	TYPE	DESCRIPTION
a	DISPLACEMENT	The design strain is the test strain value at the test relative displacement value of 0.027 in.
b	LOAD	The design strain is the test strain value at the test load of 108.1 kips as determined from an inelastic finite element analysis.
c	ANALYSIS	The design strain is the analysis strain determined from the inelastic finite element analysis, ($\epsilon_{md} = 0.49\%$ or $\epsilon_{wd} = 0.69\%$) at a relative displacement of 0.027 inches.

The Displacement approach, Approach (a), utilized only test data to determine the margin-to-failure and relied only on an elastic finite element model to determine the design displacement of 0.027 inches. The design displacement, however, was quite small and in some instances proved to be difficult to consistently measure. A review of the test data for some specimens showed inconsistent load/displacement values for displacements near the design condition. Approach (b) used the load cell data to determine the design strain which was more reliable than the displacement data. The load, however, was determined from an inelastic analysis. Approach (c) relied solely on an analytically determined design strain. In most cases all three approaches determined consistent margin-to-failure values. For some specimens, however, Approach (a) determined significantly greater margin-to-failure ratios than the other two approaches due to inaccurate displacement measurements.

Criteria

The following criteria was developed prior to the test to judge whether results were acceptable. Specimen failure in excess of these limits will ensure that adequate safety margins exist.

The acceptability of the margin-to-failure results were assessed as follows :

1. Average strain ratio of 3.0 or greater for all unflawed specimens, and
2. Minimum strain ratio of 2.0 or greater for any flawed or unflawed specimen.

RESULTS AND DISCUSSION

Summaries of the results for matched and undermatched specimens are presented in Table 3. The margin-to-failure values reported in these tables were determined by dividing the failure strain by the design strain associated with the largest stress allowable permitted by elastic-based criteria. Margin-to-failure ratios presented in these tables are calculated using the Load approach, Approach (b). Margin-to-failure ratios show a declining trend from matched, unflawed specimens to undermatched, flawed specimens.

TABLE 3 Minimum and Average Margin-to-Failure

TYPE	TEST PLATE	WELD	MARGIN - TO - FAILURE	
			MINIMUM	AVERAGE
MATCHED UNFLAWED	PD20719	MIL-120S-1	6.6	17.2
	PD20741	MIL-120S-1	11.0	11.5
	PD20743	MIL-12018	19.9	26.5
	PD20745	MIL-12018	10.5	13.0
MATCHED FLAWED	PD20719	MIL-120S-1	4.6	6.5
	PD20741	MIL-120S-1	13.3	15.3
	PD20743	MIL-12018	21.6	25.1
	PD20745	MIL-12018	9.5	12.6
UNDER- MATCHED UNFLAWED	PD20720	MIL-100S-1	3.7	7.2
	PD20734	MIL-100S-1	17.0	17.0
	PD20744	MIL-11018	2.1	3.3
	PD20746	MIL-11018	8.4	9.4
UNDER- MATCHED FLAWED	PD20720	MIL-100S-1	1.7	3.8
	PD20734	MIL-100S-1	6.4	7.3
	PD20744	MIL-11018	2.8	5.5
	PD20746	MIL-11018	4.9	6.6

Results of maximum strain, load and displacement for matched specimens are summarized in Table 4. With two exceptions, all matched specimens failed in the base plate member by gross section yielding at an applied load of approximately 140 kips. For specimens that failed in the base plate, the maximum load (148.5 KIP) was reached with approximately 0.40 inches of displacement in the specimen and then dropped off to the point of fracture, which occurred at an average of 0.965 inches of total displacement. The measured strain value used in the margin-to-failure for all specimens where failure occurred in the base material was at least 4.51 percent (PD20745 DTS-4).

Post test examination indicated ductile tensile failure in those specimens where failure occurred in the base material. For specimens where failure occurred in the weld, a normal shear failure was evident.

The only matched specimens where failure occurred in the weld proper were specimens DISC and DTS-6, both from test plate PD20719. These specimens were intentionally flawed and welded with MIL-120S-1 electrode with high heat input and lean chemistry to minimize weld strength. Examination of the specimens after failure indicated significant lack-of-fusion running the length of the tension-side weld. The resulting margin-to-failure for both specimens, however, is well above the limit required by this test for acceptability. Both specimen welds failed at applied loads slightly over 130 kips. Both the load versus displacement and load versus strain curves, up to the point of fracture, were similar to the matched specimens which failed in the base material. Maximum displacement and maximum measured strain were considerably lower.

TABLE 4 Maximum Strain, Load, and Displacement - Matched Specimens

TYPE	TEST PLATE	SPECIMEN NUMBER	MAXIMUM STRAIN (%)	MAXIMUM LOAD (KIP)	MAXIMUM DISPL. (IN)	FAILURE	
						PLATE	WELD
MATCHED UNFLAWED	PD20719	DTS-2	10.9	148.5	0.989	X	
		DTS-3	8.82	139.0	0.990	X	
	PD20741	DTS-8	5.69	136.9	0.932	X	
		DTS-10	5.18	139.1	0.999	X	
	PD20743	DTS-1	15.12	143.6	0.996	X	
		DTS-5	8.67	140.4	0.953	X	
	PD20745	DTS-4	4.51	140.9	0.933	X	
		DTS-5	6.83	142.7	0.912	X	
MATCHED FLAWED	PD20719	DISC	2.27	130.5	0.144		X
		DTS-6	3.75	131.4	0.218		X
	PD20741	DTS-3	7.77	136.3	0.999	X	
		DTS-4	6.25	136.2	0.937	X	
	PD20743	DTS-7	9.55	133.6	0.956	X	
		DTS-9	11.17	142.0	0.969	X	
	PD20745	DTS-9	5.39	139.9	0.975	X	
		DTS-10	7.53	139.3	0.968	X	

Undermatched specimens, with one exception, failed in the fillet weld (Table 5). The average load and displacement at failure was 138.5 kips and 0.20 inches for unflawed (failure in weld only) and 132.5 kips and 0.17 inches for flawed for the undermatched specimens. A review of the loading path indicates the specimens failed at maximum load with no drop off in loading, as in the previous case. None of the specimens that failed in the weld reached the displacement level (0.40 inches) of matched specimens where the load peaked before dropping off. This indicates that the strain was concentrating in the fillet weld. Several of the undermatched specimens failed at loads in excess of 140 kips, resulting in margins considerably in excess of the acceptance limit. It should be noted that the average margin-to-failure was higher for undermatched specimens where the welding procedure used produced higher weld metal yield strengths.

Two specimens had low margin-to-failure, failing at low levels of strain, load, and displacement (PD20744 DTS-1 and PD20720 DTS-10). Both of these specimens failed with low (approximately 1.0 percent) strain values measured at the strain gage locations on the base material member. Failure occurred when the strength capacity of the weld was exceeded. Post test examination of the specimen indicated normal weld shear.

The only undermatched specimen that failed in the base material was PD20734 DTS-8. This specimen was initially tested to a load level of 134.0 kips. At this point, the test machine load stud threads failed. Upon repair of the test machine, the specimen was remounted and tested to failure. As a result of this load sequence, it is theorized that the weld was considerably strengthened by the work hardening of being loaded initially into the plastic range. This is evidenced by the fact that the specimen failed in the base material at a considerable load and displacement. A review of the load versus displacement plot indicated the load dropped off after attaining a maximum value, similar to the behavior of the matched specimens.

TABLE 5 Maximum Strain, Load, and Displacement - Undermatched Specimens

TYPE	TEST PLATE	SPECIMEN NUMBER	MAXIMUM STRAIN (%)	MAXIMUM LOAD (KIP)	MAXIMUM DISPL. (IN)	FAILURE	
						PLATE	WELD
UNDER - MATCHED UNFLAWED	PD20720	DTS-2	2.75	137.5	0.239		X
		DTS-5	5.37	143.0	0.360		X
	PD20734	DTS-8	2.61	134.0	0.163	X	
			7.16	142.1	0.906		
		DTS-10	3.09	143.3	0.133		X
	PD20744	DTS-1	0.95	128.2	0.072		X
		DTS-4	2.01	132.8	0.130		X
	PD20746	DTS-1	3.88	141.9	0.239		X
		DTS-4	4.60	143.5	0.223		X
UNDER - MATCHED FLAWED	PD20720	DTS-7	2.61	130.6	0.197		X
		DTS-10	0.88	123.0	0.146		X
	PD20734	DTS-3	3.40	137.0	0.195		X
		DTS-5	2.99	130.5	0.197		X
	PD20744	DTS-5	3.33	134.9	0.184		X
		DTS-7	1.25	127.8	0.083		X
		DTS-8	2.56	132.1	0.197		X
	PD20746	DTS-7	2.17	135.9	0.150		X
		DTS-8	4.15	141.1	0.222		X

Margin-to-Failure (MTF) Summary

Margin-to-failure values are summarized in Tables 6 and 7 for a matched weld configuration and Tables 8 and 9 for an undermatched weld configuration with averages and minimums calculated for each of the four weld process types. The three methods of computing the margin-to-failure, as detailed in the previous section, are presented for comparison. Unflawed and flawed averages and minimums are separated in order to assess the flaw tolerance of each of the configurations. If gages near the weld were present, they are included in the average and minimum values. Strain gages that had premature failure are not included in the calculation unless all the pertinent gages failed. This occurred several times at relatively large strains. For these limited cases, the largest strain recorded was used in the margin-to-failure calculations in order to minimize the skew of the results. In cases where both tensile gages failed prior to the specimen, a gage on the compression side of the specimen was used to estimate the failure strain. This was possible because, at strains above approximately 1.0 percent, the specimen is experiencing virtually an axial pull. In addition, this approach added a slight degree of conservatism to the MTF calculations.

TABLE 6 HY-100 Matched Weld Configuration - Average Margin-to-Failure

TEST PLATE SPECIMEN	TEST RUNS	FLAWED/ UNFLAWED	FILLER WIRE	PRE- HEAT (°F)	MTF DISPL.	MTF LOAD	MTF ANAL.
PD20719 DTS 2, 3	406 904	UNFLAWED	MIL 120S-1	250	17.6	17.2	15.9
PD20719 DISC, 6	604 804	FLAWED	MIL 120S-1	250	7.1	6.5	6.0
PD20741 DTS 10, 8	4204 5204*	UNFLAWED	MIL 120S-1	225	13.2	11.5	10.9
PD20741 DTS 4, 3	4104 5304	FLAWED	MIL 120S-1	225	18.2	15.3	14.4
PD20743 DTS 5, 1	2604 3005	UNFLAWED	MIL 12018	275	27.5	26.5	24.9
PD20743 DTS 7, 9	2505 2904	FLAWED	MIL 12018	275	23.8	25.1	20.9
PD20745 DTS 5, 4	6204 6304*	UNFLAWED	MIL 12018	225	12.3	13.0	11.6
PD20745 DTS 9, 10	5105 6404	FLAWED	MIL 12018	225	17.0	12.6	13.2
AVERAGE OF MATCHED SPECIMENS (UNFLAWED)					17.7	17.1	15.8
AVERAGE OF MATCHED SPECIMENS (FLAWED)					16.5	14.9	13.6
AVERAGE OF MATCHED SPECIMENS (ALL)					17.1	16.0	14.7

* All gages failed prior to specimen failure for Test Runs 5204 and 6304. These resulted in a lower average Margin-to-Failure (MTF) value due to the premature gage failure.

TABLE 7 HY-100 Matched Weld Configuration - Minimum Margin-to-Failure

TEST PLATE SPECIMEN	TEST RUNS	FLAWED/ UNFLAWED	FILLER WIRE	PRE- HEAT (°F)	MTF DISPL.	MTF LOAD	MTF ANAL.
PD20719 DTS 2, 3	406 904	UNFLAWED	MIL 120S-1	250	6.9	6.6	7.7
PD20719 DISC, 6	604* 804	FLAWED	MIL 120S-1	250	5.0	4.6	4.5
PD20741 DTS 10, 8	4204 5204**	UNFLAWED	MIL 120S-1	225	11.8	11.0	10.1
PD20741 DTS 4, 3	4104 5304	FLAWED	MIL 120S-1	225	17.4	13.3	12.8
PD20743 DTS 5, 1	2604 3005	UNFLAWED	MIL 12018	275	19.4	19.9	17.1
PD20743 DTS 7, 9	2505 2904	FLAWED	MIL 12018	275	23.2	21.6	18.9
PD20745 DTS 5, 4	6204 6304**	UNFLAWED	MIL 12018	225	10.0	10.5	9.2
PD20745 DTS 9, 10	5105 6404	FLAWED	MIL 12018	225	16.0	9.5	11.0

* Inappropriate sample selected for Test Run 604 (sample should have been discarded).

** All gages failed prior to specimen failure for Test Runs 5204 and 6304. These resulted in a lower minimum Margin-to-Failure (MTF) value due to the premature gage failure.

TABLE 8 HY-100 Undermatched Weld Configuration - Average Margin-to-Failure

TEST PLATE SPECIMEN	TEST RUNS	FLAWED/ UNFLAWED	FILLER WIRE	PRE- HEAT (°F)	MTF DISPL.	MTF LOAD	MTF ANAL.
PD20720 DTS 2, 5	506 704	UNFLAWED	MIL 100S-1	250	14.4	7.2	6.4
PD20720 DTS 10, 7	1004 1104	FLAWED	MIL 100S-1	250	4.7	3.8	3.5
PD20734 8 PD20731 10	2704, 3104 5400*	UNFLAWED	MIL 100S-1	150	16.3	17.0	14.6
PD20734 DTS 5, 3	2003 2304	FLAWED	MIL 100S-1	150	6.9	7.3	6.5
PD20744 DTS 1, 4	2405 4304	UNFLAWED	MIL 11018	275	3.1	3.3	2.9
PD20744 DTS 7, 5, 8	2103, 2204 2804**	FLAWED	MIL 11018	275	5.8	5.5	4.7
PD20746 DTS 1, 4	5004 6004	UNFLAWED	MIL 11018	225	9.2	9.4	8.4
PD20746 DTS 7, 8	4004 6104	FLAWED	MIL 11018	225	7.9	6.6	5.7
AVERAGE OF UNDERMATCHED SPECIMENS (UNFLAWED)					10.8	9.2	8.1
AVERAGE OF UNDERMATCHED SPECIMENS (FLAWED)					6.3	5.8	5.1
AVERAGE OF UNDERMATCHED SPECIMENS (ALL)					8.6	7.5	6.6

- * Test machine failed prior to specimen for Test Run 2704. Test Run 5400 is a continuation of the test. Test Run 3104 had a data recording error (disk) which caused an intermittent loss of data.
- ** Extra sample tested (33rd sample, Test Run 2804).

TABLE 9 HY-100 Undermatched Weld Configuration - Minimum Margin-to-Failure

TEST PLATE SPECIMEN	TEST RUNS	FLAWED/ UNFLAWED	FILLER WIRE	PRE- HEAT (°F)	MTF DISPL.	MTF LOAD	MTF ANAL.
PD20720 DTS 2, 5	506 704	UNFLAWED	MIL 100S-1	250	11.5	3.7	4.6
PD20720 DTS 10, 7	1004 1104	FLAWED	MIL 100S-1	250	2.7	1.7	1.5
PD20734 8 PD20731 10	2704, 3104 5400*	UNFLAWED	MIL 100S-1	150	16.3	17.0	14.6
PD20734 DTS 5, 3	2003 2304	FLAWED	MIL 100S-1	150	5.2	6.4	6.0
PD20744 DTS 1, 4	2405 4304	UNFLAWED	MIL 11018	275	1.8	2.1	1.9
PD20744 DTS 7, 5, 8	2103, 2204 2804**	FLAWED	MIL 11018	275	2.1	2.8	2.3
PD20746 DTS 1, 4	5004 6004	UNFLAWED	MIL 11018	225	8.0	8.4	7.9
PD20746 DTS 7, 8	4004 6104	FLAWED	MIL 11018	225	6.7	4.9	4.2

- * Test machine failed prior to specimen for Test Run 2704. Test Run 5400 is a continuation of the test. Test Run 3104 had a data recording error which caused an intermittent loss of data.
- ** Extra sample tested (33rd sample, Test Run 2804).

In addition to the premature gage failures, other anomalies occurred throughout the test series including a case of intermittent loss of recorded data due to a disk error, a test machine failure, and the selection of an inappropriately matched flawed sample. Margin-to-failure values for all specimens that possessed some testing problems were above 4.5, which is above the average required value of 3.0. Therefore, none of these anomalies significantly affected the purpose of the test and no retesting was performed.

Detailed tables are presented in Appendix 3. The tables include maximum strains, load and displacement values, and individual margin-to-failure values for the appropriate strain gages as well as any discrepancies that occurred during the test. The tables are ordered sequentially by run number.

Figures 7 and 8 plot the average and minimum margin-to-failure values for the four types of weld assemblies using all three methods of calculation. All three methods of calculation show the same declining trend with a matched unflawed weld possessing the largest margin and an undermatched flawed weld with the least margin. Figure 7 also illustrates that the required average margin to failure of 3.0 is achieved for all weld configurations.

FIGURE 7 Average Margin-to-Failure vs. Weld Configuration

Figure 8 demonstrates that the minimum margin-to-failure of 2.0 required for all specimens is readily achieved for the matched welded assemblies. However, several of the undermatched specimens had margins near or below the limit of 2.0 (Runs 1004, 2103, and 2405). Nominal failure strain for these specimens ranged from 0.75 percent to 1.24 percent which are substantially below the ultimate strain of ~6.0 percent and failure strain of ~20.0 percent normally associated with HY-100 material.

FIGURE 8 Minimum Margin-to-Failure vs. Weld Configuration

Figure 9 is a scatter plot of the individual margin-to-failure values based upon the Load approach (Displacement and Analysis approaches are similar). Each symbol represents an MTF value derived from an individual strain gage. Figure 9 illustrates the same declining trend shown in Figures 7 and 8, as well as the data spread associated within each assembly type. It is also interesting to note that the anomalies in the test series (gage failures, inappropriate sample selected, and a double pull test) are manifested in the scatter plot by their significant deviation from the mean values.

In order to examine the margin-to-failure values near the weld for the samples with reduced instrumentation, an analytical design curve was developed. If the calculated strain near the weld is plotted as a function of the relative displacement across the 8.0 inch test specimen and then normalized such that the strain at the design displacement of 0.027 inches is one, a margin-to-failure curve is developed (see Figure 10). By plotting the test displacement at failure the associated margin-to-failure value was readily determined. Table 10 presents the test relative displacement values at failure for all the test specimens with the associated margins-to-failure determined from Figure 10. For Test Runs 406 and 506, instrumentation near the weld area was present. A comparison of the values determined from that test data and those determined utilizing Figure 10 shows good agreement, except for Test Run 506 utilizing the Displacement approach. As stated previously, inconsistent load/displacement values were present in some of the test data at the relatively low design displacement value which resulted in artificially high margin-to-failure values. Test Runs 2103 and 2405 have calculated margins below 2.0 near the weld. These low margins were also shown from nominal test strain data that was recorded.

FIGURE 9 Margin-to-Failure Scatter Plot Based on Load Approach Calculations for Mid-plate Strains

FIGURE 10 Margin-to-Failure Curve Near Test Weld Based on Analytical Predictions

TABLE 10 Margin-to-Failure Displacement Values Near Test Weld - All Specimens

PLATE	SPECIMEN	RUN	WELD CONF.	TEST DISPL. @ FAILURE	MTF (FIGURE 10)	AVG. MTF FROM TEST		
						DISPL.	LOAD	ANAL.
PD20719	DST-2	406	M/U	0.989	8.1	6.9	6.6	7.7
PD20720	DST-2	506	U/U	0.239	4.9	14.1	4.3	4.8
						TEST NOTES		
PD20719	DISC	604	M/F	0.144	3.2	Inappropriate sample		
PD20720	DST-5	704	U/U	0.360	6.7			
PD20719	DST-6	804	M/F	0.218	4.6			
PD20719	DST-3	904	M/U	0.990	8.1			
PD20720	DST-10	1004	U/F	0.146	3.2			
PD20720	DST-7	1104	U/F	0.197	4.2			
PD20734	DST-5	2003	U/F	0.197	4.2			
PD20744	DST-7	2103	U/F	0.083	1.9			
PD20744	DST-5	2204	U/F	0.184	4.0			
PD20734	DST-3	2304	U/F	0.195	4.2			
PD20744	DST-1	2405	U/U	0.072	1.7			
PD20743	DST-7	2505	M/F	0.956	8.1			
PD20743	DST-5	2604	M/U	0.953	8.1			
PD20734	DST-8	2704	U/U	0.163	3.6	Test machine failure		
PD20744	DST-8	2804	U/F	0.197	4.2			
PD20743	DST-9	2904	M/F	0.969	8.1			
PD20743	DST-1	3005	M/U	0.996	8.1			
PD20734	DST-10	3104	U/U	0.133	3.0	Data recording failure		
PD20746	DST-7	4004	U/F	0.150	3.4			
PD20741	DST-4	4104	M/F	0.937	8.1			
PD20741	DST-10	4204	M/U	0.999	8.1			
PD20744	DST-4	4304	U/U	0.130	3.0			
PD20746	DST-1	5004	U/U	0.239	4.9			
PD20745	DST-9	5105	M/F	0.975	8.1			
PD20741	DST-8	5204	M/U	0.932	8.1			
PD20741	DST-3	5304	M/F	0.999	8.1			
PD20734	DST-8	5400	U/U	0.906	8.1	Continuation of Run 2704		
PD20746	DST-4	6004	U/U	0.223	4.7			
PD20746	DST-8	6104	U/F	0.222	4.7			
PD20745	DST-5	6204	M/U	0.912	8.1			
PD20745	DST-4	6304	M/U	0.933	8.1			
PD20745	DST-10	6404	M/F	0.968	8.1			

WELD CONFIGURATION: M/U = MATCHED/UNFLAWED
M/F = MATCHED/FLAWED

U/F = UNDERMATCHED/FLAWED
U/U = UNDERMATCHED/UNFLAWED

Test and Analysis Results Comparison

Finite element analysis results were used in portions of the calculations for the margin-to-failure values. Comparisons of margin-to-failure values utilizing test data and those using analysis data were very favorable. To extend the comparison, load versus displacement and load versus strain values for the complete loading history were compared at the sensor locations. Alternate finite element models were evaluated including the effects of pin friction, weld material properties, and as-built dimensions.

Model Development and Parametric Investigation

The base line model shown in Figure 6 was further refined to include the pin-to-lug connections as shown in Figure 11. Loading of this model was accomplished by restraining the vertical motion of the bottom pin and applying a vertical displacement to the top pin. The pin-to-lug connections were simulated utilizing gap interface elements that model the contact and friction associated with such a connection. For this study, a coefficient of friction of 0.2 was assumed consistent with the as-tested lubricant Molykote value for steel-on-steel. The initial use of this model was to assess the concerns that the pin-to-lug connection would freely rotate. Results of the study demonstrated that the pin would rotate at the anticipated applied load. Figures 12 and 13 compare the strain predictions (at the mid section of the specimen and near the test weld) between the base line model (Figure 6) and the refined model including the pin (Figure 11). Both models produced similar results. The model including the pin was chosen for additional studies since a numerical solution was more readily obtainable at higher load levels. This is due to the fact that the base line model was loaded with equal and opposite forces and slight imbalances in load created difficulties with solution convergence. The pin model, however, was loaded by imposing displacements at the pin locations and, therefore, does not possess that inherent instability.

FIGURE 11 Finite Element Model with Pin Contact and Friction

FIGURE 12 Applied Load vs. Percent Strain at Mid Section - Comparison of Models without (Base Line) and with (Pin Friction) Load Pins

FIGURE 13 Applied Load vs. Percent Strain Near Test Weld - Comparison of Models without (Base Line) and with (Pin Friction) Load Pins

Mechanical properties and stress/strain curves for several types of steel and weld metal, including the HY-100 used to fabricate the specimens for this test, have been determined as part of the testing effort described in Reference (b). The analytical models presented up to this point in the report have used the material properties for the HY-100 base plate material; that is, weld material properties were assumed to be identical to those of the base metal.

During this test, weld metal test specimens were taken from the as-deposited fillet weld metal for both the matched and undermatched test plate assemblies. These specimens were then tested to determine as-deposited yield and ultimate stress values. These values were compared to those obtained for the same type of weld metal in Reference (b). This comparison is presented in Table 11.

TABLE 11 Weld Type Comparison - Average Yield and Average Ultimate Stress

WELD CONFIGURATION	DUCTILE TEAR SPECIMEN IDENTIFICATION	WELD PROCESS FILLER WIRE TYPE	AVERAGE YIELD STRESS (KSI)	AVERAGE ULTIMATE STRESS (KSI)
MIL-120S-1 B1V.1 BUTT JOINT	PD20689 Reference (b)	SGMAW	103.3	114.7
MIL-120S-1 PT2S.1 FILLET JOINT	PD20719	SGMAW (LEAN)	115.0	140.3
MIL-120S-1 PT2S.1 FILLET JOINT	PD20572	SGMAW	106.0	130.5
MIL-120S-1 PT2S.1 FILLET JOINT	PD20741	PGMAW (RICH)	132.3	157.3
MIL-100S-1 B1V.1 BUTT JOINT	PD20690 Reference (b)	SGMAW	89.0	98.7
MIL-100S-1 PT2S.1 FILLET JOINT	PD20720	SGMAW (LEAN)	94.8	118.0
MIL-100S-1 PT2S.1 FILLET JOINT	PD20734	PGMAW (RICH)	97.5	123.8

Table 11 shows significant variation in weld material properties based on weld configuration. Since detailed stress/strain data was not developed for the fillet type weld used in this test (only yield and ultimate strength were determined), the curve developed in Reference (b) from a B1V.1 butt joint was used. To examine the effects of weld properties in the analysis, the material properties for an HY-80 weld type Mil-100S-1 butt weld were included. This material was selected since, of the pertinent available data, it had the largest difference from the HY-100 base metal. Figures 14 and 15 compare the strain predictions which were obtained from the two models. The initial model used the base plate material properties for both the plate and weld metal. This curve is labeled "Base Metal Properties" on both figures. Results from the second model, which have been described above, use different material properties for the base and weld metal. This data is represented on the figures by data points labeled "Base & Weld Metal Properties." Strain versus load from the analytical models is plotted at the mid-section of the specimen and near the test weld. Again, both analysis models produced similar results. It can be concluded that the localized inelastic behavior in the weld has negligible effects on the general inelastic behavior of the specimen up to, but not including, failure. This removes the concern of mechanical property dissimilarities in base metal versus weld metal for correlation work as well for the use of the results in calculating margin-to-failure values. It also removes the complexity of having two finite element models for the matched and undermatched weld conditions.

These parametric studies have removed the concern for the two major assumptions made in the finite element analysis, namely, the pin-to-lug friction effects and weld material properties. The use of either the base line model that neglects friction or the pin model that includes friction result in essentially the same specimen response. The lack of true stress-strain weld data for the as-tested fillets is not significant, since localized effects in the weld do not affect the strain values at the sensor locations. However, these localized effects can be of great concern in modeling the tearing and or fracture of a fillet weld connection. The analyses contained within this report do not attempt to model this behavior, and rely solely upon the test in determining the effects on the reduction of strength in a connection.

The finite element models used in the following correlation work use the HY-100 base plate material curves from Reference (b) for the specimen, lugs, pins and welds. In addition, the model that includes the pin-to-lug connections is used for ease of load application. Other models, already presented, would result in a similar response.

FIGURE 14 Applied Load vs. Percent Strain at Mid Section - Comparison of Results with and without Using Weld Metal Material Properties

FIGURE 15 Applied Load vs. Percent Strain Near the Test Weld - Comparison of Results with and without Using Weld Metal Material Properties

Correlation Results

Figure 16 shows the deformed shape of the nominal finite element model used in the analysis-to-test correlation study. Two additional similar models were developed that modified the specimen thickness to the as-tested condition. Specifically, the specimen thickness was increased from 0.80 inches to 0.81 and 0.82 inches. Results are summarized in Appendix 4. These models are referred to as the "As-Built" analysis.

FIGURE 16 Nominal 3-D Solid Finite Element Model Used in Correlation Study

The first two specimens tested had extensive instrumentation (see Figure 4). Comparisons to load, relative displacement across the 8.0 inch specimen, and strain are made in Appendix 4 (Figures A4-1 through A4-4). For these specimens, analytical results under-predicted the response by approximately 10 percent at the higher strain values. A review of the transverse gages (Gages 2,5 and 10) shows similar results. Slightly better agreement was achieved with the second specimen tested. A review of the Test Run 506 (Figure A4-3) load versus relative displacement response shows a significant deviation from the analytical results at small values of displacement. This deviation is not present in the load versus strain plots nor in Test Run 406; thus indicating a measurement error in the displacement response. This anomaly was discussed in the previous section as rationale for alternate approaches to determine the margin-to-failure values.

Figures A4-5 through A4-10 illustrate the correlation of test and analysis data for the next six tested specimens. These specimens have a reduced set of strain gage instrumentation (see Figure 5) over the first two specimens, but still permit a reasonable assessment of the specimen's response. Test Runs 604 and 704 show improved correlation with the under-prediction of analytical results reduced to approximately 4.0 percent. The remaining four comparisons (Figures A4-7 to A4-10) show excellent agreement with the exception of some of the displacement data at low strains for reasons previously stated. In all cases, analysis predictions represented either a conservative or actual estimate of the test specimens ultimate load capability.

CONCLUSIONS

The elastic stress criteria limits, as previously stated in the Introduction section, are $1.0 S_u$ for general membrane stress and $2.0 S_u$ for membrane-plus-bending stress. The average margin-to-failure, determined by dividing the failure strain determined in the test by the design strain associated with the largest stress allowable permitted by the elastic criteria, for the flawed and unflawed specimens using a matched welding system is substantial, approximately 16.0. The average margin-to-failure for the flawed and unflawed specimens using an undermatched welding system is less than half that of the matched systems, approximately 7.5. All average values for unflawed specimens exceed the acceptance limit of 3.0.

The minimum margin-to-failure for the flawed and unflawed specimens using a matched welding system exceeded the acceptance limit (4.6 vs. 2.0). Two of the specimens using an undermatched welding system yielded margin-to-failure values very near or below the minimum acceptable value of 2.0. (Unflawed specimen PD20744 DTS-1 at 2.1 and flawed specimen PD20720 DTS-10 at 1.7.) All other undermatched specimens yielded margin-to-failure values in excess of the 2.0 acceptance limit.

Although the low values from these two specimens may indicate a concern, the practice of undermatched welding should not be considered inappropriate. The test was formulated to produce low strength welds in half of the test specimens. This was accomplished by setting parameters (heat input, preheat, chemical composition, and welding position) such that strength would tend toward the low range. These two specimens were in this low strength category. Even for welds intentionally fabricated for low strength, with purposely induced weld defects, the strength margin for the worst tested specimen is still substantial. Furthermore, the manner of load application and design of the test specimen allowed no load redistribution which would normally occur in typical structures.

The reduction in margin-to-failure was greater when going from a matched to undermatched welding system than from an unflawed to flawed weld specimen. The majority of matched welding system specimens failed by fracture in the specimen base plate metal rather than fracture through the fillet weld. The majority of the undermatched specimens failed by fracture through the fillet weld.

Specimen failure was either by ductile tensile failure in the base material member or shear failure through the fillet weld. Premature failure due to unstable ductile tearing or inadequate flaw tolerance was not evident for the matched welded specimens, as attested by the margin-to-failure values.

The overall performance of the undermatched specimens, based on the average margin-to-failure, was adequate. For all but one specimen, failure occurred in the weld before the base material member reached ultimate strain. This indicates that, for the undermatched specimens under tensile loading, a strain concentration exists at the weld due to its lower threshold of yielding as compared to the higher yield strength of the base material. The fact that two specimens failed near or slightly below the acceptance limit of this test, at relatively low strain levels in the base material, highlights the concern for closer examination of the use of undermatched welding in this type of application. However, concluding that undermatched welding systems provide inadequate strength margins, based solely on this limited test, cannot be made.

Based upon the results of this test series the following conclusions can be drawn:

1. The Load approach provides the most consistent and accurate measure for determining the margin-to-failure values.
2. There is a distinct declining trend in the margin-to-failure values, with the matched unflawed weld possessing the largest margin and an undermatched flawed weld with the least margin.
3. The intentional flaw on average reduces the margin in the specimen but not as significantly as the change in margin from a matched to an undermatched system when loaded in tension. (Other loading conditions were not evaluated.)
4. The average margin-to-failure values for the flawed/unflawed matched fillet welded specimens are substantial (MTF = ~16.0).
5. The minimum margin-to-failure values for the flawed/unflawed matched fillet welded specimens are adequate (MTF = 4.6).
6. The average margin-to-failure values for the flawed/unflawed undermatched welded specimens meet the average allowable margin of 3.0 (MTF = ~7.5).
7. Several of the 17 flawed/unflawed undermatched welded specimens failed with margins near or below the minimum allowable limit of 2.0. These failures were at nominal strains of approximately one percent, significantly below the ultimate design strain of approximately 6.0 percent.
8. The majority of the matched welded specimens (14 of 16) failed in the base plate material of the specimen, demonstrating that the weld connection is stronger than the plate material.
9. The majority of the undermatched specimens (16 of 17) failed in the weld. The full capability of the structure (test specimen) was therefore not obtained. These failures are most likely attributed to a strain dumping phenomenon in which strains were concentrated in the fillet weld when the specimen was exposed to a tensile load which exceeded elastic limits of the material.
10. Correlation between test data and inelastic finite element results are favorable with results ranging from very good (-10 percent underprediction) to excellent (~0.0 percent error).

REFERENCES

- (a) ABAQUS User's Manual, Version 5.3, Hibbitt, Karlsson and Sorensen, Inc., 1993
- (b) Electric Boat Corporation Report TDA-19194, Material Properties Test to Determine Ultimate Strain and True Stress-True Strain Curves for High Yield Steels, K. R. Arpin, T. F. Trimble, July, 2001

APPENDIX 1 - WELD METAL MECHANICAL PROPERTIES

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20719	SGMAW	120S-1 (Lean)	Horiz Fillet	51.2	51.8	3	3	250/275

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	138	112	18	71
	AWT-6	139	114	20	70
	AWT-7	141	116	20	69
	AWT-8	143	118	20	70
Backup Weld	AWT-1	141	116	18	67
	AWT-2	136	112	18	70
	AWT-3	132	107	18	67
	AWT-4	136	114	18	74

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1					
DTS-1	S2					
DTS-2	S1	No	0.210	0.210	0.149	0.147
DTS-2	S2	No	0.215	0.205	0.155	0.153
DTS-3	S1	No	0.216	0.206	0.158	0.139
DTS-3	S2	No	0.209	0.202	0.148	0.136
DTS-4	S1					
DTS-4	S2					
DTS-5	S1					
DTS-5	S2					
DTS-DISC	S1	Yes	0.184	0.212	0.161	0.165
DTS-DISC	S2	Yes	0.233	0.228	0.180	0.168
DTS-6	S1	Yes	0.210	0.204	0.173	0.152
DTS-6	S2	Yes	0.220	0.219	0.173	0.161
DTS-7	S1					
DTS-7	S2					
DTS-8	S1					
DTS-8	S2					
DTS-9	S1					
DTS-9	S2					
DTS-10	S1					
DTS-10	S2					

- Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.
2) Specimen DTS-DISC was tested, but results were out of the ordinary. Therefore, specimen DTS-9 was substituted.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20720	SGMAW	100S-1 (Lean)	Horiz Fillet	54.9	55.0	3	3	250/275

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	119	96	22	75
	AWT-6	115	93	22	74
	AWT-7	116	94	22	75
	AWT-8	122	96	22	75
Backup Weld	AWT-1	121	99	20	74
	AWT-2	116	94	20	76
	AWT-3	118	96	20	73
	AWT-4	114	92	20	78

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1					
DTS-1	S2					
DTS-2	S1	No	0.222	0.208	0.163	0.148
DTS-2	S2	No	0.222	0.218	0.160	0.146
DTS-3	S1					
DTS-3	S2					
DTS-4	S1					
DTS-4	S2					
DTS-5	S1	No	0.225	0.219	0.171	0.171
DTS-5	S2	No	0.229	0.221	0.177	0.174
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1	Yes	0.232	0.217	0.188	0.166
DTS-7	S2	Yes	0.237	0.211	0.188	0.163
DTS-8	S1					
DTS-8	S2					
DTS-9	S1					
DTS-9	S2					
DTS-10	S1	Yes	0.224	0.221	0.187	0.191
DTS-10	S2	Yes	0.223	0.220	0.169	0.175

Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20734	PGMAW	100S-1 (Lean)	Vertical	26.3	27.5	4	4	150/175

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	124	99	27	65
	AWT-6	121	95	27	70
	AWT-7	127	98	22	70
	AWT-8	123	107	29	71
Backup Weld	AWT-1	122	98	29	71
	AWT-2	128	101	24	73
	AWT-3	116	102	24	71
	AWT-4	118	100	22	60

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1					
DTS-1	S2					
DTS-2	S1					
DTS-2	S2					
DTS-3	S1	Yes	0.255	0.278	0.161	0.206
DTS-3	S2	Yes	0.290	0.255	0.176	0.207
DTS-4	S1					
DTS-4	S2					
DTS-5	S1	Yes	0.262	0.252	0.183	0.196
DTS-5	S2	Yes	0.265	0.261	0.205	0.183
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1					
DTS-7	S2					
DTS-8	S1	No	0.285	0.286	0.200	0.229
DTS-8	S2	No	0.285	0.292	0.214	0.231
DTS-9	S1					
DTS-9	S2					
DTS-10	S1	No	0.255	0.264	0.186	0.197
DTS-10	S2	No	0.253	0.289	0.173	0.192

- Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.
2) Testing of Specimens DTS-8 and DTS-10 were invalid due to failure in the bolt attaching top clevis to test machine and failure to record all data. Therefore, Specimens DTS-7 and DTS-9 were substituted.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20741	PGMAW	120S-1 (Rich)	Vertical	33.0	32.4	3	3	225/250

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	159	133	16	64
	AWT-6	161	136	13	71
	AWT-7	153	129	13	65
	AWT-8	156	131	17	69
Backup Weld	AWT-1	153	134	2	69
	AWT-2	160	141	16	70
	AWT-3	158	134	11	66
	AWT-4	160	136	11	70

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1					
DTS-1	S2					
DTS-2	S1					
DTS-2	S2					
DTS-3	S1	Yes	0.249	0.251	0.160	0.188
DTS-3	S2	Yes	0.271	0.262	0.166	0.191
DTS-4	S1	Yes	0.244	0.258	0.159	0.181
DTS-4	S2	Yes	0.238	0.259	0.163	0.188
DTS-5	S1					
DTS-5	S2					
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1					
DTS-7	S2					
DTS-8	S1	No	0.259	0.258	0.167	0.181
DTS-8	S2	No	0.275	0.253	0.148	0.178
DTS-9	S1					
DTS-9	S2					
DTS-10	S1	No	0.197	0.198	0.158	0.168
DTS-10	S2	No	0.218	0.239	0.148	0.196

- Notes: 1) Area bounding by ≤ triangle totally filled with weld originating at weld toe on test member.
2) AWT-1 broke outside of the gage length (just ahead of the shoulder).

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20743	SMAW	12018 (Lean)	Horiz Fillet	44.3	44.4	6	6	275/300

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	121	104	16	66
	AWT-6	137	117	18	70
	AWT-7	135	115	16	57
	AWT-8	131	115	20	63
Backup Weld	AWT-1	129	112	20	59
	AWT-2	127	112	16	60
	AWT-3	136	114	18	60
	AWT-4	132	124	18	62

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1	No	0.245	0.259	0.193	0.178
DTS-1	S2	No	0.229	0.257	0.199	0.209
DTS-2	S1					
DTS-2	S2					
DTS-3	S1					
DTS-3	S2					
DTS-4	S1					
DTS-4	S2					
DTS-5	S1	No	0.252	0.270	0.187	0.227
DTS-5	S2	No	0.249	0.269	0.211	0.215
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1	Yes	0.239	0.261	0.173	0.214
DTS-7	S2	Yes	0.243	0.274	0.192	0.248
DTS-8	S1					
DTS-8	S2					
DTS-9	S1	Yes	0.239	0.282	0.199	0.225
DTS-9	S2	Yes	0.240	0.247	0.203	0.219
DTS-10	S1					
DTS-10	S2					

Notes: 1) Area bounding by ≤ triangle totally filled with weld originating at weld toe on test member.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20744	SMAW	11018 (Lean)	Horiz Fillet	53.5	54.7	5	5	275/300

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	118	94	24	63
	AWT-6	122	100	22	66
	AWT-7	128	108	24	65
	AWT-8	126	106	20	67
Backup Weld	AWT-1	126	101	22	64
	AWT-2	123	99	20	68
	AWT-3	120	102	16	68
	AWT-4	125	99	22	65

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1	No	0.280	0.220	0.213	0.200
DTS-1	S2	No	0.230	0.225	0.171	0.193
DTS-2	S1					
DTS-2	S2					
DTS-3	S1					
DTS-3	S2					
DTS-4	S1	No	0.263	0.231	0.205	0.181
DTS-4	S2	No	0.222	0.238	0.174	0.188
DTS-5	S1	Yes	0.252	0.207	0.220	0.160
DTS-5	S2	Yes	0.266	0.220	0.220	0.184
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1	Yes	0.210	0.219	0.164	0.189
DTS-7	S2	Yes	0.217	0.243	0.161	0.180
DTS-8	S1	Yes	0.203	0.237	0.165	0.195
DTS-8	S2	Yes	0.232	0.255	0.184	0.198
DTS-9	S1					
DTS-9	S2					
DTS-10	S1					
DTS-10	S2					

Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20745	SMAW	12018 (Rich)	Horiz Fillet	30.7	30.4	5	7	225

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	132	121	20	69
	AWT-6	141	127	18	68
	AWT-7	145	129	13	60
	AWT-8	146	142	16	61
Backup Weld	AWT-1	131	120	22	64
	AWT-2	140	130	20	65
	AWT-3	153	134	13	58
	AWT-4	141	127	18	56

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1					
DTS-1	S2					
DTS-2	S1					
DTS-2	S2					
DTS-3	S1					
DTS-3	S2					
DTS-4	S1	No	0.189	0.196	0.161	0.180
DTS-4	S2	No	0.175	0.197	0.151	0.172
DTS-5	S1	No	0.206	0.213	0.184	0.193
DTS-5	S2	No	0.190	0.188	0.161	0.163
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1					
DTS-7	S2					
DTS-8	S1					
DTS-8	S2					
DTS-9	S1	Yes	0.193	0.188	0.172	0.162
DTS-9	S2	Yes	0.216	0.230	0.178	0.200
DTS-10	S1	Yes	0.212	0.203	0.171	0.174
DTS-10	S2	Yes	0.188	0.208	0.167	0.178

Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Assembly No.	Process	Filler Wire (Rich/Lean)	Welding Position	Avg Heat Input (kJ/in)		No. Beads Deposited		Preheat/ Interpass Temp. -°F
				Test Side Weld	Back Side Weld	Test Side Weld	Back Side Weld	
PD20746	SMAW	11018 (Rich)	Horiz Fillet	30.0	30.0	6	7	225

Heat No. R1874, Slab 4B. Rolling direction perpendicular to welding direction.

WELD METAL TENSILE TEST RESULTS					
Side	Specimen No.	Ultimate Tensile (KSI)	Yield (KSI)	Elongation in 0.45 in. (%)	Reduction in Area (%)
Test Weld	AWT-5	129	102	20	64
	AWT-6	124	106	22	58
	AWT-7	125	112	22	60
	AWT-8				
Backup Weld	AWT-1				
	AWT-2	129	102	22	66
	AWT-3	125	109	20	57
	AWT-4	129	115	22	61

WELD METAL TENSILE TEST RESULTS						
Specimen No.	Macro No.	Macro Defects?	Total Reinforcement Area (in ²)		≤ 45° Triangle (Note 1) in ²	
			Test Weld	Backup Weld	Test Weld	Backup Weld
DTS-1	S1	No	0.183	0.214	0.154	0.178
DTS-1	S2	No	0.174	0.234	0.150	0.181
DTS-2	S1					
DTS-2	S2					
DTS-3	S1					
DTS-3	S2					
DTS-4	S1	No	0.192	0.188	0.169	0.160
DTS-4	S2	No	0.205	0.186	0.182	0.152
DTS-5	S1					
DTS-5	S2					
DTS-DISC	S1					
DTS-DISC	S2					
DTS-6	S1					
DTS-6	S2					
DTS-7	S1	Yes	0.185	0.191	0.164	0.145
DTS-7	S2	Yes	0.199	0.191	0.167	0.165
DTS-8	S1	Yes	0.231	0.198	0.206	0.181
DTS-8	S2	Yes	0.201	0.219	0.182	0.186
DTS-9	S1					
DTS-9	S2					
DTS-10	S1					
DTS-10	S2					

- Notes: 1) Area bounded by ≤ triangle totally filled with weld originating at weld toe on test member.
2) AWT-1 and AWT-8 were not tested since the stress-strain curves indicated that the specimens were probably pre-strained (probably during the machining process).

APPENDIX 2 - WELD PHOTOGRAPHS

Specimen PD 20719 DISC, Side 2 - Flawed
Matched SGMAW Process Run 604

Specimen PD 20719 DTS-2, Side 1 - Unflawed
Matched SGMAW Process Run 406

Specimen PD 20719 DTS-6, Side 1 - Flawed
Matched SGMAW Process Run 804

Specimen PD 20743 DTS-1, Side 2 - Unflawed
Matched SMAW Process Run 3005

Specimen PD 20745 DTS-9, Side 1 - Flawed
Matched SMAW Process Run 5105

Specimen PD 20720 DTS-2, Side 2 - Unflawed
Undermatched SGMAW Process Run 506

Specimen PD 20720 DTS-10, Side 2 - Flawed
Undermatched SGMAW Process Run 1004

Specimen PD 20734 DTS-5, Side 1 - Flawed
Undermatched PGMAW Process Run 2003

Specimen PD 20744 DTS-1, Side 2 - Unflawed
Undermatched SMAW Process Run 2405

Specimen PD 20746 DTS-7, Side 2 - Flawed
Undermatched SMAW Process Run 4004

APPENDIX 3 - TABULATION OF TEST DATA

ELECTRIC BOAT CORPORATION
REPORT NO. TDA-19196

Specimen PD20719 DTS-2 Run 406	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed SGMAW/120S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain Analytical Design Weld Strain	0.027 inches 108.1 kips 0.49% Tension Side 0.69% Tension Side				
Maximum Load = 148.5 kips Maximum Displacement = 0.989 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	5.1	0.47	0.48	10.9	10.6	10.4	Gage Failure
02	Tension Side Mid Plate Trans	-1.6	-0.13	-0.13	N/A	N/A	N/A	Gage Failure
03	Tension Side Mid Plate Axial	10.9	0.45	0.45	24.2	24.2	22.2	
04	Tension Side Weld Axial	3.2	0.76	0.79	4.2	4.1	4.6	Gage Failure
05	Tension Side Weld Trans	-1.5	-0.20	-0.21	N/A	N/A	N/A	
06	Tension Side Weld Axial	5.3	0.77	0.80	6.9	6.6	7.7	
07	Compression Side Mid Plate Axial	4.8	0.21	0.22	N/A	N/A	N/A	Gage Failure
08	Compression Side Mid Plate Axial	8.3	0.19	0.20	N/A	N/A	N/A	
09	Compression Side Weld Axial	3.1	0.08	0.08	N/A	N/A	N/A	
10	Compression Side Weld Trans	-1.2	-0.05	-0.05	N/A	N/A	N/A	
11	Compression Side Weld Axial	3.3	0.09	0.09	N/A	N/A	N/A	

Specimen PD20720 DTS-2 Run 506	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SGMAW/100S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain Analytical Design Weld Strain	0.027 inches 108.1 kips 0.49% Tension Side 0.69% Tension Side				
Maximum Load = 137.5 kips Maximum Displacement = 0.239 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.75	0.24	0.49	11.5	5.6	5.6	
02	Tension Side Mid Plate Trans	-1.19	-0.06	-0.12	N/A	N/A	N/A	
03	Tension Side Mid Plate Axial	2.79	0.18	0.37	15.5	7.5	5.7	
04	Tension Side Weld Axial	3.42	0.28	0.93	12.2	37	4.9	
05	Tension Side Weld Trans	-1.18	-0.06	-0.23	N/A	N/A	N/A	
06	Tension Side Weld Axial	3.17	0.20	0.64	15.9	4.9	4.6	
07	Compression Side Mid Plate Axial	2.77	0.10	0.32	N/A	N/A	N/A	
08	Compression Side Mid Plate Axial	2.75	0.03	0.19	N/A	N/A	N/A	
09	Compression Side Weld Axial	1.38	0.07	0.21	N/A	N/A	N/A	
10	Compression Side Weld Trans	-0.78	-0.02	-0.06	N/A	N/A	N/A	
11	Compression Side Weld Axial	1.27	0.01	0.04	N/A	N/A	N/A	

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Specimen PD20719 DISC Run 604	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SGMAW/120S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 130.5 kips Maximum Displacement = 0.144 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.20	0.44	0.48	5.0	4.6	4.5	
02	Tension Side Mid Plate Axial	2.27	0.41	0.44	5.5	5.2	4.6	
03	Compression Side Mid Plate Axial	2.16	0.20	0.25	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	2.26	0.18	0.23	N/A	N/A	N/A	

Specimen PD20720 DTS-5 Run 704	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SGMAW/100S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 143.0 kips Maximum Displacement = 0.360 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	4.90	0.35	0.43	14.0	11.4	10.0	Gage Failure
02	Tension Side Mid Plate Axial	5.37	0.32	0.38	16.8	14.1	11.0	
03	Compression Side Mid Plate Axial	5.22	0.22	0.28	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	5.42	0.17	0.23	N/A	N/A	N/A	

Specimen PD20719 DTS-6 Run 804	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SGMAW/120S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 131.4 kips Maximum Displacement = 0.218 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	3.65	0.43	0.47	8.5	7.8	7.4	
02	Tension Side Mid Plate Axial	3.57	0.39	0.43	9.2	8.3	7.3	
03	Compression Side Mid Plate Axial	3.75	0.27	0.30	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	3.57	0.23	0.26	N/A	N/A	N/A	

Specimen PD20719 DTS-3 Run 904	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed SGMAW/120S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 139.0 kips Maximum Displacement = 0.990 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	8.12	0.41	0.42	19.8	19.3	16.6	
02	Tension Side Mid Plate Axial	8.39	0.43	0.45	19.5	18.6	17.1	
03	Compression Side Mid Plate Axial	8.64	0.24	0.28	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	8.82	0.25	0.29	N/A	N/A	N/A	

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Specimen PD20720 DTS-10 Run 1004	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed SGMAW/100S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 123.0 kips Maximum Displacement = 0.146 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	0.88	0.32	0.49	2.8	1.8	1.8	
02	Tension Side Mid Plate Axial	0.75	0.28	0.44	2.7	1.7	1.5	
03	Compression Side Mid Plate Axial	0.81	0.14	0.29	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	0.69	0.11	0.25	N/A	N/A	N/A	

Specimen PD20720 DTS-7 Run 1104	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed SGMAW/120S-1 Lean Horizontal Fillet 250 / 275 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 130.6 kips Maximum Displacement = 0.197 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.59	0.39	0.44	6.6	5.9	5.3	
02	Tension Side Mid Plate Axial	2.59	0.38	0.44	6.8	5.9	5.3	
03	Compression Side Mid Plate Axial	2.61	0.22	0.26	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	2.60	0.21	0.26	N/A	N/A	N/A	

Specimen PD20734 DTS-5 Run 2003	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed PGMAW/100S-1 Rich Vertical 150 / 175 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 130.5 kips Maximum Displacement = 0.197 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.99	0.36	0.43	8.3	7.0	6.1	
02	Tension Side Mid Plate Axial	2.94	0.38	0.46	7.7	6.4	6.0	
03	Compression Side Mid Plate Axial	2.92	0.19	0.29	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	2.99	0.17	0.26	N/A	N/A	N/A	

Specimen	Weld Configuration	Undermatched/Flawed	Elastic Displacement at Design Stress	0.027 inches				
PD20744	Weld Process/Filler Wire	SMAW/11018 Lean	Analytical Load at Elastic Displacement	108.1 kips				
DTS-7	Weld Position	Horizontal Fillet	Analytical Design Nominal Strain	0.49% Tension Side				
Run 2103	Preheat/Interpass Temp.	275 / 300 F						
Maximum Load = 127.8 kips Maximum Displacement = 0.083 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	1.24	0.59	0.45	2.1	2.8	2.5	
02	Tension Side Mid Plate Axial	1.14	0.48	0.40	2.4	2.9	2.3	
03	Compression Side Mid Plate Axial	1.25	0.48	0.30	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	1.16	0.37	0.24	N/A	N/A	N/A	

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Specimen	Weld Configuration	Undermatched/Flawed	Elastic Displacement at Design Stress	0.027 inches				
PD20744	Weld Process/Filler Wire	SMAW/11018 Lean	Analytical Load at Elastic Displacement	108.1 kips				
DTS-5	Weld Position	Horizontal Fillet	Analytical Design Nominal Strain	0.49% Tension Side				
Run 2204	Preheat/Interpass Temp.	275 / 300 F						
Maximum Load = 134.9 kips Maximum Displacement = 0.184 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	3.33	0.59	0.46	5.6	7.2	6.8	
02	Tension Side Mid Plate Axial	3.23	0.46	0.40	7.0	8.1	6.6	
03	Compression Side Mid Plate Axial	3.33	0.53	0.30	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	3.25	0.40	0.24	N/A	N/A	N/A	

Specimen PD20734 DTS-3 Run 2304	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed PGMAW/100S-1 Rich Vertical 150 / 175 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 137.0 kips Maximum Displacement = 0.195 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	3.40	0.65	0.47	5.2	7.2	6.9	
02	Tension Side Mid Plate Axial	3.39	0.52	0.39	6.5	8.7	6.9	
03	Compression Side Mid Plate Axial	2.87	0.53	0.30	N/A	N/A	N/A	Gage Failed
04	Compression Side Mid Plate Axial	3.37	0.40	0.23	N/A	N/A	N/A	

Specimen PD20744 DTS-1 Run 2405	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SMAW/11018 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 128.2 kips Maximum Displacement = 0.072 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	0.95	0.53	0.45	1.8	2.1	1.9	
02	Tension Side Mid Plate Axial	0.94	0.49	0.41	1.9	2.3	1.9	
03	Compression Side Mid Plate Axial	1.01	0.39	0.28	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	1.01	0.35	0.25	N/A	N/A	N/A	

Specimen PD20743 DTS-7 Run 2505	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SMAW/12018 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 133.6 kips Maximum Displacement = 0.956 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	5.96	0.40	0.43	14.9	13.9	12.2	Gage Failed
02	Tension Side Mid Plate Axial	9.28	0.40	0.43	23.2	21.6	18.9	
03	Compression Side Mid Plate Axial	9.55	0.23	0.31	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	9.29	0.23	0.31	N/A	N/A	N/A	

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Specimen PD20743 DTS-5 Run 2604	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed SMAW/120S-1 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 140.4 kips Maximum Displacement = 0.953 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	8.36	0.43	0.42	19.4	19.9	17.1	
02	Tension Side Mid Plate Axial	8.67	0.41	0.40	16.8	17.2	14.0	Gage Failure
03	Compression Side Mid Plate Axial	7.40	0.32	0.29	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	3.31	0.31	0.28	N/A	N/A	N/A	Gage Failure

Specimen PD20734 DTS-8 Run 2704	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed PGMAW/100-S Rich Vertical 150 / 175 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 134.0 kips Maximum Displacement = 0.163 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.61	0.42	0.50	6.2	5.2	5.3	
02	Tension Side Mid Plate Axial	2.59	0.32	0.37	8.1	7.0	5.3	
03	Compression Side Mid Plate Axial	2.60	0.18	0.22	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	2.65	0.28	0.35	N/A	N/A	N/A	
NOTE : Test Machine Stud-to-Fixture Thread Failure Prior to Specimen Failure								

Specimen PD20744 DTS-8 Run 2804	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed SMAW/11018 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 132.1 kips Maximum Displacement = 0.197 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.49	0.25	0.37	10.0	6.7	5.1	
02	Tension Side Mid Plate Axial	2.51	0.32	0.46	7.8	5.4	5.1	
03	Compression Side Mid Plate Axial	2.54	0.11	0.24	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	2.56	0.17	0.32	N/A	N/A	N/A	

Specimen PD20743 DTS-9 Run 2904	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SMAW/12018 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 142.0 kips Maximum Displacement = 0.969 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	8.14	0.58	0.43	14.0	18.9	16.6	Gage Failure
02	Tension Side Mid Plate Axial	11.17	0.46	0.39	24.3	28.6	22.8	
03	Compression Side Mid Plate Axial	3.11	0.54	0.31	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	3.47	0.42	0.26	N/A	N/A	N/A	Gage Failure

Specimen PD20743	Weld Configuration Matched/Unflawed	Weld Process/Filler Wire SMAW/12018 Lean	Weld Position Horizontal Fillet	Preheat/Interpass Temp. 275 / 300 F	Maximum Load = 143.6 kips Maximum Displacement = 0.996 inches				
DTS-1 Run 3005	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side							
Gage Number	Description	Maximum Test Strain %	Displ Load	Test Design Strain %	Displ Load	Test Margin to Failure	Analytical Margin to Failure	Problems	
01	Tension Side Mid Plate Axial	13.07	0.47	0.50	27.8	26.1	26.7		
02	Tension Side Mid Plate Axial	15.12	0.43	0.45	35.2	33.6	30.9		
03	Compression Side Mid Plate Axial	3.50	0.25	0.28	N/A	N/A	N/A	Gage Failure	
04	Compression Side Mid Plate Axial	5.02	0.19	0.21	N/A	N/A	N/A	Gage Failure	

Specimen PD20734	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undematched/Unflawed PGMAW/100S-1 Rich Vertical 150 / 175 F	Maximum Load = 143.3 kips Maximum Displacement = 0.133 inches										
Run 3104	DTS-10	0.49% Tension Side	108.1 kips	0.027 inches	Elastic Displacement at Design Stress	Analytical Load at Elastic Displacement	Analytical Design Nominal Strain						
Gage Number	Description	Maximum Test Strain %	Displ Load	Test Design Strain %	Displ Load	Test Margin to Failure	Analytical Margin to Failure	Problems					
									Tension Side Mid Plate Axial				3.08
									Tension Side Mid Plate Axial				3.09
									Compression Side Mid Plate Axial				3.09
									Compression Side Mid Plate Axial				3.07
01													
02													
03													
04													

NOTE: Data Recording Failure - Intermittent Loss of Data

Specimen PD20746	Weld Configuration Undermatched/Flawed	Weld Process/Filler Wire SMAW/11018 Rich	Weld Position Horizontal Fillet	Preheat/Interpass Temp. 225 / 225 F	Maximum Load = 135.9 kips Maximum Displacement = 0.150 inches											
Run 4004	DTS-7	0.027 inches	108.1 kips	0.49% Tension Side	Elastic Displacement at Design Stress	Analytical Load at Elastic Displacement	Analytical Design Nominal Strain									
Gage Number	Description	Maximum Test Strain %	Displ Load	Test Design Strain %	Displ Load	Test Margin to Failure	Analytical Margin to Failure	Problems	01	Tension Side Mid Plate Axial	2.04	0.28	0.39	7.3	5.2	4.2
									02	Tension Side Mid Plate Axial	2.15	0.32	0.44	6.7	4.9	4.4
									03	Compression Side Mid Plate Axial	2.17	0.17	0.28	N/A	N/A	N/A
									04	Compression Side Mid Plate Axial	2.10	0.13	0.23	N/A	N/A	N/A

Specimen PD20741	Weld Configuration Matched/Flawed	Weld Process/Filler Wire PGMAW/120S-1 Rich	Weld Position Vertical	Preheat/Interpass Temp. 225 / 250 F	Maximum Load = 136.2 kips Maximum Displacement = 0.937 inches				
Run 4104	DTS-4 Weld Position					Analytical Design Nominal Strain 0.49% Tension Side			
	Weld Process/Filler Wire					Elastic Displacement at Design Stress 108.1 kips 0.027 inches			
Gage Number	Description	Maximum Test Strain %	Displ Load	Test Design Strain %	Displ Load	Test Margin to Failure	Analytical Margin to Failure	Problems	
01	Tension Side Mid Plate Axial	4.28	0.34	0.44	17.4*	13.3*	12.8*	Gage Failure	
02	Tension Side Mid Plate Axial	4.82	0.36	0.47	N/A	N/A	N/A		
03	Compression Side Mid Plate Axial	6.25	0.20	0.29	N/A	N/A	N/A		
04	Compression Side Mid Plate Axial	6.25	0.18	0.27	N/A	N/A	N/A		

* Gage 03 max test strain used with Gage 02 design strain to calculate MTF's (these MTF's used in summary table).

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Specimen PD20741 DTS-10 Run 4204	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed PGMAW/120S-1 Rich Vertical 225 / 250 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 139.1 kips Maximum Displacement = 0.999 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	4.97	0.42	0.45	11.8	11.0	10.1	Gage Failure
02	Tension Side Mid Plate Axial	3.67	0.42	0.45	8.7	8.2	7.5	Gage Failure
03	Compression Side Mid Plate Axial	3.96	0.22	0.27	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	5.18	0.22	0.27	N/A	N/A	N/A	Gage Failure
NOTE : All gages failed, therefore Gage 01 included in summary tables								

Specimen PD20744 DTS-4 Run 4304	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SMAW/11018 Lean Horizontal Fillet 275 / 300 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 132.8 kips Maximum Displacement = 0.130 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	1.88	0.43	0.42	4.4	4.5	3.8	
02	Tension Side Mid Plate Axial	1.94	0.45	0.44	4.3	4.4	4.0	
03	Compression Side Mid Plate Axial	2.01	0.27	0.26	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	1.97	0.27	0.26	N/A	N/A	N/A	

Specimen PD20746 DTS-1 Run 5004	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SMAW/11018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 141.9 kips Maximum Displacement = 0.239 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	3.85	0.48	0.46	8.0	8.4	7.9	
02	Tension Side Mid Plate Axial	3.88	0.43	0.42	9.0	9.2	7.9	
03	Compression Side Mid Plate Axial	3.56	0.25	0.23	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	3.51	0.28	0.26	N/A	N/A	N/A	Gage Failure

Specimen PD20745 DTS-9 Run 5105	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SMAW/12018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 139.9 kips Maximum Displacement = 0.975 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	3.87	0.25	0.46	15.5	8.4	7.9	Gage Failure
02	Tension Side Mid Plate Axial	5.39	0.30	0.57	18.0	9.5	11.0	Gage Failure
03	Compression Side Mid Plate Axial	3.16	0.11	0.31	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	4.29	0.05	0.20	N/A	N/A	N/A	Gage Failure
NOTE : All gages failed, therefore Gage 02 included in summary tables								

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Specimen PD20741 DTS-8 Run 5204	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed PGMAW/120S-1 Rich Vertical 225 / 250 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 136.9 kips Maximum Displacement = 0.932 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	4.01	0.36	0.44	11.1	9.1	8.2	Gage Failure
02	Tension Side Mid Plate Axial	3.04	0.39	0.48	14.6	11.9	11.6	Gage Failure
03	Compression Side Mid Plate Axial	3.55	0.21	0.29	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	5.69	0.19	0.26	N/A	N/A	N/A	
* Gage 04 max test strain used with Gage 02 design strain to calculate MFT's (these MTF's used in summary table).								

Specimen PD20741 DTS-3 Run 5304	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed PGMAW/120S-1 Rich Vertical 225 / 250 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 136.3 kips Maximum Displacement = 0.999 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	6.07	0.42	0.46	14.5	13.2	12.4	Gage Failure
02	Tension Side Mid Plate Axial	7.77	0.41	0.45	19.1	17.3	15.9	Gage Failure
03	Compression Side Mid Plate Axial	4.58	0.23	0.28	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	2.51	0.24	0.29	N/A	N/A	N/A	Gage Failure

Specimen PD20734 DTS-8 Run 5400	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed PGMAW/100S-1 Rich Vertical 150 / 175 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 142.1 kips Maximum Displacement = 0.906 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	6.16	0.44	0.43	14.0	14.3	12.6	Gage Failure
02	Tension Side Mid Plate Axial	7.16	0.44	0.42	16.3	17.0	14.6	
03	Compression Side Mid Plate Axial	7.06	0.38	0.37	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	6.95	0.39	0.38	N/A	N/A	N/A	
NOTE : Continuation of Run 2704 in which test machine failed (second pull - no Kaman sensor)								

Specimen PD20746 DTS-4 Run 6004	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Unflawed SMAW/11018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 143.5 kips Maximum Displacement = 0.223 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	4.60	0.44	0.44	10.5	10.5	9.4	
02	Tension Side Mid Plate Axial	4.12	0.42	0.42	9.8	9.8	8.4	Gage Failure
03	Compression Side Mid Plate Axial	4.26	0.23	0.24	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	3.64	0.25	0.25	N/A	N/A	N/A	Gage Failure

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Specimen PD20746 DTS-8 Run 6104	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Undermatched/Flawed SMAW/11018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 141.1 kips Maximum Displacement = 0.222 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	2.62	0.42*	0.42*	9.8*	9.8*	8.4*	Gage Failure
02	Tension Side Mid Plate Axial	2.58	0.40	0.40	6.5	6.5	5.3	Gage Failure
03	Compression Side Mid Plate Axial	4.13	0.25	0.25	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	4.15	0.27	0.27	N/A	N/A	N/A	
* Gage 03 max test strain used with Gage 01 design strain to calculate MFT's (these MTF's used in summary table).								

Specimen PD20745 DTS-5 Run 6204	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed SMAW/12018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 142.7 kips Maximum Displacement = 0.912 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	6.83	0.47	0.44	14.5	15.5	13.9	
02	Tension Side Mid Plate Axial	4.40	0.44	0.42	10.0	10.5	9.0	Gage Failure
03	Compression Side Mid Plate Axial	3.88	0.27	0.24	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	3.36	0.30	0.27	N/A	N/A	N/A	Gage Failure

Specimen PD20745 DTS-4 Run 6304	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Unflawed SMAW/12018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 140.9 kips Maximum Displacement = 0.933 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	4.51	0.45	0.43	10.0	10.5	9.2	Gage Failure
02	Tension Side Mid Plate Axial	3.22	0.44	0.42	7.3	7.7	6.6	Gage Failure
03	Compression Side Mid Plate Axial	3.81	0.29	0.26	N/A	N/A	N/A	Gage Failure
04	Compression Side Mid Plate Axial	3.62	0.30	0.27	N/A	N/A	N/A	Gage Failure
NOTE : All gages failed, therefore Gage 01 included in summary tables								

Specimen PD20745 DTS-10 Run 6404	Weld Configuration Weld Process/Filler Wire Weld Position Preheat/Interpass Temp.	Matched/Flawed SMAW/12018 Rich Horizontal Fillet 225 / 225 F	Elastic Displacement at Design Stress Analytical Load at Elastic Displacement Analytical Design Nominal Strain	0.027 inches 108.1 kips 0.49% Tension Side				
Maximum Load = 139.3 kips Maximum Displacement = 0.968 inches								
Gage Number	Description	Maximum Test Strain %	Test Design Strain %		Test Margin to Failure		Analytical Margin to Failure	Problems
			Displ	Load	Displ	Load		
01	Tension Side Mid Plate Axial	5.05	0.47	0.48	16.0	15.7	15.4	Gage Failure
02	Tension Side Mid Plate Axial	3.89	0.43	0.44	9.0	8.8	7.9	Gage Failure
03	Compression Side Mid Plate Axial	7.53	0.22	0.24	N/A	N/A	N/A	
04	Compression Side Mid Plate Axial	4.36	0.28	0.30	N/A	N/A	N/A	Gage Failure
* Gage 03 max test strain used with Gage 01 design strain to calculate MFT's (these MTF's used in summary table).								

APPENDIX 4 - ANALYSIS-TO-TEST CORRELATION CURVES

Key for figures in this appendix:

Test SG-XX	Measured strain value at strain gage location "XX" (see Figure 5).
Test	Measured relative displacement along specimen length.
Nominal Analysis	Predicted analysis values assuming nominal specimen thickness of 0.80 inches.
As Built Analysis	Predicted analysis values assuming as-built specimen thicknesses of 0.81 and 0.82 inches. These two thicknesses were used to determine sensitivity of specimens being within specified tolerance of $0.80 + 0.01/- 0.0$ inches (0.81 inches) and an out of tolerance condition (0.082 inches). The results showed negligible difference between the two conditions.

Figure A4-1 Test and Analysis Results Comparisons
Specimen PD20719 DTS-2 Run 406 - Matched/Unflawed

Figure A4-2 Test and Analysis Results Comparisons
Specimen PD20719 DTS-2 Run 406 - Matched/Unflawed

Figure A4-3 Test and Analysis Results Comparisons
Specimen PD20720 DTS-2 Run 506 - Undermatched/Unflawed

Figure A4-4 Test and Analysis Results Comparisons
Specimen PD20720 DTS-2 Run 506 - Undermatched/Unflawed

Figure A4-5 Test and Analysis Results Comparisons
 Specimen PD20719 DTS-C Run 604 - Matched/Flawed

Figure A4-6 Test and Analysis Results Comparisons
Specimen PD20720 DTS-5 Run 704 - Undermatched/Unflawed

Figure A4-7 Test and Analysis Results Comparisons
Specimen PD20719 DTS-6 Run 804 - Matched/Flawed

Figure A4-8 Test and Analysis Results Comparisons
Specimen PD20719 DTS-3 Run 904 - Matched/Unflawed

Figure A4-9 Test and Analysis Results Comparisons
Specimen PD20720 DTS-10 Run 1004 - Undermatched/Flawed

Figure A4-10 Test and Analysis Results Comparisons
Specimen PD20720 DTS-7 Run 1104 - Undermatched/Flawed