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FATIGUE PERFORMANCE OF FRICTION WELDED STUDS

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ABSTRACT

Early in the life of the Genesis spar, cracking developed at the welded connections between the riser guide supports and the hull wall plate. The cracking was caused by the movements of the top-tensioned risers within the steel guide frames in the moon pool of the structure. The remedial action taken to minimize the riser movements and its effects on the hull involved the use of novel rubber bumpers, which were installed in lieu of the steel guides. The bumpers around the periphery of the moon pool were fastened to the hull wall via threaded studs that were friction welded to the hull wall plate underwater.

This paper describes a testing program specifically designed to qualify the fatigue performance of the stud-plate friction welds. Results verify the use of the F2 S-N curve from British Standard 7608 with a single slope for the design of the friction-welded connections subjected to axial load. It was also found that the fatigue performance of friction welds is sensitive to the stud preload. One unique feature of the fatigue failure mode of the connection, when the load is transferred through the stud into the plate, is that cracking takes place along the semi-circular heat-affected zone (HAZ) of the bond-line between the stud and the plate, and not through the hull plate thickness. As a result, failure of a stud connection does not compromise the structural integrity of the spar hull.

Keywords: Friction stud weld, fatigue, riser support, fatigue data

INTRODUCTION

Fatigue cracking was detected in the welded connections between the riser guide frame supports and the moon pool wall in the Genesis Spar structure installed in the Gulf of Mexico in 2,650 ft of water. Several options were considered to mitigate the cracking, including the attachment of novel rubber bumper guides to the moon pool wall via friction-welded threaded studs (FWS), as illustrated in Fig. 1. Each stud is preloaded in tension via a nut reacting on a collar or sleeve placed between the nut and the wall plate; the intent of the preload is to minimize the in-service fatigue loads in the studs as the risers contact the bumper. The stud loads are ultimately transferred to the moon pool wall by the weld, creating a potential source of fatigue cracking. It was the intent of the design to exclude any such cracking.

Early fatigue tests on friction welded studs [Harrison '64] addressed the effect of FWS studs as simple passive attachments to plates. Later work [Williams, et al. '92] investigated the performance of friction welding as a means to attach studded straps to enhance shear transfer in grouted connections. More recent efforts were aimed at; (a) evaluating the fatigue resistance of friction welded solid steel bars and the use of friction welding to attach anodes to pipelines [Manteghi '94] and (b) effecting repairs in lieu of standard underwater welding [Blakemore '00]. However, none of the available data directly applied to the underwater application at hand,

which included axial load transfer through the studs.

Thus, a fatigue testing program was devised and implemented to generate relevant endurance data and identify the potential modes of failure for various levels of stud preload when the cyclic load was transferred (1) through the stud to the plate and (2) directly to the plate with the stud acting as passive attachment. The specific friction welds using the relevant stud and plate materials and equipment were first independently qualified for offshore deployment underwater.

This paper presents the details of the fatigue test specimen configurations and stud preloading, testing equipment, and experimental procedures. The fatigue test data were compared to a codified design S-N curve (F2) used in design. Based on the results of this study, the fatigue performance of the FWS was qualified and successfully deployed offshore underwater during the retrofit of the Genesis riser guide systems.

FRICTION WELDED STUD (FWS)

The advantage of friction welding studs is to produce high-integrity welds in water depths where wet welding may be very difficult or impossible, without expensive and complex hyperbaric welding chambers.

To friction weld a stud, the stud is pressed perpendicularly against the base plate, to which it is to be attached. The stud then is rotated at high speed, thereby generating enough heat to plasticize the joining materials in contact. Unlike the conventional fusion welding process, the materials in the friction weld remain in the solid phase at all times with no melting occurring.

An extensive effort was made to qualify a friction welding procedure that met all the mechanical, metallurgical, and operational requirements set for the Genesis repair, including deployment offshore and execution underwater. Detailed description of the welding equipment and procedure is outside the scope of this paper. Figure 2 shows a general view of the underwater equipment and a macro section of one weld, displaying the bond line, heat affected zones, and flashes of excess material.

TESTING PROGRAM

The testing program was designed to generate fatigue data that would capture the three potential modes of failure due to the presence of the stud;

namely, failure in the stud itself, failure in the weld, and failure in base plate.

Test Series

Three series of FWS test specimens were devised, representing different loading modes deemed to arise from the actual fastening of the bumper to hull wall.

Series 1: In this series, the load is applied directly to the stud and is carried fully by the stud into the hull plate through the friction weld. Series 1 represents the worst case scenario, and is the limiting case of Series 2 when there is no preload.

Series 2: This series most closely simulates the actual load transfer condition and is a more general case of Series 1. Here, a sleeve is placed around the stud and a nut is torqued against the sleeve, putting the stud in tension and the sleeve in compression as both react against the plate. When the stud is loaded, an alternative load path into the plate is created through the sleeve, thus relieving the friction welded connection. With proper preloading, the Series 2 configuration should be extremely fatigue resistant.

Series 3: This series represents another possible mode of cracking due to the presence of the friction stud weld on the moon pool hull plate of the Spar, as the plate sustains global bending without live load applied through the stud.

Specimens

Fabrication: A total of thirty (30) specimens were fabricated and divided into three series of ten specimens each. The actual specimen configurations for each series are illustrated in Fig. 3. All of the specimens included full-size 0.75-in (19-mm) studs with 10 threads per inch. For Series 1 and 2 they were friction welded to 1.18-in (30-mm) thick plates; for Series 3 they were welded to 0.79-in (20-mm) thick plates.

All of the specimen components were fabricated from EH36 steel. The specimens were welded in water and machined by Oceaneering using the same friction stud welding equipment and procedure that was qualified and ultimately implemented by divers during the actual repair of Genesis moon-pool guide plate supports.

Specimen designation and loading conditions are given in Tables 1 to 3 for each series, respectively.

Assembly: For Series 1 and 2 specimens, where two FWS connections are bolted together back-to-back, care was taken to minimize angular and parallel misalignments between the two mating plates. Typical parallel misalignment on the plate edges was on the order of tenths of an inch, while angular misalignment of the stud axes was less than 0.25 degrees.

For Series 2, the stud and the retaining sleeve were preloaded by torquing a nut over a Belleville washer. As a result, when the external load is applied to the connection, the sleeve re-directs approximately 90% of it away from the friction weld.

A conventional dog-bone tensile specimen with a FWS at the center of one of the faces of the plate was used in Series 3. Most of the Series 3 specimen edges were shot peened to prevent failure away from the friction weld. The specimens were assembled at the testing laboratory using the friction welded studs made by Oceaneering.

Torque and Stud Preload: Prior to assembling Series 2 and 3 specimens, FWS connections were torqued to develop preload. The amount of the stud preload is a function of the torque applied and the stiffness of the stud and the sleeve. Stud preloads were measured using strain gages attached to the stud.

The nominal torque applied was dictated by a required stud preload of 9.5 kips (42.3 kN) needed to prevent sleeve lift off at the maximum load applied to the connection during testing. The nominal torque used in Series 2 was derived by trial-and-error exercise, in which the nut was torqued over a Belleville washer placed on top of the retaining sleeve until the measured preload reached the desired value. In this way, a nominal torque magnitude of 125 ft-lbs (0.17 kN-m) was established.

However, applying a nominal torque of 125 ft-lbs (0.17 kN-m) to the Series 2 specimens resulted in measured stud preloads ranging from 8.5 to 10.3 kips (37.8 to 45.8 kN), with an average value of 9.46 kips (42.1 kN). This preload variation is a consequence of the uncertainty of the friction

effect on torque. Two specimens of Series 2 were purposely torqued to 86% and 46% of the nominal torque to assess the effect of under torquing on fatigue.

Applying the same nominal torque to Series 3 specimens, the average measured stud preload was 10.5 kips (46.7 kN). The 10% difference in preload is likely due to the different configuration of the retaining sleeve and thickness of the base plate.

Testing Procedure

The fatigue tests were conducted at Southwest Research Institute in the Solid and Fracture Mechanics Laboratory. Figure 4 shows the specimens for each of the three test series mounted in the testing machines. For Series 1 and 2 two welded connections were assembled back-to-back and testing lasted until one connection failed. A virgin specimen was then bolted to the unfailed half and the test continued until the other side failed.

Target Lives: The main objective of the tests was to qualify the S-N curve used in fatigue damage calculations, to ensure that the FWS connection design met the required fatigue life. To that end, all tests were carried out to a target number of cycles estimated from the S-N curve assumed for the connection design plus an additional number of cycles to account for the desired level of confidence (97.5%) of the results and the sample size of each series.

Specifically, in order to qualify tests against the selected F2 S-N curve, the target fatigue lives, N_{target} , at a given stress range, ΔS , were calculated using the following equation [Maddox & Schneider '00]:

$$N_{\text{target}} \geq \frac{C_{\text{mean}}}{\Delta S^m} (10^{1.645\sigma/\sqrt{n}}) \quad (1)$$

Where C_{mean} , m , and σ are the intercept, the negative inverse slope, and the standard deviation of the F2 mean S-N curve, respectively, and n is the number of test samples.

Loading: All specimens were subjected to a single sinusoidal constant amplitude (CA) load waveform. However, a limited number of specimens for Series 1 and 2 were subjected to more than one stress range as a result of the

testing strategy adopted. The loads were converted to nominal stresses using the cross-section areas associated with either the base circle diameter of the threaded portion of the stud (0.629 in/16.0 mm) or the base plate through the location of the stud connection.

For practical reasons, the loads were chosen such that the target fatigue failures would occur between 5×10^4 and 1×10^7 cycles. Likewise, the cyclic frequency was maximized for all tests, while accurately maintaining the load range. All tests were performed in closed-loop, computer-controlled mode.

In Series 1, a constant mean load of 9.5 kips (42.3 KN) was directly applied to the stud. For Series 2 tests, once the FWS was torqued, the external load was shared between the stud and the sleeve, and higher capacity test machines were required. In order to fully utilize the capacity of test machines, Series 2 specimens were tested at a constant minimum-to-maximum load ratio, R , of 0.05, implying a variable mean external load. Because of the high residual stress levels left in the welds, variation in the mean load has only a second order effect on test results.

In Series 3, a constant mean load of 100 kips (444.8 KN) was applied directly to the plate, resulting in a nominal stress of 25 ksi (172.4 MPa) at the plate cross section through the location of the FWS. To achieve failures, stress ranges between 16.5 ksi (114 MPa) and 48.3 ksi (333 MPa) were utilized.

Because of the testing strategy employed in Series 1 and 2 with two specimens bolted back-to-back, a number of specimens were subjected to two or more different stress levels. To include these results in the analysis, an equivalent or effective single-amplitude stress range was calculated according to the following equation:

$$\sigma_{eq} = \left[\frac{\sum_{i=1}^n \sigma_i^m N_i}{\sum_{i=1}^n N_i} \right]^{1/m} \quad (2)$$

in which N_i is the cycles applied at i^{th} stress level (σ_i), n is the total number of applied stress levels,

and m is the negative inverse slope of the design S-N curve.

Strain Measurements: The specimens were strain gauged to monitor the local strain distributions and variations as cycling progressed.

Each stud of Series 1 and 2 was outfitted with four strain gages, 90° apart around the outer diameter of the stud, at a longitudinal location one inch above the plate face. A radial hole was drilled in the retaining sleeves of Series 2 specimens to accommodate the strain gage wires. For Series 3 specimens, four additional gages were mounted above and below the stud in the center axis on each face of the plate, approximately 3.25-in (82.6 mm) away from the first row of gripping bolts. These gages were designed to assess the amount of global strain in the plate.

Strain measurements were taken before each test began and were continuously monitored during the tests using a special data acquisition system. This system monitors strain level at a specific applied load magnitude and allows assessment of dynamic strain magnitudes as cycling progresses. Periodic unloads were applied to evaluate the compliance of the specimen and quantify zero-load strain offset magnitude.

FATIGUE TEST RESULTS

The results of the fatigue tests for Series 1, 2 and 3 are given in Tables 1-3, respectively. The specimens subjected to more than one level of constant amplitude loads are presented in Table 4.

Series 1 has 16 data points, of which 13 were tested at a single stress range and three (OL12, OL16, OL22) were subjected to two or more stress ranges. For the specimens subjected to multiple stress ranges, an effective stress, σ_{eq} , is calculated according to Equation (2) with $m=3.27$ representing the negative inverse slope obtained from best fit to Series 1 tests under a single stress range.

The Series 2 tests produced 12 data points, of which 10 were tested at a single stress range and two (OS-2 and OS-14) at multiple ranges. As expected, the 10 specimens of Series 2 that were fully torqued reached their life targets without failure (run-out). However, the two specimens (OS-9 and OS-12) with reduced torque levels of 80% and 46% of the specified value (125 ft-lbs or

0.17 kN-m) and tested at the high stress range did fail, demonstrating the importance of properly torquing (preloading) the studs.

All of the Series 1 and two of the Series 2 specimens failed at the heat-affected-zone of the stud friction welds. The failure was either at the plate-side HAZ (dished-in, Fig. 5a) or at the stud-side HAZ (stud-out, Fig. 5b). For the dished-in plate failure mode, the flash typically remained attached to the stud half of the failure surface, whereas for the stud-out failure mode, the flash remained attached to the base plate, along with a small portion of the stub.

All Series 3 tests resulted in failures, in which cracking initiated at the plate side of the stud-plate connection and propagated through the plate thickness (Fig. 5c). This failure mode in the base plate is of particular interest as it may impact hull integrity. This is contrasted with Series 1 and 2, whose failure modes do not result in through-thickness cracking of the hull plate.

FATIGUE DATA INTERPRETATION

The stresses used in the fatigue data interpretation presented below correspond to those nominally applied to the stud or the plate by dividing the applied external load by the stud or plate cross sectional areas. Therefore, the effects of local stress concentrations and misalignment, as they are expected to occur in the actual application, are embedded in the data.

Series 1 and 3

Unlike Series 2 tests that resulted in runouts, the tests of Series 1 and 3 did reach fatigue failure. The results of the Series 1 tests are presented in Fig. 6, along with the line fitted to the data obtained with single stress ranges. The least squares fit yielded an inverse slope of 3.27 and a standard deviation of 0.255. Note that inclusion of the three additional data points obtained from testing a single specimen under various stress ranges does not significantly alter the fitted slope, if the equivalent stress given by Eq. 2 is used. The lowest line in Fig. 6 represents the mean minus two standard deviations curve, typically used in design.

Similarly, results of the Series 3 tests are presented in Fig. 7. The negative inverse slope and the standard deviation obtained from the regression analysis are 3.47 and 0.057, respectively.

Because the F2 curve [British Standards '93] was used in the overall fatigue design of the connections, Fig. 8 compares the fit of the combined Series 1 and 3 data to the F2 design curve. To consistently conduct such comparison, the inverse slope of the F2 curve of 3 was assumed in the data fit. The calculated mean-2SD curve falls above F2 design curve. Therefore, results of Series 1 and 3 tests distinctly qualify the F2 curve.

Series 2

The results of the Series 2 tests together with the F2 curves are shown in Fig. 9. Only two failures at the lower torque values were observed (see Table 2). The remainder of the tests, which were fully torqued and are indicated as open symbols, exceeded their target lives without failing (runouts). Overall, all data from Series 2 also qualify the F2. The data surpassed the target curve, as defined by Eq. 1, by at least 120% on life without failures.

All Series

Comparison of the combined database from all three series to the F2 curve is shown in Fig. 10. All of the data fall above the F2 target curve. It should also be noted that all of the data presented herein use nominal stress ranges in the stud for Series 1 and 2 or in the plate cross section for Series 3, without consideration of local stress concentration factors.

CONCLUSIONS

- A testing program was devised and successfully completed to qualify the fatigue performance of friction welded studs (FWS) installed offshore underwater. FWS were used to attach new riser guides to the moon pool wall of the Genesis spar.
- Three series of tests for friction welded studs were designed and tested to capture all potential modes of failure of the FWS: failure in the stud itself, weld, and base plate. The objective was to qualify the F2 curve used in the fatigue design of the connections.
- A total of 36 fatigue tests in three series were carried out in air using full-scale friction welded studs under constant amplitude loading and pulsating tension conditions. The target lives for the tests accounted for the

uncertainty of the F2 S-N curve and the limited number of tests. Overall, the tests amply qualified the F2 curve with a single slope used in the connection design.

- Series 2 specimens, representing the actual preloaded connection, were tested beyond their target lives. Nevertheless, none of the tests resulted in fatigue failure due to external load applied to the stud assembly, provided that the stud is fully preloaded and maintains the preload. As expected, the fatigue performance of friction stud welds is sensitive to the stud preload as demonstrated by failures when the preload was deliberately reduced to 80% and 46% of the specified value.
- Fatigue failures of the welded connection were only obtained when the load was directly transferred through the stud (Series 1) into the plate or when the plate was loaded across a FWS attached to one of its faces (Series 3).
- The failure modes of Series 1 and 2 tests, in which the stud carried load, indicate that, in the unlikely event of cracking developing, stud separation will occur around the HAZ on the stud or the HAZ on the plate. Both of these failure modes are not through thickness, thereby preserving the integrity of the moon pool wall by avoiding leakage.
- The through-wall crack failure mode exhibited by Series 3, in which only the plate was loaded and the stud was simply preloaded, can also be safely assessed by the F2 S-N curve, making hull cracking a very unlikely event in light of the relatively small global bending stresses expected on moon-pool wall during service.

- The validity of these conclusions are contingent upon the implementation of sound QA/QC processes, the basis of which includes the use of the same equipment, materials and procedures used in the preparation of the specimens tested in this program.

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**Table 1 - Summary of Series 1 Fatigue Test Results
(At constant mean load of 9.5 kips applied to the stud)**

Specimen ID	Mounted Position	Applied Load Range [kips]	Applied Stress Range [ksi]	Applied Load Cycles N	Failure Location*	Mated with Specimen
OL-18	Top	15.300	49.23	81,713	surface	OL-19
OL-19	Bottom	15.300	49.23	123,713	stud	OL-18/5
OL-5	Top	15.300	49.23	65,960	stud	OL-19/22
OL-22	Bottom	15.300	49.23	23,960	n/a	OL-5
	Bottom	12.546	40.38	146,381	stud	OL-10
OL-10	Top	12.546	40.38	179,276	stud	OL-22/21
OL-21	Bottom	12.546	40.38	226,949	surface	OL-10/6/16
OL-6	Top	12.546	40.38	100,529	stud	OL-21
OL-16	Top	12.546	40.38	93,525	n/a	OL-21
	Top	8.080	26.00	99,533	surface	OL-3
OL-3	Bottom	8.080	26.00	938,781	surface	OL-16/7
OL-7	Top	8.080	26.00	1,188,422	stud	OL-3/12
OL-12	Bottom	8.080	26.00	663,251	n/a	OL-7/9
	Bottom	5.284	17.00	1,090,182	surface	OL-15/11
OL-9	Top	8.080	26.00	314,077	stud	OL-12
OL-15	Top	5.284	17.00	1,038,169	stud	OL-12
OL-11	Top	5.284	17.00	4,214,910	surface	OL-12/8
OL-17	Top	5.284	17.00	1,898,459	surface	OL-8
OL-8	Bottom	5.284	17.00	7,289,430	stud	OL-11/17/23

* "surface" implies the HAZ on the plate side, whereas "stud" implies the HAZ on the stud side

**Table 2 - Summary of Series 2 Fatigue Test Results
(At constant R-ratio of 0.05 applied to the stud)**

Specimen ID Top/Bottom	Torque Preload, % of 125 ft-lbs Top/Bottom	Maximum Applied Load [kips]	Applied Stress Range [ksi]	Applied Load Cycles N	Comment
OS-4 / OS-6	100 / 100	9.011	27.54	1,600,000	no failure
OS-25 / OS-14	100 / 100	9.011	27.54	917,266	no failure
OS-10 / OS-2	100 / 100	6.774	20.71	1,500,000	no failure
OS-19 / OS-2	100 / 100	6.774	20.71	12,801,796	no failure
OS-17 / OS-14	100 / 100	4.505	13.77	5,000,000	no failure
OS-5 / OS-15	100 / 100	2.268	6.93	47,588,757	no failure
OS-9 / OS-12	80 / 46	9.011	27.54	504,870	OS-12 failed
OS-9 / OS-2	80 / 100	9.011	27.54	658,477	OS-9 failed

Note: Specimens OS-2 and OS-14 were used for three and two test sequences, respectively

**Table 3 - Summary of Series 3 Fatigue Test Results
(At constant mean load on the plate of 100 kips)**

Specimen ID	Applied Load Range [kips]	Applied Stress Range [ksi]	Applied Load Cycles N	Failure Location on Stud Edge
DB-5	190.0	48.26	112,765	12 o'clock
DB-11	190.0	48.26	129,062	12 o'clock
DB-15	161.5	41.02	261,678	12 o'clock
DB-1	161.5	41.02	256,405	12 o'clock
DB-6	161.5	41.02	238,560	6 o'clock
DB-14	120.0	30.48	481,849	12 o'clock
DB-9	120.0	30.48	614,430	6 o'clock
DB-7	65.0	16.51	5,654,362	12 o'clock
DB12	65.0	16.51	5,694,614	6 o'clock
DB-8	65.0	16.51	4,823,672	6 o'clock
DB-10	65.0	16.51	5,570,317	12 o'clock

Table 4 – Equivalent Stresses for Series 1 and 2 Specimens Subjected to Multi-Stress Levels

Test Series No.	Specimen ID	Increments of Tested Cycles, N	Applied Stress Range [ksi]	Total Number of Cycles, N _t	Equivalent Stress Range [ksi]
1	OL-22	23,960	49.24		
	OL-22	146,381	40.38	170,341	41.90
1	OL-16	93,525	40.38		
	OL-16	99,533	26.00	193,058	34.66
1	OL-12	349,174	26.00		
	OL-12	314,077	26.00		
	OL-12	1,038,169	17.00		
	OL-12	52,013	17.00	1,753,433	21.45
2	OS-14	5,000,000	13.77		
	OS-14	917,266	27.54	5,917,266	17.87
2	OS-2	1,500,000	20.71		
	OS-2	12,801,796	20.71		
	OS-2	658,477	27.54	14,960,273	21.13

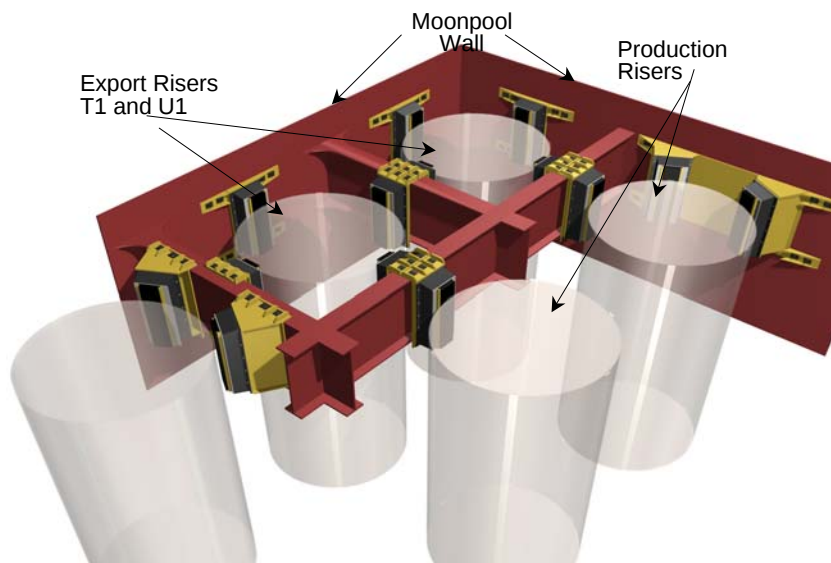


Figure 1 – Typical Riser Guide Framing in the Moonpool with the New Bumpers



Figure 2 – Welding Equipment, Friction Stud Welded Connection and Its Micro Cross Section

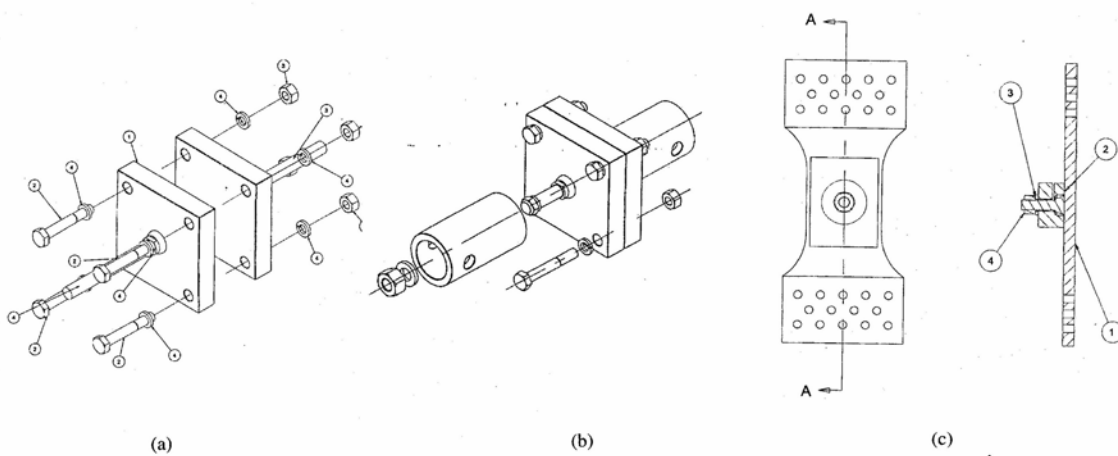


Figure 3 – Schematic of the Testing Hardware Used in
(a) Series 1, (b) Series 2 and (c) Series 3 Tests

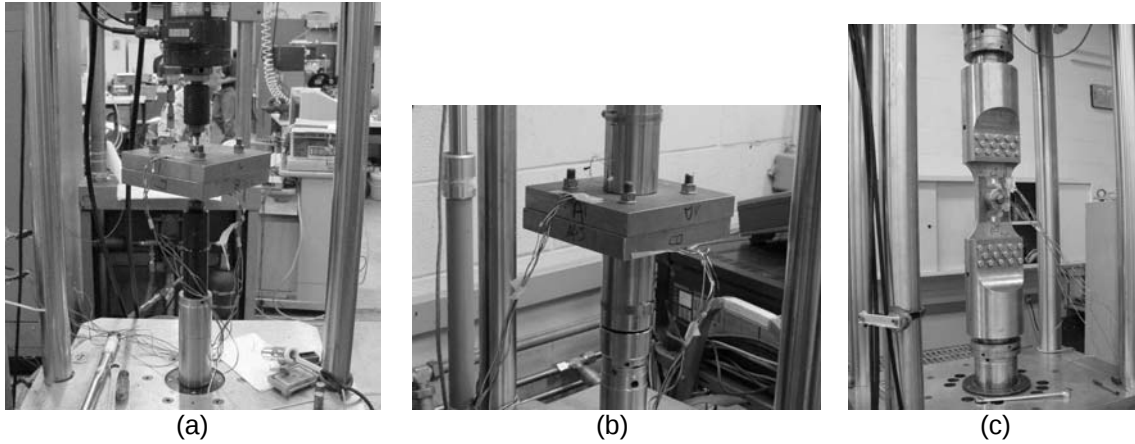


Figure 4 – Photographs of (a) Series 1, (b) Series 2 and (3) Series 3 Test Specimens Mounted in the Test Frame

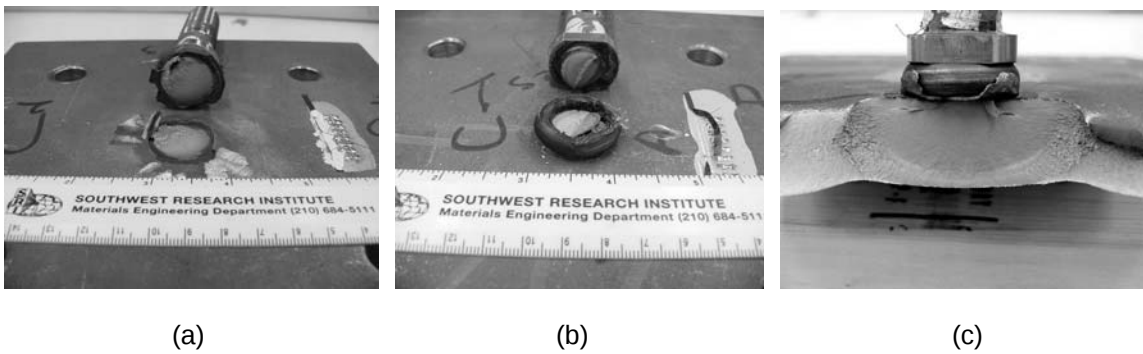


Figure 5 – Typical Failure Modes of Friction Stud Welds (a) Dish-In, (b) Stud-Out, and (c) Failure in Plate

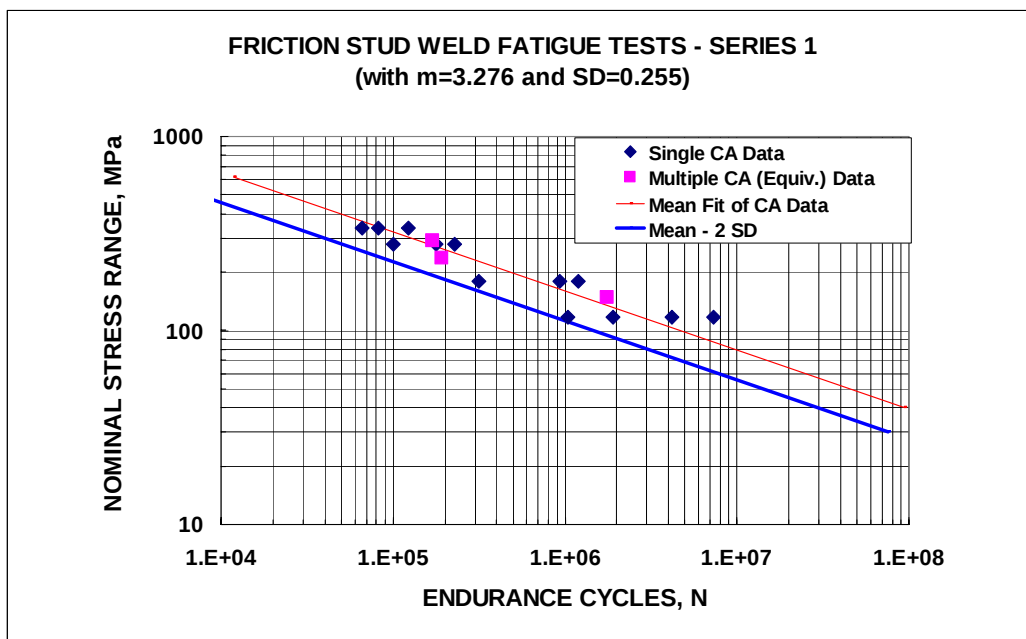


Figure 6– Series 1 Friction Stud Weld Fatigue Test Results

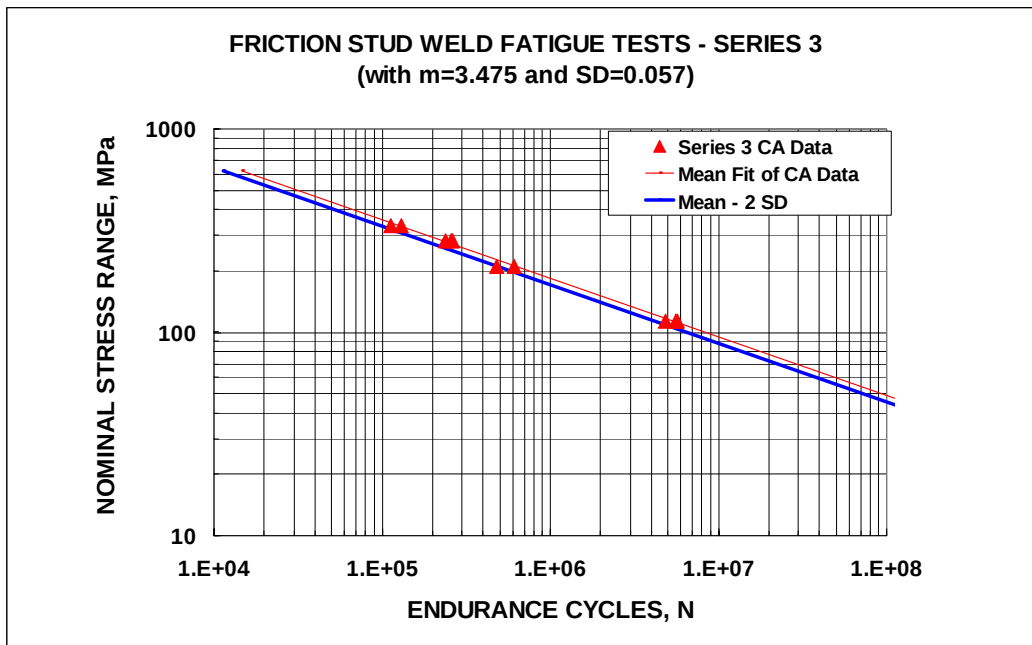


Figure 7 – Series 3 Friction Stud Weld Fatigue Test Results

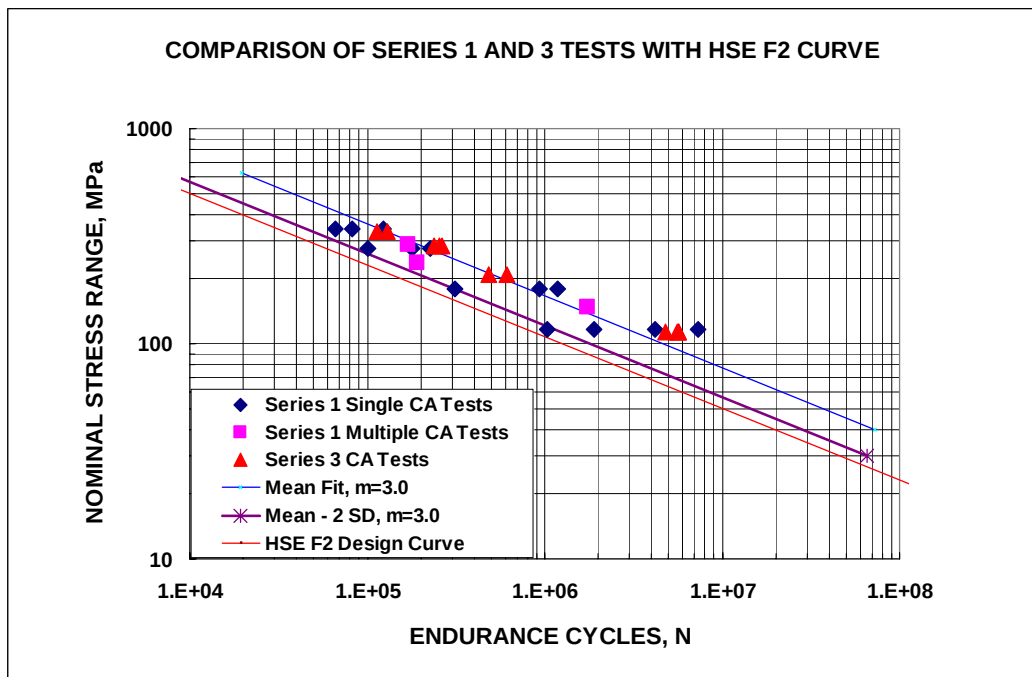


Figure 8 – Comparison of Series 1 and 3 Test Results with F2 Curve ($m=3.0$)

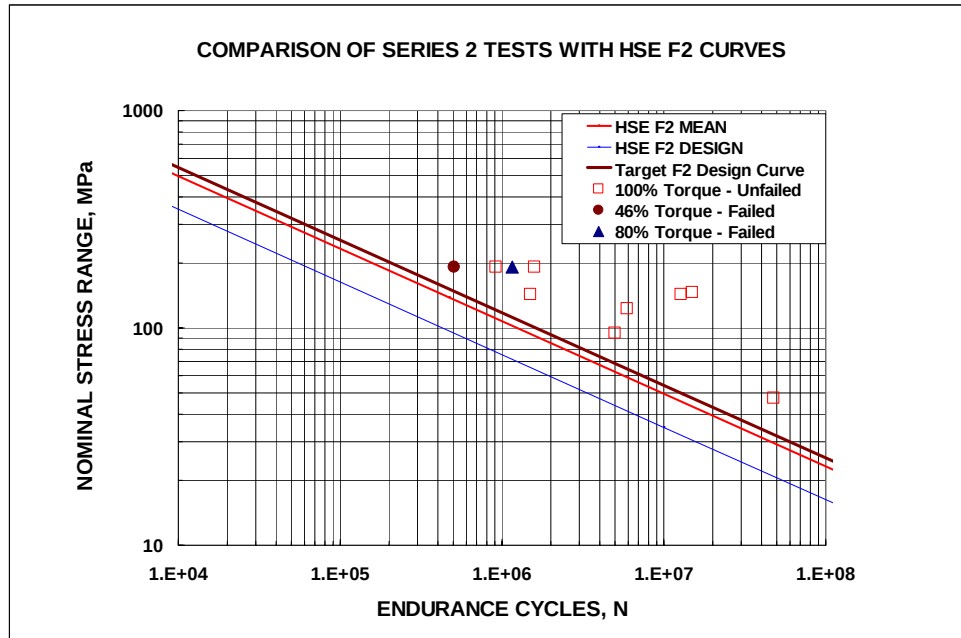


Figure 9 – Comparison of Series 2 Friction Test Results with F2 Curve ($m=3.0$)

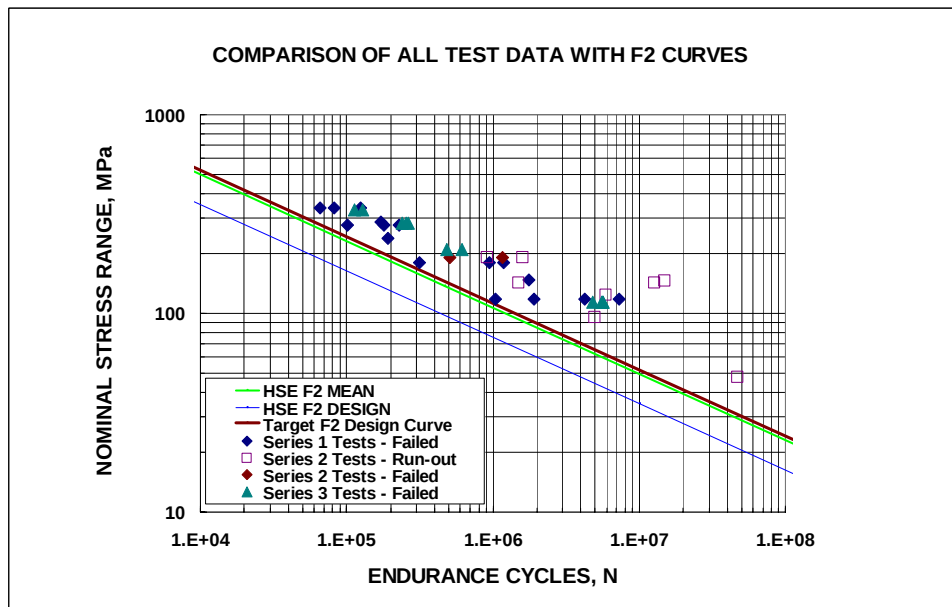


Figure 10– Comparison of All Test Data with F2 S-N Curve