Development of FEA-based Reference Stress Solutions for Level 2 and Level 3 Crack Assessments

API TECHNICAL REPORT 579-A
FIRST EDITION, MAY 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.

Users of this standard 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.

API is not undertaking to meet the duties of employers, manufacturers, or suppliers to warn and properly train and equip their employees, and others exposed, concerning health and safety risks and precautions, nor undertaking their obligations to comply with authorities having jurisdiction.

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 utilized. 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.

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.

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 INTRODUCTION 1

2 TECHNICAL BACKGROUND 1

2.1 The Traditional FAD Concept 2
2.2 Expressing a J-Integral Solution as a Dimensionless FAD 2
2.3 Benchmarking the Existing Level 2 Procedure Against FEA Results 3

3 PARAMETRIC EQUATIONS FOR ELASTIC-PLASTIC J SOLUTIONS 4

3.1 Original EPRI Handbook J Estimation Scheme 4
3.2 Contained Yielding versus Fully Plastic Deformation 5
3.3 FAD-Based Parametric Equations for the Elastic-Plastic J-Integral 5
3.4 Evaluation of Two- and Four-Term Fits to J-Integral Solutions 7
3.5 Approximation of the FEA Solutions for the New Level 2 Reference Stress 8
3.6 Combined Load Cases 8

4 FINITE ELEMENT STUDY 9

4.1 Cases Considered 9
4.2 FEACrack Software 11
4.3 WARP3D Finite Element Code 11
4.4 FEA Workflow 12
4.5 Curve Fitting the J Results 12

5 J-INTEGRAL AND REFERENCE STRESS SOLUTIONS 12

5.1 Flat Plate 13
5.1.1 Level 3 J-Integral Solutions 13
5.1.2 Level 2 Reference Stress Solutions 13
5.2 Cylindrical Shell with an Axial Crack under Pressure 14
5.2.1 Level 3 J-Integral Solutions 14
5.2.2 New Level 2 Reference Stress Solutions 14
5.3 Cylindrical Shell with a Circumferential Crack 15
5.3.1 Level 3 J-Integral Solutions 15
5.3.2 New Level 2 Reference Stress Solutions 17
5.4 Spherical Shell with a Meridional Surface Crack 18
5.4.1 Level 3 J-Integral Solutions 18
5.4.2 Level 2 Reference Stress Solutions 18
5.5 Weld Strength Mismatch Effects 18

6 FITNESS-FOR-SERVICE PROCEDURE 19

6.1 Level 2 Reference Stress 19
6.2 Level 3 J-Integral Method 19

7 NOMENCLATURE 20

8 REFERENCES 23

9 TABLES 24

10 FIGURES 113

1 INTRODUCTION

This research study provides background information that may be used to revise the Fitness-For-Service (FFS) document, API 579-1/ASME FFS-1 2021 [1] (aka "API 579"), more specifically the Part 9 Level 2 Assessment, along with a new Level 3 option for Part 9.

The Part 9 Level 2 crack-like flaw FFS procedure relies on the Failure Assessment Diagram (FAD) approach, which is the most widely used crack assessment methodology in the world. Several industry standards for crack assessment implement the FAD approach, including BS 7910 from the British Standards Institute and the R6 document from the British nuclear power generation industry.

The FAD approach was first introduced in 1976 as a simple approximation for fracture stability assessment of structural components that experience plastic deformation prior to failure. Modern industry standards use improved versions of the FAD, but the approach still contains approximations and simplifications.

The main purpose of the present work is to remove some of the approximations in the existing Part 9 Level 2 FAD procedure and thereby improve accuracy. A side benefit of this work is a new Level 3 option that is even more accurate than the improved Level 2 procedure. This study includes a large number of 3D elastic-plastic Finite Element Analyses (FEA) of components with cracks.

Most of the work product from this report will appear in future releases of API 579. The existing Level 2 reference stress solutions in Annex 9C for common component geometries (flat plates, cylindrical shells, and spherical shells) will be replaced by geometry factors inferred from FEA. The new Level 3 option consists of elastic-plastic J integral solutions from FEA with dimensionless geometry factors in tables.

2 TECHNICAL BACKGROUND

Crack stability assessments are usually based on the engineering discipline of fracture mechanics [5]. Linear Elastic Fracture Mechanics (LEFM) applies when applied stresses and strains are elastic. As the magnitude of applied stress increases, yielding begins at the crack tip and then spreads over the remaining cross section. In such cases, Elastic-Plastic Fracture Mechanics (EPFM) methodology is appropriate.

Fracture stability calculations usually entail a comparison of crack driving force with material resistance, which is more commonly known as fracture toughness. Crack driving force represents the fracture demand, while toughness is a measure of the capacity. This is analogous to the traditional mechanical design approach, where applied stress quantifies the load demand, while yield strength or tensile strength represents the capacity.

In LEFM analysis, the Mode I stress intensity factor, K_I, is the most common crack driving force parameter, while the J-integral is the most common measure of crack driving force for EPFM. Computing the latter parameter requires elastic-plastic FEA of the cracked component of interest.

The 2021 and earlier editions of the API 579 Part 9 Level 2 use a failure assessment diagram (FAD) method that combines accurate K_I solutions from elastic FEA with an approximation for plasticity effects. The work product in the present report aims to replace this approximation, which is based on limit load solutions, with geometry factors inferred from elastic-plastic FEA.

Section 2.1 below describes the FAD concept as API 579 Part 9 Level 2 currently implements it. Section 2.2 illustrates how an elastic-plastic J-integral solution can be expressed in dimensionless FAD coordinates. Section