S-N Fatigue Design and Test Data for Low-Alloy Steel Bolts

API TECHNICAL REPORT 21TR2
SECOND EDITION, JULY 2025



Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed. The use of API publications is voluntary. In some cases, third parties or authorities having jurisdiction may choose to incorporate API standards by reference and may mandate compliance.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to ensure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be used. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Classified areas may vary depending on the location, conditions, equipment, and substances involved in any given situation. Users of this technical report (TR) should consult with the appropriate authorities having jurisdiction.

Users of this TR should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

All rights reserved. No part of this work may be reproduced, translated, stored in a retrieval system, or transmitted by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission from the publisher. Contact the Publisher, API Publishing Services, 200 Massachusetts Avenue, NW, Suite 1100, Washington, DC 20001-5571.

Copyright © 2025 American Petroleum Institute

Foreword

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Suggested revisions are invited and should be submitted to the Standards Department, API, 200 Massachusetts Avenue NW, Suite 1100, Washington, DC 20001, standards@api.org.

Contents

Page

1 Scope 1

2 Normative References 1

3 Terms, Definitions, Abbreviations, and Symbols 1
3.1 Terms and Definitions 1
3.2 Abbreviations 2
3.3 Symbols 2

4 Bolting Fatigue Analysis Design Guidelines 2
4.1 Bolting Subjected to Cyclic Loading 2
4.2 Bolting S-N Fatigue Analysis Procedure 3

5 Full-Scale Fatigue Test Data for Bolting 3
5.1 Bolting Materials 3
5.2 S-N Fatigue Testing 8

6 Conclusions 47

Bibliography 49

Figures

1 Thread Root Profiles 16
2 1-in. Bolt, 1-D-M-U-7, Showing an Imperfection in the Thread Flank (White Arrows) 17
3 S-N Fatigue Curve for 1-in. Bolts in Air (Phase I) 18
4 S-N Fatigue Curve for 2-in. Bolts in Air (Phase I) 19
5 S-N Fatigue Curve for 3-in. Bolts in Air (Phase I) 20
6 S-N Fatigue Curves for 1-in. Bolts in Air and SW+CP (Phase I) 21
7 S-N Fatigue Curves for 2-in. Bolts in Air and SW+CP (Phase I) 22
8 S-N Fatigue Curves for 3-in. Bolts in Air and SW+CP (Phase I) 23
9 Schematics of Vickers Hardness Test Locations 25
10 Optical Microscopy Microstructure of the 1-in. Bolts 29
11 Optical Microscopy Microstructure of the 2-in. Bolts Magnification 200X (Phase I) 30
12 Optical Microscopy Microstructure of the 3-in. Bolts Magnification 200X (Phase I) 31
13 S-N Fatigue Curve for 1-in. Bolts in Air (Phase II) 35
14 S-N Fatigue Curve for 1-in. Bolts in an SW+CP Environment (Phase II) 36
15 S-N Fatigue Test Results for 1-in. Bolts in Air and SW+CP (Phase II) 37
16 S-N Fatigue Curve for 3-in. Bolts in Air (Phase II) 38
17 S-N Fatigue Curve for 3-in. Bolts in an SW+CP Environment (Phase II) 39
18 S-N Fatigue Test Results for 3-in. Bolts in Air and SW+CP (Phase II) 40
19 Comparison of the 1-in. and 3-in. Bolt S-N Fatigue Curves in Air (Phase II) 41
20 Comparison of the 1-in. and 3-in. Bolt S-N Fatigue Curves in SW+CP (Phase II) 42
21 Schematics of Hardness Test Locations (Phase II) 43
22 Optical Microscope Photomicrograph (Phase II) 45
23 Optical Microscope Photomicrograph (Phase II) 45
24 EDS Mapping of the Light-Colored Phase Observed (or Described) in Figure 23 46
25 SEM Photomicrograph Taken at Low Magnification for 3-in. Bolts 47

Contents

Page

Tables

1 Bolts and Nuts used for Phase I and Phase II of FSF Testing [8, 9] 4
2 Bolt and Nut Heat Numbers, Reduction Ratios, and Chemical Compositions (Phase I) 4
3 Bolts and Nuts Heat Numbers, Reduction Ratios, and Chemical Compositions (Phase II) 5
4 Heat Treatment Details of the Bolts and Nuts Prior to Machining (Phase I) 5
5 Heat Treatment Details of the Bolts and Nuts Prior to Machining (Phase II) 6
6 Mechanical Properties of the Bolts and Nuts (Phase I) 7
7 Mechanical Properties of the Bolts and Nuts (Phase II) 8
8 Load Levels Applied to Bolts (SMYS = 105 ksi [725 MPa]) (Phase I) 9
9 Load Levels Applied to Bolts (SMYS = 105 ksi [725 MPa]) (Phase II) 9
10 Bolt Dimensions and Calculated Nominal Root Area for Each Bolt Size 9
11 Applied Stress Ranges and Corresponding Loads for Each Bolt Size (Phase I) 10
12 Applied Stress Ranges and Corresponding Loads for Each Bolt Size (Phase II) 10
13 S-N Fatigue Test Results for 1-in. Bolts in Air (Phase I) 12
14 S-N Fatigue Test Results for 1-in. Bolts in an SW+CP Environment (Phase I) 13
15 S-N Fatigue Test Results for 2-in. Bolts in Air (Phase I) 13
16 S-N Fatigue Test Results for 2-in. Bolts in an SW+CP Environment (Phase I) 14
17 S-N Fatigue Test Results for 3-in. Bolts in Air (Phase I) 14
18 S-N Fatigue Test Results for 3-in. Bolts in an SW+CP Environment (Phase I) 14
19 Fatigue Test Knock-down Factors for SW+CP/Air (Phase I) 24
20 Hardness Measurement Results for 1-in. Bolt from Heat 1 (Phase I) 26
21 Hardness Measurement Results for 1-in. Bolt from Heat 2 (Phase I) 26
22 Hardness Measurement Results for 2-in. Bolt from Heat 1 (Phase I) 27
23 Hardness Measurement Results for 2-in. Bolt from Heat 2 (Phase I) 27
24 Hardness Measurement Results for 3-in. Bolt from Heat 1 (Phase I) 28
25 Hardness Measurement Results for 3-in. Bolt from Heat 2 (Phase I) 28
26 S-N Fatigue Test Results for 1-in. Bolts in Air (Phase II) 32
27 S-N Fatigue Test Results for 1-in. Bolts in SW+CP (Phase II) 33
28 S-N Fatigue Test Results for 3-in. Bolts in Air (Phase II) 34
29 S-N Fatigue Test Results for 3-in. Bolts in SW+CP (Phase II) 34
30 Knock-Down Factors for SW+CP/Air Environments at Applied Stress Ranges (Phase II) 42
31 Measured HV1 and HV10 Hardness and Converted HRC Values for the 1-in. Bolts (Phase II) 44
32 Measured HV1 and HV10 Hardness and Converted HRC Values for the 3-in. Bolts (Phase II) 44

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. It 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 scope of work was conducted in two phases; Phase I: Evaluation of bolting under cyclic loading which meets the requirements of API 17D:2011, 2nd Edition [1] standard and Phase II: Evaluation of bolting which meets the requirements of API 6A/16A [2, 3] standards. 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 (stress number of cycles to failure) or fatigue crack growth rate. The S-N fatigue evaluation can be based on either the stress concentrations of the thread profile, which will need stress concentration factor (SCF) and smooth tensile bar S-N testing, or the axial stress due to the load divided by the minimum root diameter area and full-scale bolt fatigue tests [4]. The basis of this document is the S-N approach using full-scale fatigue testing. The full-scale fatigue testing was conducted for bolts manufactured to meet API 20E [4] BSL-3. The testing was performed in two phases; Phase I was conducted to obtain S-N fatigue curve with API 17D:2011 loading conditions, Phase II was conducted with API 6A/16A loading conditions.

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*SMYS for Phase I testing and 0.5*SMYS for Phase II testing, 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 for all tests. 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 Phase I test program was to provide S-N fatigue curves for bolts that are preloaded per API Series 17 standards and are subjected to a range of alternating axial stresses. The objective of the Phase II test program was to provide S-N fatigue curves for bolts that are preloaded per API 6A/16A standards. 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 (SW) with cathodic protection (CP).

S-N Fatigue Design and Test Data for Low-Alloy Steel Bolts

1 Scope

The scope of the test program was to obtain bolting material fatigue data required to perform design verification analysis of bolting subjected to fatigue loading to assure accurate design life estimation. The bolting fatigue testing program provided S-N fatigue curves for three alternating stress ranges in air and in SW+CP environments and for bolt sizes of 1 in., 2 in. (Grade L7), and 3 in. (Grade L43) in Phase I and for bolt sizes 1 in. (Grade L7) and 3 in. (Grade L43) in Phase II.

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 root area 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 [5] Class 2A/2B.

2 Normative References

There are no normative references for this document.

3 Terms, Definitions, Abbreviations, and Symbols

3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1.1
ambient air (dry)
Room temperature and ambient pressure.

3.1.2
high-stress range fatigue cycles
HFC
Tested fatigue cycles to failure for a high-stress range or high-force condition applied.

3.1.3
low-stress range fatigue cycles
LFC
Tested fatigue cycles to failure for a low-stress range or low-force condition applied.

3.1.4
mean stress
Maximum axial stress plus minimum axial stress divided by two.

3.1.5
medium-stress range fatigue cycles
MFC
Tested fatigue cycles to failure for a medium-stress range or medium-force condition applied.

3.1.6
S-N fatigue
Stress range (S) versus number of cycles to failure (N).