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S-N Fatigue Design Guidelines and Test Data for Bolts

API TECHNICAL REPORT 21TR2
FIRST EDITION, XXXXXXXX, 202X

BALLOT DRAFT

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Introduction

The requirements for bolting fatigue assessment were a charge of the API CSOEM Multi-Segment Task Group on Bolting Failures. Due to documented subsea bolting failures defined in the BSEE QC-FIT Evaluation of Connector and Bolt Failures, the charge of the sub task group TGR-13 was the following; "*Guidance should be issued by API on when and how to perform fatigue sensitivity analysis on bolting*."

API CSOEM Bolting Report for TGR-13 and TGR-14 was issued which defined the design guidelines and provided recommendations for performing a full-scale-fatigue testing on bolting. Upon further approval, full-scale-fatigue testing was performed.

The following guidelines are provided for both design verification fatigue analysis and corresponding full scale fatigue testing that was performed.

Design verification analysis for fatigue assessment of bolting requires an evaluation for S-N or fatigue crack growth. The S-N fatigue evaluation can be based on either the stress concentrations of the thread profile, which will need stress amplification factor (SAF) or stress concentration factor (SCF) and smooth tensile bar S-N testing, or minimum root diameter stress without thread profile which will need full scale bolt fatigue tests. The basis of this document is the S-N approach using full scale fatigue testing. The purpose of the full-scale bolt fatigue testing was to obtain S-N fatigue life for bolts manufactured to meet API 20E BSL-3 and the requirements of API 17D loading condition. The fatigue testing was based on alternating axial stresses in the bolt with a defined preload. The preload was applied with the load frame to a value of 2/3*YS based on the cross-section at the root radius of the thread. The defined bolt lengths represent API flange by flange connection conservative bolt lengths for a given bolt size. The bolt to nut thread engagement met the requirements of API 6A. Each bolt tested had two bolt/nut connections where the failure of the first connection was defined as the fatigue life.

The objective of the test program was to provide S-N fatigue curves for bolts that are preloaded to API Series 17 standards and are subjected to a range of alternating axial stresses. The preload and alternating stress ranges were defined based on the cross-sectional area at the root radius of the threads. The test program evaluated bolt size effects and environments of air and saltwater with cathodic protection (CP).

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1 Scope

The scope of the test program was to obtain bolting material fatigue data required to perform design verification analysis of fatigue sensitive bolts to assure accurate design life estimation. The bolting fatigue testing program provided S-N fatigue curves for three alternating stress ranges in air and saltwater with CP and for bolt sizes of 1 in., 2 in., and 3 in.

The results of these S-N fatigue tests allow the bolting design to be assessed for S-N fatigue through structural analysis using the nominal stresses in the bolt avoiding the need to define stress and load concentrations in the bolt root radius of engaged threads.

The design guidelines and the fatigue data provided in the document are intended to be used for bolting with unified national thread with root radius (UNR) specifications of ASME B1.1.

2 Normative References

There are no referenced documents that are indispensible for the application of this document.

3 Terms, Definitions, Abbreviated terms, and Symbol

3.1 Terms and Definitions

3.1.1
High Stress Range Fatigue Cycles
HFC
Tested fatigue cycles to failure for a high stress range or high force condition applied.

3.1.2
Low Stress Range Fatigue Cycles
LFC
Tested fatigue cycles to failure for a low stress range or low force condition applied.

3.1.3
Medium Stress Range Fatigue Cycles
MFC
Tested fatigue cycles to failure for a medium stress range or medium force condition applied.

3.1.4
Stress Range
The difference between the maximum stress and minimum stress being applied.

3.2 Acronyms, Abbreviations, and Symbols

CP	Cathodic Protection
EF	Electric Furnace
HFC	High Stress Range Fatigue Cycles
FSF	Full Scale Fatigue
LFC	Low Stress Range Fatigue Cycles
MFC	Medium Stress Range Fatigue Cycles
MPS	Manufacturing Process Specification
SAF	Stress Amplification Factor
SCE	Saturated Calomel Electrode
SCF	Stress Concentration Factor
S-N	Stress – Number of Cycles to Failure
UNR	Unified National Thread with Root Radius
YS	Yield Strength
$\Delta\sigma$	Stress Range

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2SD	Two times the standard deviation value

4 Bolting Fatigue Analysis Design Guidelines

4.1 Fatigue Sensitivity Criteria for Bolting

Bolting which transfers loads of the riser systems to the wellhead should be considered fatigue sensitive and should be evaluated for cyclic loading. This includes cyclic loadings from drilling risers, workover/ completion risers and production risers. Other bolting may require fatigue evaluation depending on the operating conditions and the load path.

Fatigue sensitive bolts should typically include the bolts and nuts for flanged connections, bolts which are threaded directly into components and bolts for clamp connections.

4.2 Bolting S-N Fatigue Analysis Procedure

Fatigue sensitive bolts using unified screw threads should be designed and analyzed per these methods. The following steps should be used for the bolt fatigue anlaysis using the S-N test data available in this document.

Step 1:

The evaluation of the connection for fatigue alternating stresses is to be performed without modeling the threads as the fatigue curves have been defined based on full scale bolt fatigue testing, as presented in section 5. The bolt fatigue stress analysis, without the threads modeled, should be conducted using linear elastic material properties. The minimum specified yield strength should be used for the analysis per the API and ASTM standards or supplier defined minimum yield strength material specification.

Step 2:

Apply the bolt preload to a minimum of 67% of bolt yield strength.

Step 3:

Apply the applicable loads. The analysis of bolting for fatigue should define the alternating stresses in the highest loaded bolt of the component for defined cyclic loads of pressure, temperature and external loads. The maximum stress of the alternating stress range should not exceed the allowable axial stress limit of 83% of the minimum yield strength of bolt based on minimum root diameter. Both axial and bending stresses in the bolt should be considered for the fatigue evaluation. Bolt bending stress should be converted to equivalent tension stress and combined with the axial stress to define the total alternating stress range.

Combinations of internal pressure, external bending/tension and thermal induced cyclic loads should be evaluated for fatigue of the bolting. Thermal loads should be evaluated for both thermal expansion/ contraction loads that result in external load of the connection and the thermal expansion of the connection which produces direct loads on the bolting. Cyclic loads should include axial preload and all external loads.

Step 4:

Calculate the stress range for the bolt. The stress range due to cyclic load should be defined as the minimum stress due to bolt preload or the minimum stress due to external loading, whichever is the smaller value, and the maximum stress due to external cyclic load.

Step 5:

Using the stress range, calculate the fatigue life for the bolt using the S-N test data in section 5. The stress range of the bolt shank is the stress value to define the total cycles to failure for a given environment based full scale test data. No mean stress correction for applying this method is necessary. Palmgren-Miner‘s Rule should be used for accumulated damage for assessing different cyclic load cases.

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The bolts being assessed shall have the same parameters as the bolts that were used in the full-scale fatigue testing in section 5. Key parameters are the thread form, thread processing, material, material processing and bolt preload. Interpolation of fatigue curves is acceptable for bolt diameter sizes greater than 1 in. and smaller than 3 in. having an 8-UNR thread diameter.

5 Full-Scale-Fatigue Test Data for Bolting

5.1 Bolting Materials

5.1.1 General

Three sizes of (1 in., 2 in., and 3 in.) bolts and nuts were used for conducting the full scale fatigue (FSF) testing of low alloy steel. Depending on the diameter, bolts and nuts sizes, materials, and corresponding standards are given in Table 1.

Table 1 - Bolts and Nuts used for Phase 1 of FSF Testing of LAS Bolting

Bolt Size, (in.)	Bolt Material and Corresponding Standards	Nut Size (in.)	Nut Material and Corresponding Standards
1 (8 UNR Class 2A)	ASTM A320, Grade L7	1 (8 UNC Class 2B)	ASTM A194, Grade 7L
2 (8 UNR Class 2A)	ASTM A320, Grade L7	2 (8 UNC Class 2B)	ASTM A194, Grade 7L
3 (8 UNR Class 2A)	ASTM A320, Grade L43-Modified	3 (8 UNC Class 2B)	ASTM A194, Grade 7L

All bolts and nuts were manufactured in accordance with API 20E BSL-3. Two heats from each bolt size were procured from two different manufacturers, defined as supplier 1 (Heat 1) and supplier 2 (Heat 2) for variability of the tested samples. For each size 23 bolts and 41 nuts were procured from each manufacturer.

5.1.2 Bolting Materials Manufacturing Procedure

Low alloy steel was produced by electric furnace (EF) with secondary refinement using vacuum degassing. Hot rolled bars were heat treated, and then bolts and nuts were machined by the manufacturers. Prior to manufacture of the bolts and nuts, manufacturing process specifications (MPS) were prepared by the manufacturers and approved by the API technical team for this project.

All the threads were machined (cut) threads. The Heat 1 bolts were double ended studs and the heat 2 bolts were full threaded bolts. All the nuts were machined from barstock.

5.1.3 Bolting Materials Chemical Composition

Heat numbers, hot rolled reduction ratio, and chemical composition of the bolts and nuts, are given in Table 2.

Table 2 –Bolts and Nuts Heat Numbers, Reduction Ratios, and Chemical Composition

Bolt Heats	Heat No.	Forged Bar RR	Bolt/Nut	C	Mn	P	S	Si	Cr	Mo	B	Ni

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Heat 1	J5568	788:1	1 in. bolt	0.41	0.97	0.011	0.003	0.23	1.03	0.2	0.0004	-
	W1577 (31 off)	378:1	1 in. nut	0.42	0.97	0.008	0.007	0.28	0.98	0.2	0.0002	-
	L8484 (10 off)	443:1	1 in. Nut	0.41	0.97	0.008	0.01	0.25	0.98	0.20	0.0002	-
	L9638	159.7:1	2 in. bolt	0.41	0.98	0.007	0.007	0.30	1.07	0.15	0.0002	-
	L9500	132:1	2 in. nut	0.41	0.97	0.008	0.001	0.26	0.98	0.20	0.0002	-
	W1084	102.2:1	3 in. Bolt	0.41	0.78	0.009	0.002	0.25	0.87	0.27	0.0002	1.79
	W0884	49.3:1	3 in. Nut	0.41	0.98	0.008	0.005	0.27	0.99	0.2	0.0002	
Heat 2	632560	189.8	1 in. Bolt	0.41	0.86	0.008	0.002	0.29	1.09	0.25	0.0002	
	633517	109.6	1 in. Nut	0.40	0.88	0.008	0.002	0.34	1.01	0.23	0.0003	
	633517	76.1	2 in. Bolt	0.40	0.88	0.008	0.002	0.34	1.01	0.23	0.0003	
	633860	27.4	2 in. Nut	0.41	0.88	0.007	0.003	0.27	1.03	0.24	0.0004	
	631641	34.6	3 in. Bolt	0.40	0.74	0.007	0.004	0.28	0.82	0.3	0.0003	1.91
	631641	34.6	3 in. Bolt	0.40	0.74	0.007	0.004	0.28	0.82	0.3	0.0003	1.91
	633860	14	3 in. Nut	0.41	0.88	0.007	0.003	0.27	1.03	0.24	0.0004	

5.1.4 Bolting Materials Heat Treatment

Heat treatment conditions of the bolts and nuts performed by the manufacturers prior to machining are given in Table 3.

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Table 3 - Heat Treatment Details of the Bolts and Nuts Prior to Machining

Bolt Heats	Heat No.	Bolt / Nut	Normalizing			Austenitizing			Tempering		
	-	-	Temp (F)	Time (h)	Cooling Media	Temp (F)	Time (h)	Cooling Media	Temp. (F)	Time (h)	Cooling Media
Heat 1	J5568	1 in. Bolt	1650	2.5	Air	1575	2.5	Polymer	1160	3.0	Water
	W1577 (31 off)	1 in. Nut	1650	2.5	Air	1550	2.5	Polymer	1160	3.0	Water
	L8484 (10 off)	2 in. Bolt	1650	3	Air	1575	3.0	Polymer	1160	3.5	Water
	L9638	2 in. Nut	1650	3.0	Air	1550	3.0	Polymer	1160	3.5	Water
	L9500	3 in. Bolt	1650	3.0	Air	1575	3.0	Oil	1st:1165 2nd:1115	3.5 3.5	Water Water
	W1084	3 in. Nut	1650	3.5	Air	1550	3.5	Polymer	1160	3.5	Water
Heat 2	W0884	1 in. Bolt	-	-	-	1580	1.67	Oil	1148	2.33	Polymer
	633517	1 in. Nut	-	-	-	1580	1.5	Oil	1148	2.33	Polymer
	633517	2 in. Bolt	-	-	-	1580	1.67	Oil	1148	2.33	Polymer
	633860	2 in. Nut	-	-	-	1580	1.5	Oil	1148	2.33	Polymer
	631641 (11 off)	3 in. Bolt	-	-	-	1580	1.67	Oil	1st:1148 2nd:1148	2.5 2.5	Polymer Polymer
	631641 (12 off)		-	-	-	1580	1.67	Oil	1st:1148 2nd:1148	2.5 2.5	Polymer Polymer
	633860	3 in. Nut	-	-	-	1580	1.5	Oil	1148	2.33	Polymer

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5.1.5 Bolting Materials Mechanical Properties

Mechanical properties including yield strength at 0.2% offset line, ultimate tensile strength (UTS), percent elongation, percent reduction in area (RA), Hardness in Rockwell C scale, Charpy V-Notch impact value at -75° F (Heat 1) and -150° F (Heat 2) given in Table 4.

Table 4 - Mechanical Properties of the Bolts and Nuts

Bolt Heats	Heat No.	Bolt/ Nut	Yield Strength (ksi)	UTS (ksi)	Elongation %	RA %	Hardness HRC or (HB)	CVN Impact Value,
Heat 1	J5568	1 in. Bolt	116.7	133.3	23.5	63	28-28	88, 82, 82 ft.lbs at -75 °F
	W1577 (31 off)	1 in. Nut	-	-	-	-	28-31	74, 74, 76 ft.lbs at -75 °F
	L8484 (10 off)	1 in. Nut	-	-	-	-	27-30	74, 74, 72 ft.lbs at -75 °F
	L9638	2 in. Bolt	117.4	135.0	23	63.2	28-29	62, 66, 77 ft.lbs at -75 °F
	L9500	2 in. Nut	-	-	-	-	28-30	79, 76, 77 ft.lbs at -75 °F
	W1084	3 in. Bolt	120.9	138.7	24.0	63.2	29-30	76, 80, 80 ft.lbs at -75 °F
	W0884	3 in. Nut	-	-	-	-	30-32	32, 46, 33 ft.lbs at -75 °F
Heat 2	632560	1 in. Bolt	113.8	130.7	22.4	62.1	28-29 (272-279)	33, 26, 31 ft.lbs at -150 F
	633517	1 in. Nut	-	-	-	-	29-30 (281-294)	26.5, 28, 29.5 ft.lbs at -150 F
	633517	2 in. Bolt	105.9	128.9	24.0	63.1	28-29 (273-294)	21.4, 20.7, 20.7 ft.lbs at -150 F
	633860	2 in. Nut	-	-	-	-	29-29 (278-293)	34.7, 33.2 29.5 ft.lbs at -150 F
	631641 (11 off)	3 in. Bolt	113.9	132.3	25.0	62.3	28-28 (283-291)	31, 31, 32.5 ft.lbs at -150 F
	631641 (12 off)	3 in. Bolt	115.3	133.5	24.4	63.4	28-29 (278-293)	26.6, 25.8 28.8 ft.lbs at -150 F
	633860	3 in. Nut	-	-	-	-	26-26 (278-297)	21.4, 26.5, 28.03 ft.lbs at -150 F

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5.2 S-N Fatigue Testing

5.2.1 General

Full-scale fatigue test of low alloy steel bolts was conducted for bolt sizes of 1 in., 2 in. and 3 in. diameter from two different manufacturers at three different load levels within the specified load range provided in Table 5. Each bolt size was threaded in accordance with AMSE B1.1, Class 2 or 3, with 1 in.-8UNR, 2 in.-8UNR and 3 in.-8UNR threads, respectively.

Table 5 - Load Levels Applied to Bolts (SMYS = 105ksi [725 MPa])

Stress Range Designation	**Minimum Stress %SMYS, ksi (MPa)**	**Maximum Stress %SMYS, ksi (MPa)**
LFC	67%, 70 (485)	75%, 79 (544)
MFC[a]	67%, 70 (485)	83%, 87 (602)
MFC + 10%	67%, 70 (485)	91%, 95 (627)
HFC	67%, 70 (485)	100%, 105 (725)
a Load range was defined due to 1 in. bolts showing infinite life at MFC stress range.		

Table 6 shows the bolt dimensions and the calculated nominal root diameter and corresponding nominal root area for each bolt size.

Table 6 - Bolt Dimensions and Calculated Nominal Area for Each Bolt Size

Bolt Diameter in. (cm)	**Bolt Length in. (cm)**	**Class 2A Nominal Root Diameter in. (cm)**	**Nominal Root Area in.^{2} (cm^2)**
1 (2.54)	7 (17.8)	0.8390 (2.131)	0.5528 (3.566)
2 (5.08)	18 (45.7)	1.8382 (4.669)	2.6538 (17.121)
3 (7.62)	28 (71.1)	2.8376 (7.208)	6.3239 (40.799)

Table 7 shows the stress range designation, stress range and corresponding loads that were applied to each bolt size during testing both in ambient air (dry) and SW+CP (wet) environments, respectively. The reason for stress range designation MFC + 10% will be discussed in the next section. Tests in ambient air were conducted to produce reference S-N curves for each bolt size.

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Table 7 - Applied Stress Ranges and Corresponding Loads for Each Bolt Size

Bolt Diameter in. (cm)	Stress Range Designation	Stress Range, Δσ, ksi (MPa)	Min. Load, lbs (kN)	Max. Load, lbs (kN)
1 (2.54)	HFC	35 (241)	38,890 (173)	58,223 (259)
	MFC + 10%	25 (174)	38,890 (173)	52,828 (215)
	MFC	17 (116)	38,890 (173)	48,332 (194)
2 (5.08)	HFC	35 (241)	186,584 (830)	278,527 (1239)
	MFC + 10%	25 (174)	186,584 (830)	231,104(1028)
	MFC	17 (116)	186,584 (830)	231,094 (928)
3 (7.62)	HFC	35 (241)	445,554 (1982)	664,958 (2958)
	MFC + 10%	25 (174)	445,554 (1982)	551,906(2455)
	MFC	17 (118)	445,554 (1982)	551,884 (2218)

5.2.2 S-N Fatigue Testing in Ambient Air (Dry)

After a detailed and thorough load frame alignment and calibration procedure, two load frames (MTS 1000 kN and Instron 300 kN) were used to test the 1 in. bolts. The purpose of two load frames was to speed up the completion of the 1 in. bolt tests. The 2 in. and 3 in. bolts were tested using an Instron 4000 kN load frame. The test frequency for each bolt size was the maximum that the specific load frame could apply. For all bolt sizes, the maximum/minimum applied loads as well as maximum/minimum displacements at the specific applied stress range were recorded and saved for post-test reviewing.

The actual stress range designation for all bolt sizes in ambient air are shown in Table 7. The stress range designation MFC + 10% was selected during testing of 1 in. bolts. This is because several 1 in. bolts at MFC stress range designation exhibited infinite lives (run-out). Therefore, the stress range designation shown in Table 7 was used for all bolt sizes not only to provide three different stress ranges to complete the 1 in. bolt size testing program, but also consistency for all bolt sizes.

5.2.3 S-N Fatigue Testing in Saltwater with CP (Wet)

For SW+CP testing, the same load frames were used for each specific bolt size. Each load frame was again subjected to a complete and thorough load frame alignment and calibration procedure as the in ambient air tests.

The saltwater test solution consisted of 3.5 wt.% Sodium Chloride (NaCl) in deionized water. The purpose of using deionized water was to avoid precipitation of calcareous scale on the surface of the bolts during testing which can reduce hydrogen uptake during cathodic protection. The target solution pH of 8.2 was achieved and kept constant with the addition of either NaOH/NaCl solution of pH = 12 or HCl/NaCl solution of pH = 2. The saltwater oxygen concentration was reduced and maintained at less than 20ppb during each test. The saltwater temperature in the test chamber was controlled and maintained at 39.2°F (4°C).

Prior to initiation of testing, each bolt size was pre-charged at an applied potential of -1050 mV (versus saturated calomel electrode [SCE]) for four (4) days under pre-load and the applied potential was maintained on the bolt until termination of the test. After pre-charging period, the specific stress range designation (Table 7) was applied to each bolt size at the frequency of 0.3 Hz until bolting failure.

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For each bolt size tested in SW+CP, the following data were recorded:

- Test solution temperature in the test chamber
- Maximum/minimum load as well as maximum/minimum displacement
- Oxygen concentration
- Solution pH
- Cathodic protection potential
- Number of cycles to failure

5.2.4 S-N Fatigue Testing in Ambient Air (Dry) and Saltwater with CP (Wet)

Table 8, Table 9 and Table 10 show the S-N test results for the 1 in., 2 in. and 3 in. bolts, respectively. Due to exhaustion of allocated load frame times by the laboratory, some of the stress range designations indicated in Table 5 were not conducted for 2 in. and 3 in. bolts in ambient air and SW+CP.

Table 8: S-N Fatigue Test Results for 1 in. Bolts in Ambient Air (Dry) and SW+CP (wet) Conditions

Heat / Test Condition	Specimen ID	Δ σ ksi [MPa]	Tested Cycles	Comment
1/Dry	1-D-H-U-1	35 [241]	46,373	
1/Dry	1-D-H-U-2	35 [241]	46,788	
1/Dry	1-D-H-U-5	35 [241]	44,212	
1/Dry	1-D-M-U-3-2	25 [174]	139,104	MFC + 10%
1/Dry	1-D-M-U-4	25 [174]	141,828	MFC + 10%
1/Dry	1-D-M-U-6-2	25 [174]	202,464	MFC + 10%
1/Dry	1-D-M-U-7	17 [118]	717,557	
1/Dry	1-D-M-U-3	17 [118]	3,249,584	runout
1/Dry	1-D-M-U-6	17 [118]	3,590,920	runout
1/Dry	1-D-M-U-8	17 [118]	24,181,373	runout
2/Dry	1-D-H-O-1	35 [241]	60,415	
2/Dry	1-D-H-O-2	35 [241]	68,082	
2/Dry	1-D-H-O-3	35 [241]	49,611	
2/Dry	1-D-M-O-4-2	25 [174]	29,4771	MFC + 10%

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2/Dry	1-D-M-O-5	17 [118]	703,439	
2/Dry	1-D-M-O-7	17 [118]	1,141,077	
2/Dry	1-D-M-O-4	17 [118]	2,493,418	runout
2/Dry	1-D-M-O-6	17 [118]	12,933,856	runout
1/Wet	1-W-H-U-1	35 [241]	22,699	
1/Wet	1-W-H-U-2	35 [241]	21,144	
1/Wet	1-W-H-U-3	35 [241]	19,981	
1/Wet	1-W-M-U-4	25 [174]	41,875	MFC + 10%
1/Wet	1-W-M-U-5	25 [174]	36,311	MFC + 10%
1/Wet	1-W-M-U-6	17 [118]	149,290	
1/Wet	1-W-M-U-7	17 [118]	147,983	
1/Wet	1-W-M-U-8	17 [118]	133,662	
1/Wet	1-W-M-U-9	17 [118]	163,450	
2/Wet	1-W-H-O-1	35 [241]	19,423	
2/Wet	1-W-H-O-2	35 [241]	21,147	
2/Wet	1-W-H-O-3	35 [241]	26,837	
2/Wet	1-W-M-O-4	17 [118]	189,014	
2/Wet	1-W-M-O-5	17 [118]	256,895	
2/Wet	1-W-M-O-6	17 [118]	189,002	
2/Wet	1-W-M-O-7	17 [118]	158,313	
2/Wet	1-W-M-O-9	17 [118]	149,135	correct potential
2/Wet	1-W-M-O-10	17 [118]	299,241	correct potential
2/Wet	1-W-M-O-11	17 [118]	180,708	correct potential

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2/Wet	1-W-L-O-8	9 [59]	1,635,607	LFC*****, run out. Test stopped
2/Wet	1-W-L-O-12	12 [80]	1,260,569	LFC*****+4%, run out. Test stopped

***** Tests conducted for information

Table 9: S-N Fatigue Test Results for 2 in. Bolts in Ambient Air (Dry) and SW+CP (Wet) Conditions

Heat / Test Condition	**Test String**	**Δ σ [ksi]**	**Tested Cycles**	**Comment**
1/Dry	2-D-H-U-1	35 [239]	33,824	
1/Dry	2-D-H-U-2	35 [239]	31,852	
1/Dry	2-D-H-U-3	35 [239]	35,448	
1/Dry	2-D-M-U-4	17 [118]	299,286	
1/Dry	2-D-M-U-5	17 [118]	322,676	
1/Dry	2-D-M-U-6	17 [118]	285,899	
1/Dry	2-D-L-U-7	11.6 [80]	16,735,547	LFC*****+4%, run out. Test stopped
2/Dry	2-D-H-O-1	35 [239]	42,600	
2/Dry	2-D-H-O-2	35 [239]	41,957	
2/Dry	2-D-H-O-3	35 [239]	40 975	
2/Dry	2-D-M-O-4	17 [118]	353,630	
2/Dry	2-D-M-O-5	17 [118]	352,474	
2/Dry	2-D-M-O-6	17 [118]	257,321	
1/Wet	2-W-H-U-1	35 [239]	22,753	
1/Wet	2-W-H-U-2	35 [239]	24,290	
1/Wet	2-W-H-U-3	35 [239]	25,807	

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1/Wet	2-W-M-U-4	17 [118]	123,493	
2/Wet	2-W-H-O-1	35 [239]	28,133	
2/Wet	2-W-H-O-2	35 [239]	26,871	
2/Wet	2-W-H-O-3	35 [239]	27,206	
***** Tests conducted for information				

Table 10: S-N Fatigue Test Results for 3 in. Bolts in Ambient Air (Dry) and SW+CP (Wet) Conditions

Heat /Test Condition	**Test String**	**∆ σ [ksi]**	**Tested Cycles**	**Comment**
1/Dry	3-D-H-U-1	35 [239]	28,931	
1/Dry	3-D-H-U-2	35 [239]	28,990	
1/Dry	3-D-H-U-3	35 [239]	28,968	
1/Dry	3-D-M-U-4	17 [118]	245,237	
1/Dry	3-D-M-U-5	17 [118]	327 091	
1/Dry	3-D-M-U-6	17 [118]	238 083	
1/Dry	3-D-M-U-7	8.4 [58]	10,482,717	LFC, run out
2/Dry	3-D-H-O-1	35 [239]	30,095	
2/Dry	3-D-H-O-2	35 [239]	29,989	
2/Dry	3-D-H-O-3	35 [239]	30,254	
2/Dry	3-D-M-O-4	17 [118]	199,318	
2/Dry	3-D-M-O-5	17 [118]	223,213	
2/Dry	3-D-M-O-6	17 [118]	203,548	
2/Dry	3-D-L-O-7	8.4 [58]	10,883,093	LFC, run out
1/Wet	3-W-H-U-1	35 [239]	23,676	
1/Wet	3-W-M-U-4	17 [118]	116,184	

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1/Wet	3-W-M-U-5	17 [118]	112,301	
2/Wet	3-W-H-O-1	35 [239]	25,649	
2/Wet	3-W-H-O-2	35 [239]	24,395	
2/Wet	3-W-H-O-3	35 [239]	25,516	
2/Wet	3-W-M-O-4	17 [118]	115,689	
2/Wet	3-W-M-O-5	17 [118]	128,350	

5.2.5 1 in. Bolt Evaluation at MFC (Δσ = 17 [118 MPa])

Table 1 shows that at applied stress range designation of MFC or Δσ = 17 ksi (118 MPa), the 1 in. bolts from both manufacturers exhibited both finite lives and run-outs. The discrepancy in fatigue lives at this specific applied stress range was surprising and thus prompted an investigation into possible differences in the two load frames that were used to test the 1 in. bolts, as well as differences in the thread root profiles between the bolts supplied by the two manufacturers.

Thorough investigation of the applied maximum and minimum loads at Δσ = 17ksi (118 MPa) between the two load frames using dummy test specimens showed that the test result discrepancy for 1 in. bolts in ambient air is not due to the load frames.

Metallurgical investigation of possible differences in the thread root profile of the 1 in. bolts from Heat 1 and Heat 2 provided some interesting insight. Figure 1 is a high magnification image showing general condition at the thread root profile of the 1 in. bolts provided by the two manufacturers. Comparison of the image illustrate that the thread root profile of the 1 in. bolts from one of the manufacturers contain smoother thread root profile (1a) than the bolts from the other manufacturer which contain much rougher surface (white arrow in 1b).

The much rougher thread root profile could be due to a worn machine tool or chatter due to excessive pressure during threading. The surface imperfections of the root profile will act as a stress riser and will have a significant effect on reducing the number of cycles to fatigue crack initiation and hence, total fatigue life of the bolts. Scanning electron microscopy (SEM) image in Figure 1c clearly shows fatigue crack initiation from the surface imperfections on the thread root which can result in a finite life at the applied stress range of Δσ = 17 ksi (118 MPa). An example is 1 in. bolt with test laboratory designation 1-D-M-O-5 where N_f = 703,439 cycles. A bolt with smooth thread root profile, such as 1-D-M-U-6 in Table 8, has shown infinite life (run-out).

Further investigation of the 1 in. bolts with smooth thread root profiles showed that some of the bolts did contain an imperfection (e.g., potentially due to tool mark) that went all the way around the first thread flank as shown in Figure 2. Even with a smooth thread root profile, such imperfections on the thread flanks will act as stress riser and will have a significant effect on reducing the number of cycles to crack initiation and hence, total fatigue life of the bolt. 1 in. bolt with test laboratory designation 1-D-M-U-7 shown in Figure 2 exhibited a fatigue life of N_f = 717,557 cycles as indicated in Table 8 with a smooth thread root profile.

The metallurgical investigation of the 1 in. bolts clearly illustrates that even though the bolts from the two different manufacturers were compliant with requirements of API 20E BSL-3, thread root profiles and thread flank conditions can have a significant effect on the bolting fatigue life.

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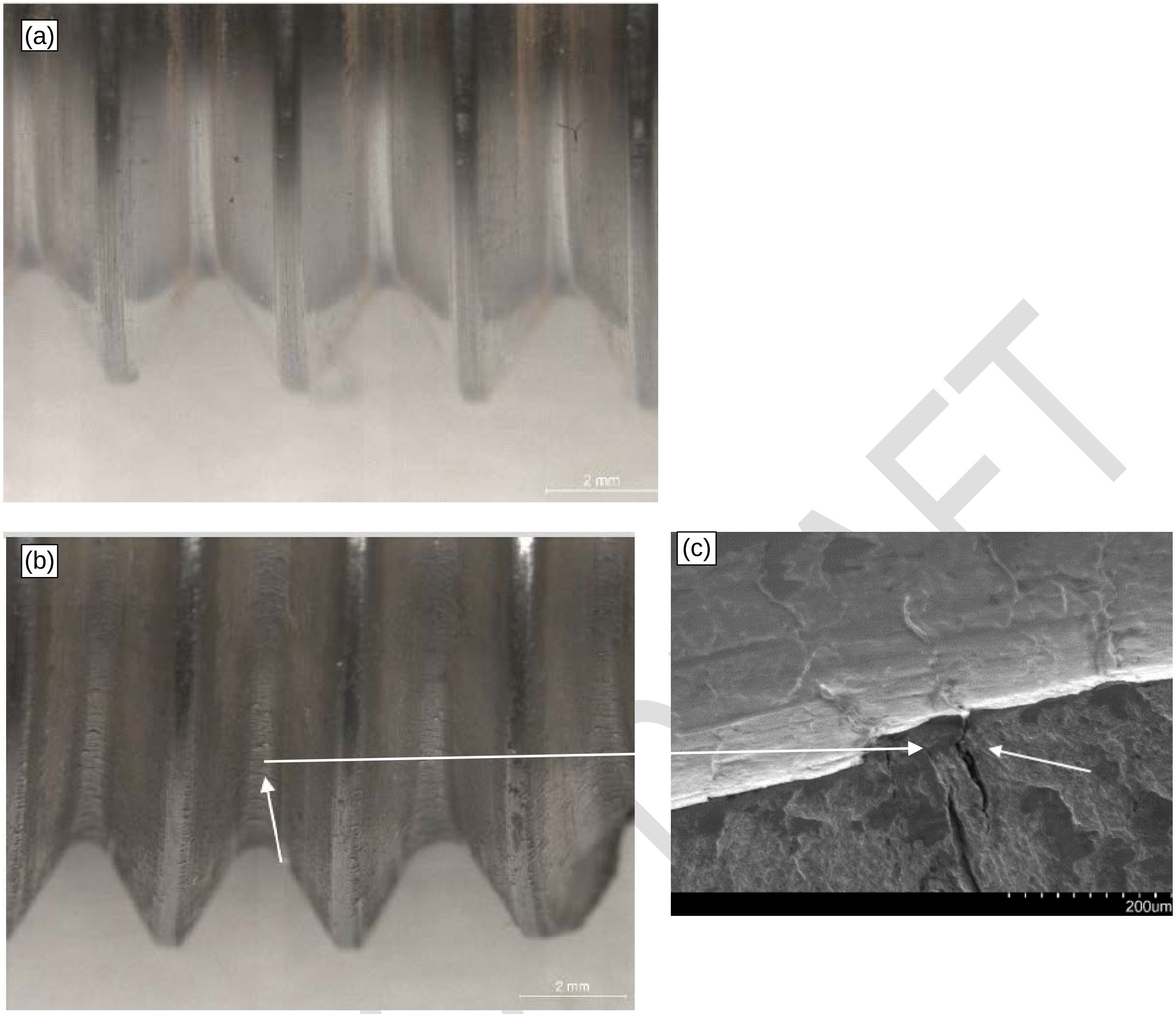

Key

(a) Smoother surface from the Heat 1.

(b) Rougher profile due to machining chatter (white arrow) from the Heat 2.

(c) SEM image illustrating crack initiation (white arrow) from the rougher thread root

Figure 1 - Thread Root Profiles for 1 in. Bolts from the Two Heats (Manufacturers)

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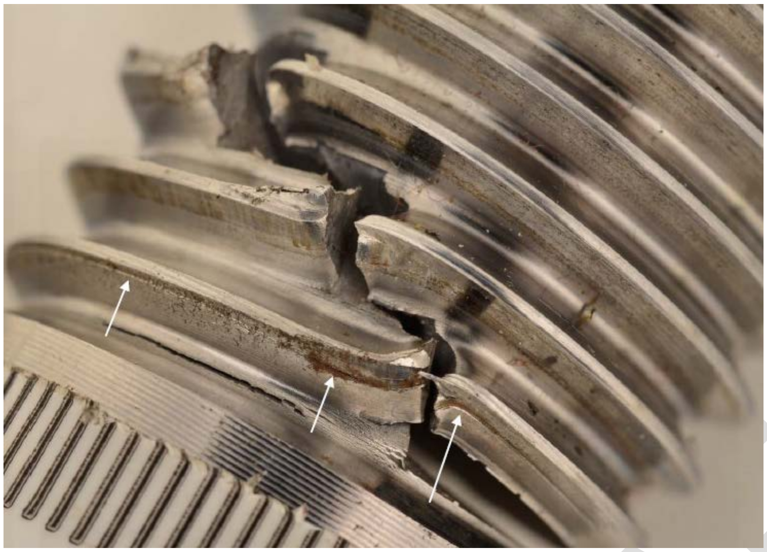

Figure 2 - 1 in. Bolt,1-D-M-U-7 Showing an Imperfection

5.2.6 Applied Cathodic Potential Effects

Midway through testing of 1 in. bolts in SW+CP, it was realized that the tested bolts were exposed to a more negative potential (-1095 mV versus SCE) instead of -1050mV versus SCE. The higher negative applied potential was due to using an SCE reference electrode with a different salt concentration. The higher negative applied potential meant that the already tested 1 in. bolts could have higher absorbed atomic hydrogen and hence, higher hydrogen permeation through the bolts which could have resulted in lower fatigue life.

In order to check this difference in applied potential and its effect on fatigue lives, three (3) extra 1 in. bolts were tested at the correct applied potential of -1050 mV (versus SCE with the correct salt concentration) as shown in Table 8. All bolts were exposed to a stress range of Δσ = 17ksi (118 MPa). The results in Table 8 illustrates that at the correct applied potential, the corresponding fatigue lives are in the same range as the bolts exposed to the higher negative potential. This ensured that the initial tests in SW+CP were not adversely affected by the slightly lower negative applied potential.

Figure 3, Figure 4 and Figure 5 show the S-N fatigue curves obtained for the 1 in., 2 in. and 3 in. bolts in ambient air, respectively. The plots also show the mean and mean -2 SD (standard deviation). The statistical analysis was performed in accordance with requirements of ASTM E739. One of the requirements of ASTM E739 is that only data points with finite life can be used for statistical analysis. The figures also contain the regression analysis data for each bolt size below each plot. The regressions analysis was conducted for the S-N curve with the following power law equation:

$$N = a(\Delta\sigma)^{-m}$$

or

$$logN = loga - mlog\Delta\sigma$$

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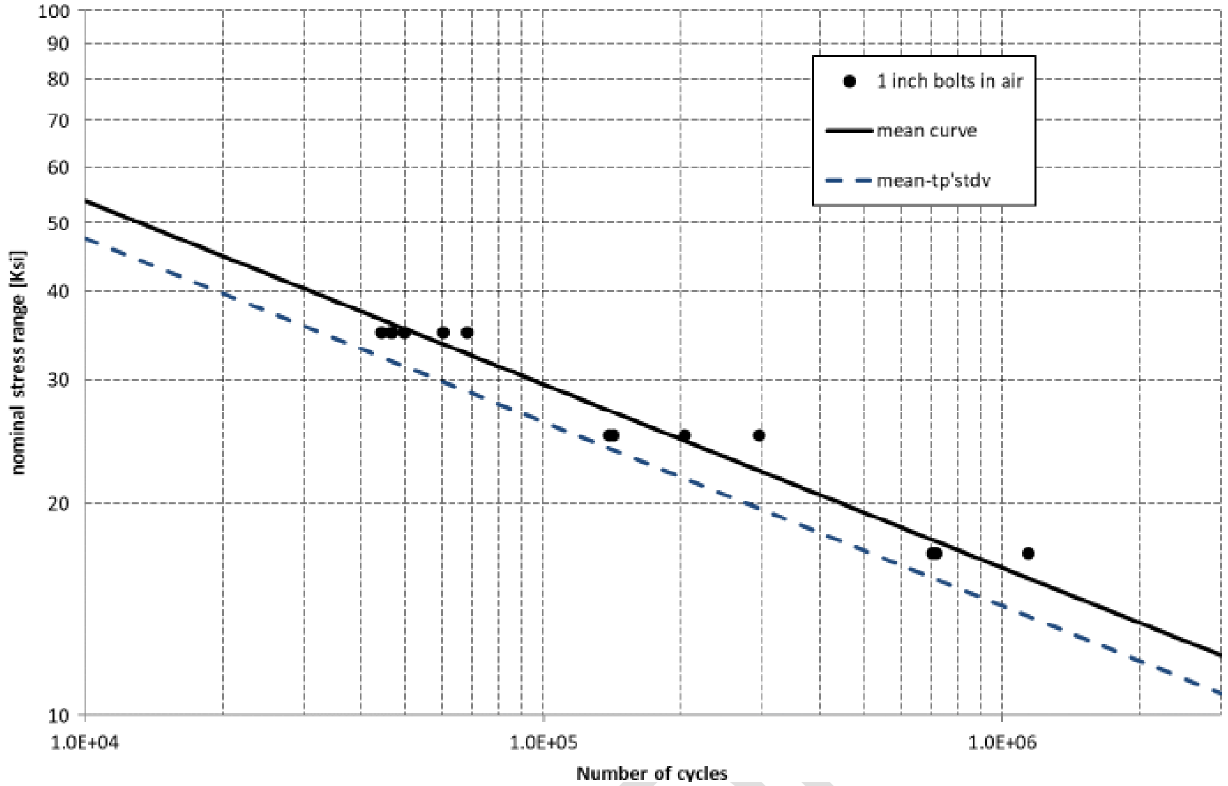

1" air data	ASTM (ksi)
m =	3.84
$\log a_1$(mean)	10.637
StD ($\log\overline{a_1}$)	0.103
Tp (13 test data)	2.201
Mean-Tp*stdv	10.410

Figure 3 - S-N fatigue Curve for 1 in. Bolts in Ambient Air

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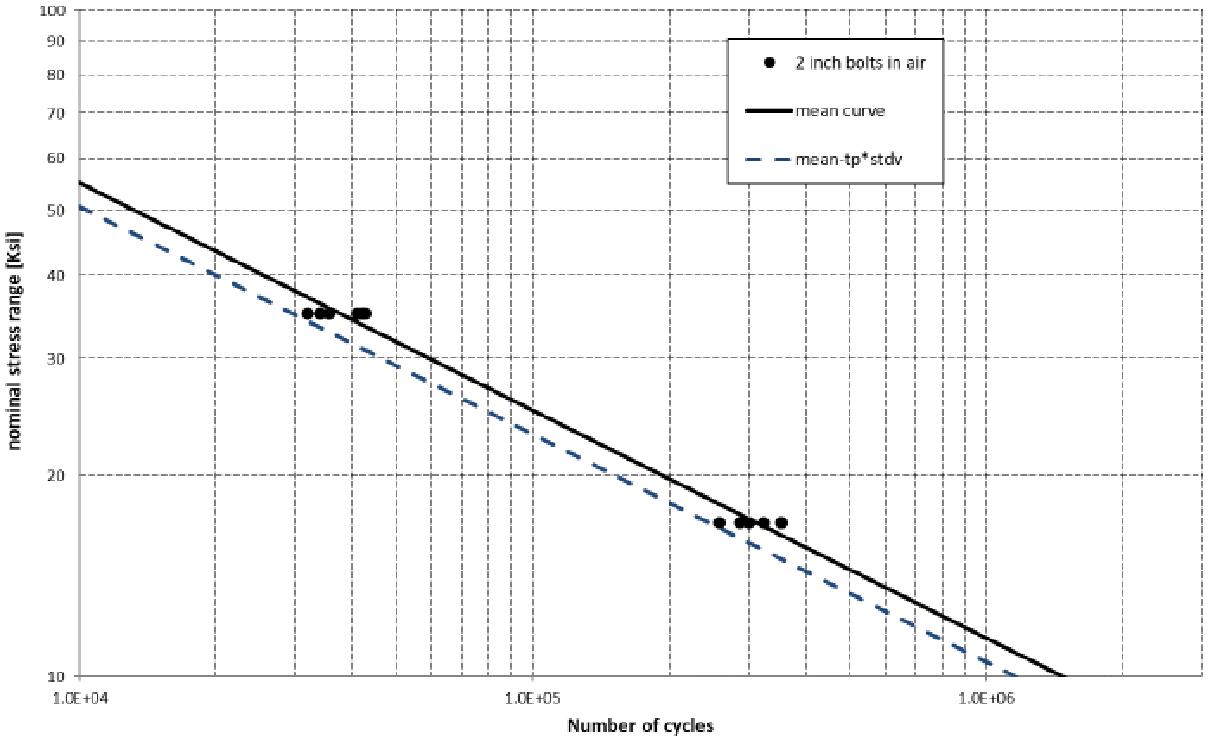

2” air data	ASTM (ksi)
m =	2.923
$\log a_1$(mean)	9.088
StD ($\log\overline{a_1}$)	0.052
Tp (13 test data)	2.228
Mean-Tp*stdv	8.973

Figure 4 - S-N Fatigue Curve for 2 in. Bolts in Ambient Air

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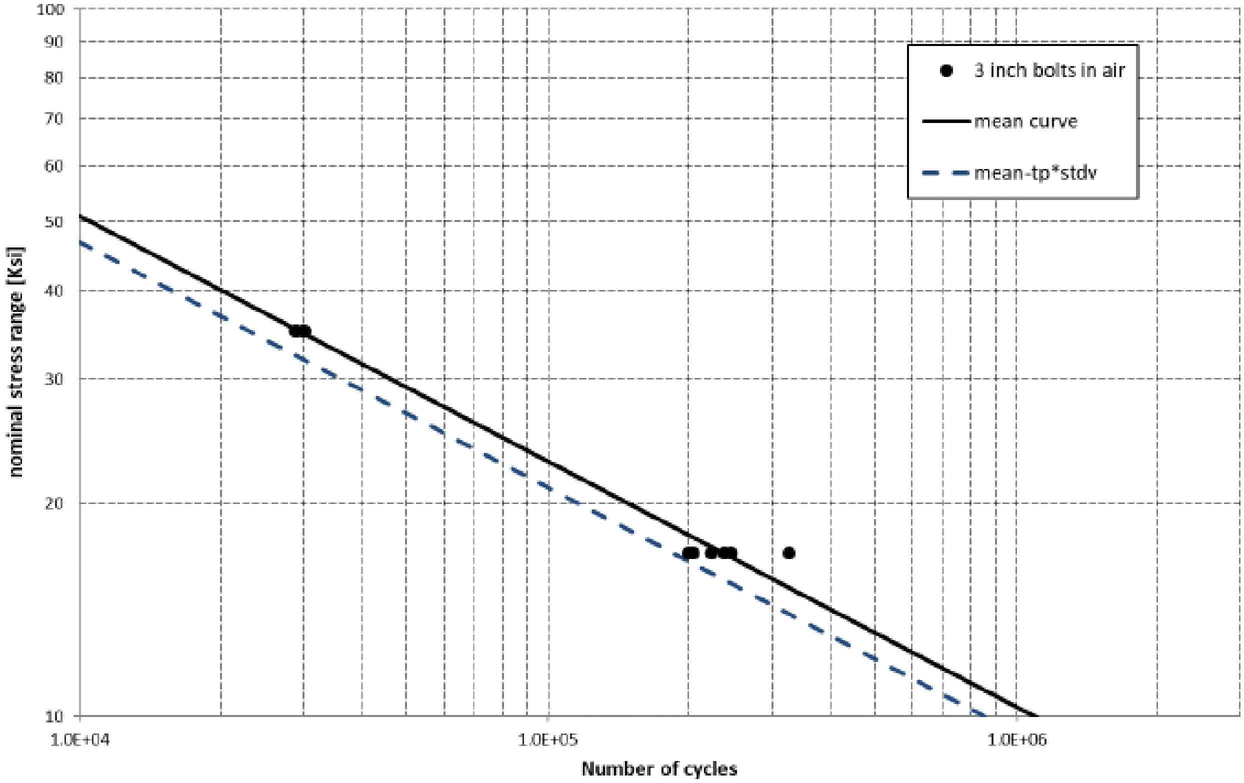

3” air data	ASTM (ksi)
m =	2.878
$\log a_1$(mean)	8.915
StD ($\log\overline{a_1}$)	0.053
Tp (13 test data)	2.228
Mean-Tp*stdv	8.796

Figure 5 - S-N Fatigue Curve for 3 in. Bolts in Ambient Air

Figure 6 compares the Mean-2SD deviation S-N fatigue curves for the 1 in., 2 in. and 3 in. bolts. The plot shows that bolt fatigue life decreases with increasing bolt size. This is illustrated by an increase in the slope of the curves as bolt size increases. A recent Offshore Technology Confere paper by Lim et.al [7] has shown that as the bolt diameter increases bolt stiffness increases which results in a higher root radius stress concentration factor (SCF). As a result, at a specific applied stress range, the root radius stress concentration factor for the 3 in. bolt will be the highest. This results in a lower number of cycles for crack initiation and therefore, lower fatigue life.

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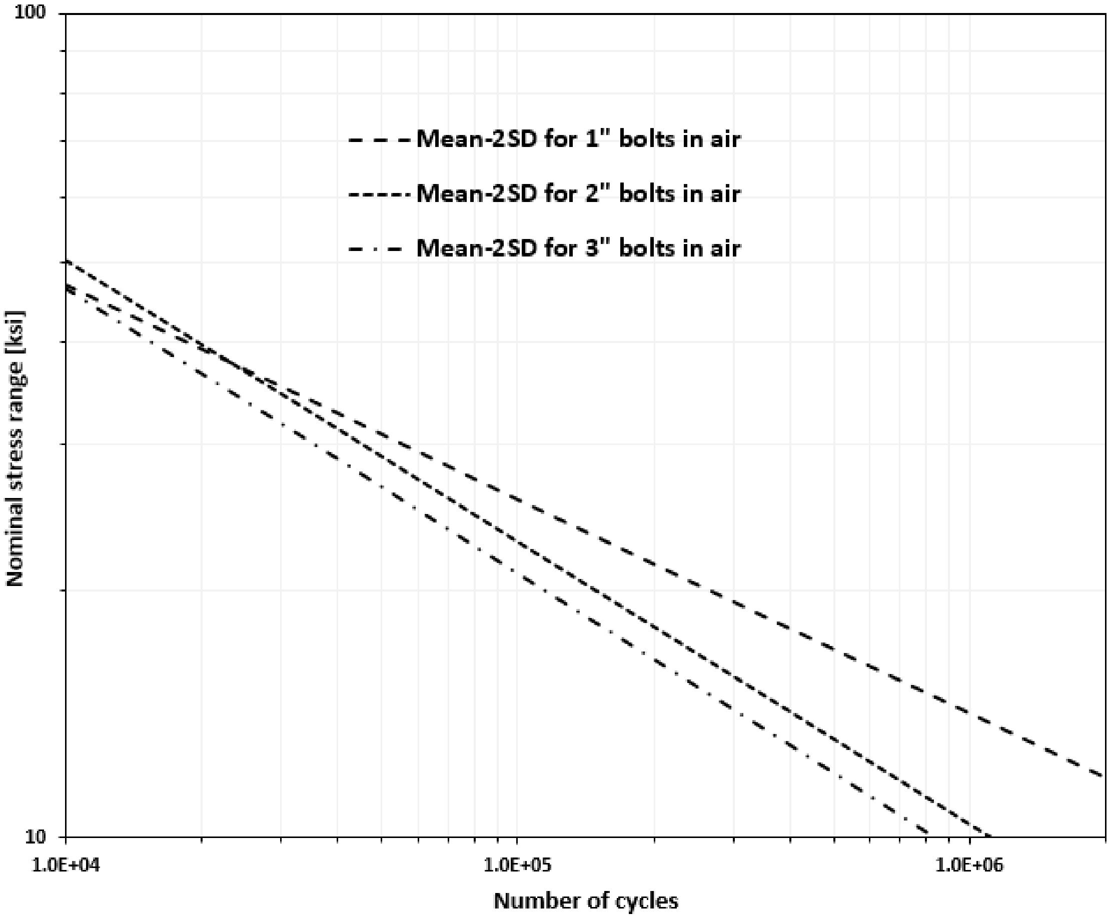

Figure 6 -Comparison of Mean-2SD S-N Fatigue Curves for the 1 in., 2 in. and 3 in. Bolts Tested in Ambient Air

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Figure 7, Figure 8 and Figure 9 show and compares the S-N fatigue curves obtained for the 1 in., 2 in. and 3 in. bolts in ambient air and SW+CP, respectively. The plots also show the mean and mean -2 SD (standard deviation) in both environments. The statistical analysis for the curves in SW+CP were also performed in accordance with requirements of ASTM E739. The figures also contain the regression analysis data for each bolt size in SW+CP at the bottom of each plot.

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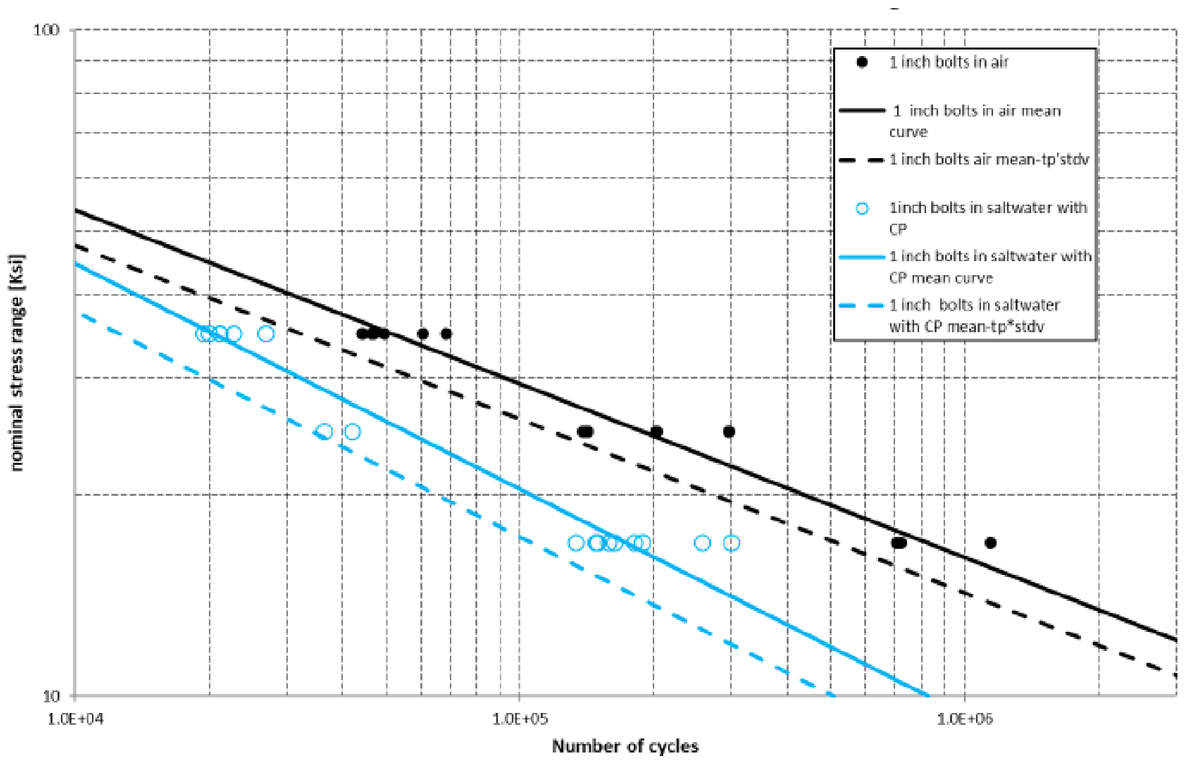

1” saltwater with CP data	ASTM (ksi)
m =	2.956
$\log a_1$(mean)	8.874
StD ($\log \overline{a_1}$)	0.101
Tp (13 test data)	2.110
Mean-Tp*stdv	8.662

Figure 7 - S-N fatigue Curves for 1 in. Bolts in Ambient Air and SW+CP

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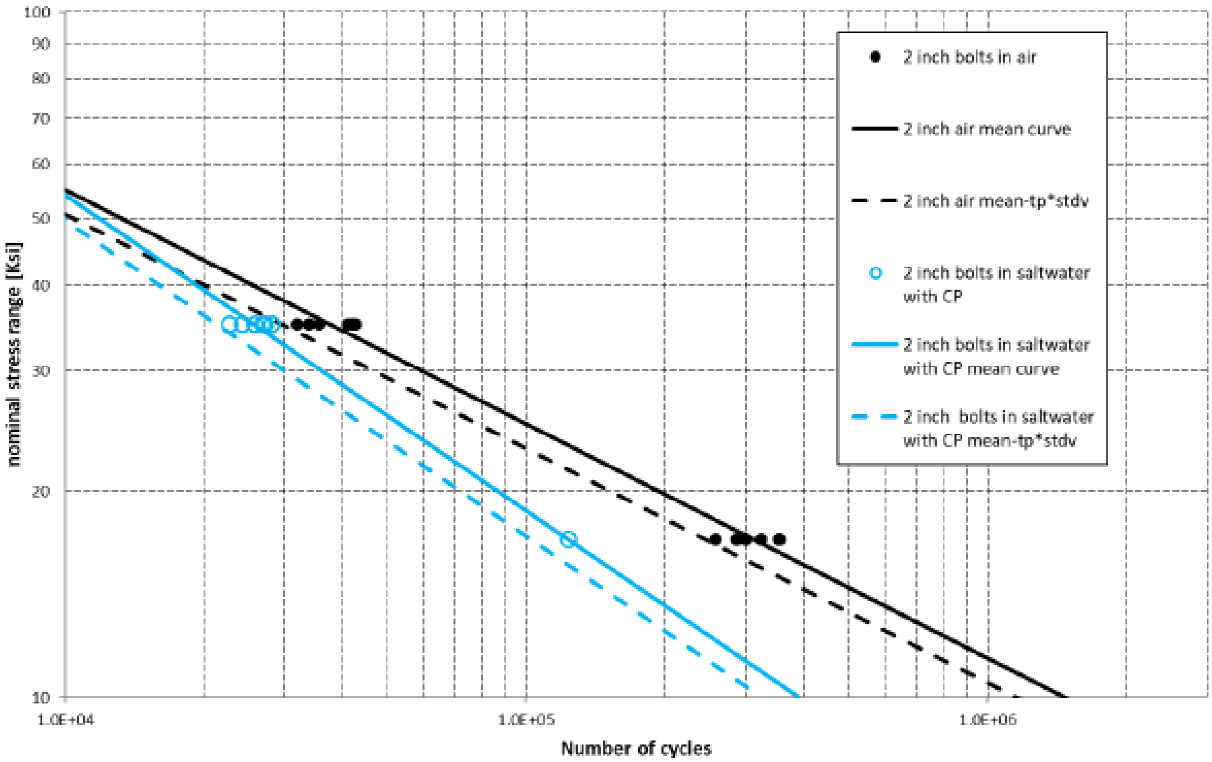

2” saltwater with CP data	ASTM (ksi)
m =	2.170
$\log a_1$(mean)	7.761
StD ($\log\overline{a_1}$)	0.031
Tp (13 test data)	2.571
Mean-Tp*stdv	7.680

Figure 8 - S-N Fatigue Curves for 2 in. Bolts in Ambient Air and SW+CP

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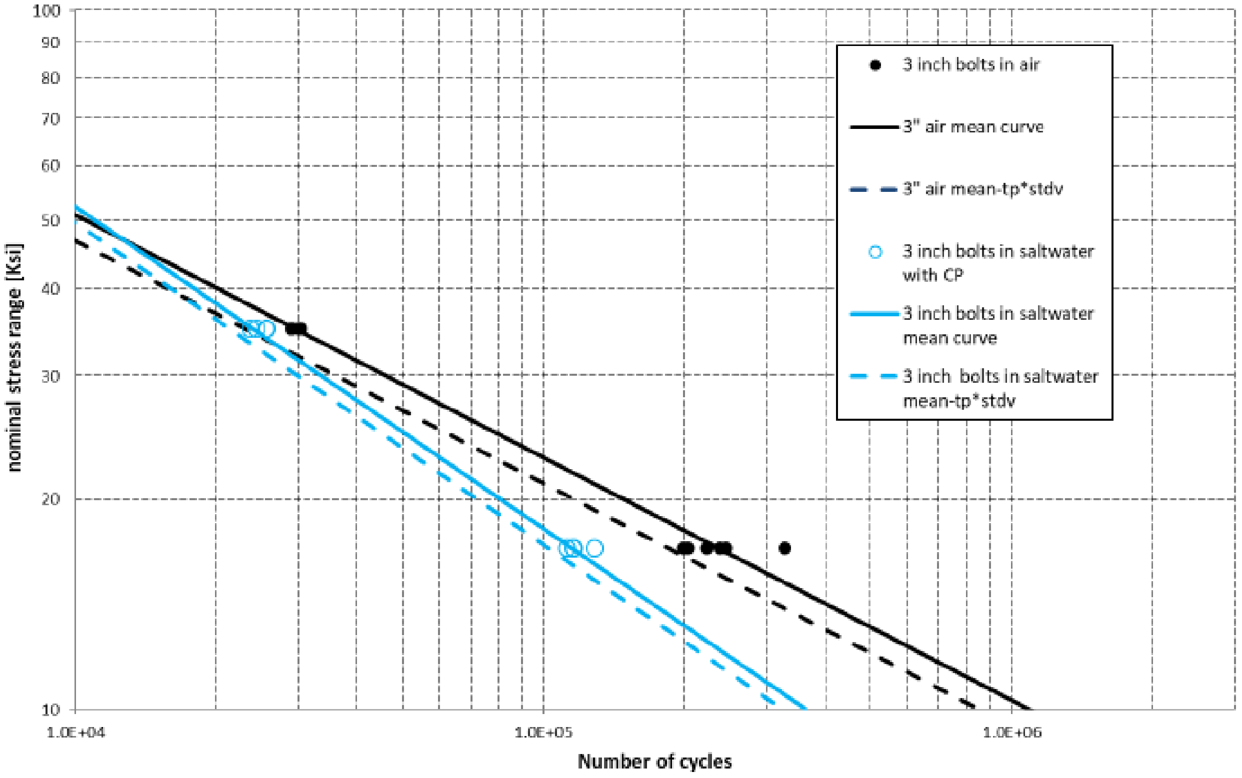

3” saltwater with CP data	ASTM (ksi)
m =	2.160
$\log a_1$(mean)	7.730
StD ($\log\overline{a_1}$)	0.020
Tp (13 test data)	2.447
Mean-Tp*stdv	7.681

Figure 9 - S-N Fatigue Curves for 3 in. Bolts in Ambient Air and SW+CP

The data illustrated in these figures shows that at high stress ranges and for all bolt sizes the fatigue lives in SW+CP are close to the fatigue lives in air. Also, the larger the bolt diameter, the closer the fatigue lives in SW+CP are to the air values at high stress ranges. At lower stress ranges and for all bolt sizes, the fatigue lives in SW+CP are lower than the lives in ambient air resulting in steeper S-N curves.

The results illustrate that at high stress ranges, fatigue lives in SW+CP and in ambient air are mostly dominated by the root radius stress concentration factor. At lower stress ranges, fatigue lives in SW+CP are mostly dominated by the diffusion of atomic hydrogen to the fracture process zone just below the root radius of the bolt resulting in lower cycles to crack initiation and hence, lower overall fatigue life as compared to ambient air.

Figure 10 compares the Mean-2SD deviation S-N fatigue curves for the 1 in., 2 in. and 3 in. bolts in SW+CP. The data clearly shows increase in slopes of the curves as the bolt size increases and the difference between the slopes for the 2 in. and 3 in. are minimal. The data also shows that at high stress ranges, lower fatigue life is obtain from for the 1 in. bolt as compared to the 2 in. and 3 in. bolts. This was unexpected and the observed results at high stress range are due to lack of enough data and hence, proper statistical analysis for the 2 in. and 3 in. bolts at MFC + 10% (25 ksi [174 MPa]) and MFC (17 ksi [118 MPa]) stress ranges in

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SW+CP (wet) environment. As indicated earlier, lack of data was due to exhaustion of allocated load frame time at the laboratory to complete the SW+CP testing.

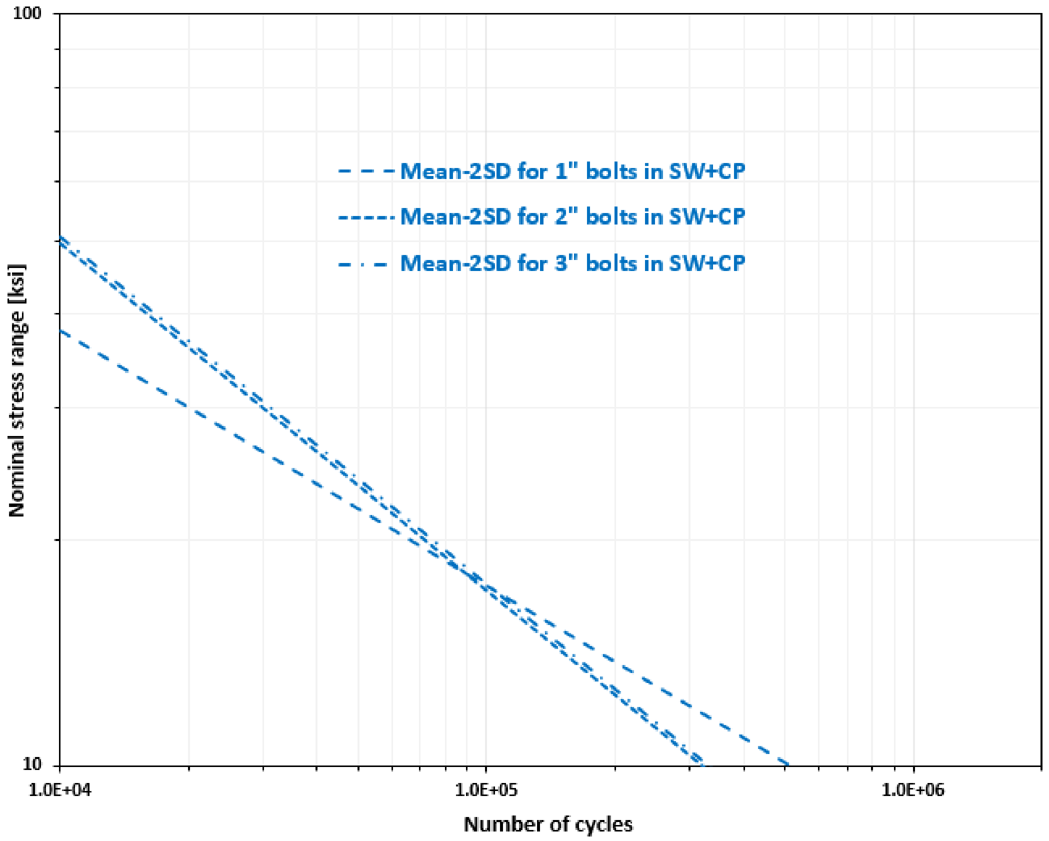

Figure 10 - Comparison of Mean-2SD S-N Fatigue Curves for the 1 in., 2 in. and 3 in. Bolts Tested in Ambient Air

Based on the developed S-N fatigue curves for 1 in., 2 in. and 3 in. bolts in ambient air and SW+CP, Table 11 provides a “knock-down” factor for different stress levels for different bolt sizes.

Table 11 - Fatigue Test Knock-down Factors for SW+CP/Ambient Air

Stress Range ksi [MPa]	**1 in.**	**2 in.**	**3 in.**
$\Delta\sigma = 35$ [241]	0.42	0.68	0.85
$\Delta\sigma = 25$ [174]	0.20		
$\Delta\sigma = 17$ [118]	0.21	0.40	0.50

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6 Conclusions

Full scale S-N fatigue testing of 1 in., 2 in., and 3 in. low alloy steel bolting in air and saltwater with CP conditions provided valuable data that can be used for the applicable designs. The main conclusions are the following.

1. Bolt fatigue limits have decreasing fatigue life with increasing bolt size. This is due to increased stiffness and increased root radius stress concentration with increasing bolt size.

2. 1 in. fatigue test series had several runouts at the lower alternating stress range (17 ksi) which indicates that the 1 in. bolt size is approaching a fatigue threshold limit for constant amplitude loading. It is believed that without surface discontinuities identified the fatigue life indicates and endurance limit for alternating stress of approximately 17 ksi.

3. The fatigue reduction factor for saltwater with CP is affected by both bolt size and alternating stress level. The higher the alternating stress and the larger the bolt, the less the reduction factor in environment. This is attributed to hydrogen diffusion being more dominate at the lower alternating stress levels.

4. The log- log plot of the slope for the fatigue curves for the saltwater with CP tests is steeper than the slope of the curve for the air tests. This again is due to the influence of the hydrogen diffusion at lower stress levels.

5. The failure of each bolt initiated in the root radius of the first thread where the circumferential crack growth was at a faster rate than the depth growth. Applying the developed tensile fatigue curves for determining the fatigue life where the maximum surface alternating stress without SCF for bending or a combination of alternating tension plus bending are defined would result in very conservative values[8] .

6. The knock down factor due to saltwater influence is less for the 2 in. and 3 in. bolts than for the 1 in. bolts. From the free regression evaluation, the 2 in. and 3 in. bolts in saltwater with CP show very similar fatigue results regardless of the bolt sizes.

7. There we no bolt fatigue failures due to thread shear. All bolts demonstrated no susceptibility to shear failure of the threads from testing and post test evaluation. All the bolt failures observed were due to crack initiation at the first engaged thread root in bolt thread, which propagated radially through the cross section of the bolt (tensile type failure).

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