Process Equipment Fitness-for-Service Assessments Using API RP 579

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Abstract

Fitness for service assessment is performed to make sure that process plant equipment, such as pressure vessels, piping, and tanks, will operate safely and reliably for some desired future period. API Recommended Practice 579 provides a general procedure for assessing fitness for service. The assessment procedure evaluates the remaining strength of the equipment in its current condition, which may be degraded from its original conditions. Common degradation mechanisms include corrosion, localized corrosion, pitting and crevice corrosion, hydrogen attack, embrittlement, fatigue, high-temperature creep, and mechanical distortion. Methods for evaluating the strength and remaining service life of equipment containing these types of degradation are presented and reviewed. Examples are presented to illustrate the application of these methods to process plant equipment.

Introduction

Process plant equipment is often exposed to corrosive environments and/or elevated temperatures. Under these conditions, the material used in this equipment can degrade or age with time in service. As important equipment such as pressure vessels, piping, and storage tanks become older, the plant operator must decide if they can continue to operate safely and reliably to avoid injuries to personnel and the public, environmental damage, and unexpected shutdowns. Fitness for service assessment procedures provide a means for helping the plant operator make these decisions based on sound, established engineering principles.

Fitness for service assessment is a multi-disciplinary engineering analysis of equipment to determine if it is fit for continued service until the end of a desired period of operation, such as until next turnaround or planned shutdown. Common reasons for assessing the fitness for service of equipment include the discovery of a flaw such as a locally thin area (LTA) or crack, failure to meet current design standards, and plans for operating under more severe conditions than originally expected. The main products of fitness for service assessment are (1) a decision to run, alter, repair, monitor, or replace the equipment and (2) guidance on inspection interval for the equipment. Fitness for service assessment applies analytical methods to evaluate flaws, damage, and material aging.

The analytical methods are based on stress analysis, but they also require information on equipment operations, nondestructive examination (NDE), and material properties. Stress analysis may be performed using standard handbook or design code formulas or by means of finite element analysis (FEA). With modern computer technology, the use of FEA is quite common. Fitness for service assessment requires both knowledge of past operating conditions and a forecast of future operating conditions. Interaction with operations personnel is required to obtain these data. NDE is used to locate, size, and characterize flaws. The material properties

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should include information of material damage mechanisms and behavior in the service environment, especially on the effects of corrosion and temperature.

Fitness for service assessment is required for a number of reasons. These reasons include the following items:

1. maintaining the safety of plant personnel and the public
2. complying with OSHA 1910 process safety management (PSM) rules
3. protecting the environment for accidental releases of damaging substances
4. reliably operating aging facilities
5. maintaining safe and reliable operations with increased run lengths and decreased shutdown periods
6. determining the feasibility of increasing the severity of operations
7. rationalizing the damage found by more rigorous in-service inspections than found by inspections performed during original construction

To develop a consistent, sound engineering approach to fitness for service assessment, a joint industry program was initiated by the Materials Properties Council, Inc. (MPC) in 1990. The MPC program concentrated on the development of technology, and its results have been disseminated through publications and symposia, especially ASME PVP Volumes.[1-6] The culmination of this program was the development and publication of the API 579 Recommended Practice (RP) on Fitness-For-Service.[7]

The draft of API RP 579 was started in 1994, and the first edition was published in January 2000. API RP 579 is organized in modular fashion based on type of material damage or flaw to facilitate its use and updating. It incorporates a three-level assessment approach. The level of conservatism decreases with increasing level of assessment, but detail of analysis and data increase with increasing level of assessment. Level 1 assessment may be performed by an inspector or a plant engineer. Level 2 assessment requires at least a plant engineer, whereas Level 3 assessment must be performed by an expert engineers or by a team of engineers that includes at least one expert engineer. Application of the higher levels of assessment is often limited by a lack of materials properties data and accurate operating data.

Each section of API RP 579 clearly identifies the data requirements and the applicability and limitations of the assessment procedures. Flow charts, figures, and examples are provided to simplify use of the procedures. There are also recommendations for in-service monitoring and/or remedial methods to apply in situations where assessment is "difficult." Each section gives advice on stress analysis techniques, NDE measurements, and sources of materials properties. As an essential step in a fitness for service assessment, the minimum remaining life (RL) of a component must be evaluated. The minimum value of remaining life is the basis for establishing the inspection interval. In cases where it is not possible to evaluate the remaining life, some type of monitoring must be employed to make sure that any problem that may develop in future service is detected and addressed.

Figure 1 shows the table of contents for API RP 579, and Figure 2 lists the appendices included in API RP 579. All portions except Section 10 and Appendix H are completed. Those two portions are being developed for inclusion in future editions. Section 1 is an introduction to the document, while Section 2 provides of general overview description of the procedure used in each of the remaining sections. There is a separate section (3 through 11) for each flaw type or condition covered by the document. Each of these nine sections is organized in the same consistent manner. Common information utilized by more than one section is in the appendices. API RP 579 is largely self-contained so users do not have to refer to many other documents. One exception to this principle is that materials data need to obtained from Section II of the ASME Boiler and Pressure Vessel Code. The developers of API RP 570 plan to compile data for service-exposed materials and add them to Appendix F in the future.

- **Section 1 - Introduction**
- **Section 2 - Fitness-For-Service Engineering Assessment Procedure (General Roadmap for Sections 3 through 11)**
- **Section 3 - Assessment of Equipment for Brittle Fracture**
- **Section 4 - Assessment of General Metal Loss**
- **Section 5 - Assessment of Local Metal Loss**
- **Section 6 - Assessment of Pitting Corrosion**
- **Section 7 - Assessment of Blisters and Laminations**
- **Section 8 - Assessment of Weld Misalignment and Shell Distortions**
- **Section 9 - Assessment of Crack-Like Flaws**
- **Section 10 - Assessment of Components Operating in the Creep Regime**
- **Section 11 - Assessment of Fire Damage**

Figure 1. Table of Contents of API RP 579.

- **Appendix A - Thickness, MAWP, and Membrane Stress Equations for a FFS Assessment**
- **Appendix B - Stress Analysis Overview for a FFS Assessment**
- **Appendix C - Compendium of Stress Intensity Factors**
- **Appendix D - Compendium of Reference Stress Solutions**
- **Appendix E - Residual Stresses in a Fitness-For-Service Evaluation**
- **Appendix F - Materials Properties for a FFS Assessment**
- **Appendix G - Deterioration and Failure Modes**
- **Appendix H - Validation**
- **Appendix I - Glossary of Terms and Definitions**
- **Appendix J - Technical Inquiries**

Figure 2. Appendices of API RP 579.

The procedures given in API RP 579 are aimed at equipment operating in the petroleum and chemical industry. API RP 579 addresses flaws commonly found in pressure vessels, piping, and tanks and both present integrity and remaining life of components. It includes analytical procedures, material properties, NDE guidelines, and documentation requirements. API RP 579 applies to the following items:

1. components designed and constructed to the ASME Boiler and Pressure Vessel Code, Section I and ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2
2. piping designed to ASME B31.1 and 31.3 piping codes
3. storage tanks designed and constructed to API 620 and API 650

The owner-user has overall responsibility for the assessment procedures. The inspector has to make sure that requirements of applicable API inspection codes are satisfied and provide inspection data. He may perform some screening analyses (Level 1) and ensures that the assessment results are documented and filed. The engineer is responsible to owner-user for most of the assessment work, except that screening analyses can be performed by the inspector with the engineer's review. The inspector is qualified per API codes, while the engineer should have at least two years of relevant experience. The engineering disciplines that are typically required for fitness for service assessments include: materials or metallurgy, mechanical or structural, inspection or NDE, fracture mechanics, and petroleum or chemical.

General Evaluation Procedure

Each section of API RP 579 has a fitness for service (FFS) evaluation procedure consisting of the following eleven parts:

1. General
2. Applicability and Limitations of the FFS Assessment Procedures
3. Data Requirements
   - 3.1 Original Equipment Design Data
   - 3.2 Maintenance and Operational History
   - 3.3 Required Data/Measurements for a FFS Assessment
   - 3.3 Recommendations for Inspection Techniques and Sizing Requirements
4. Assessment Techniques and Acceptance Criteria
5. Remaining Life Evaluation
6. Remediation
7. In-Service Monitoring
8. Documentation
9. References
10. Tables and Figures
11. Example Problems

The API RP 579 procedure employs a remaining strength factor (RSF), which is defined as follows:

$$RSF = L_{DC}/L_{UC} \tag{1}$$

L_{DC} is the limit or plastic collapse load of the damaged component, and L_{UC} is the limit or plastic collapse load of the undamaged component. The procedure also allows pressure vessels, piping, and tanks to be rerated. For rerating pressure vessels and piping, the following expressions apply:

$$MAWP_r = MAWP\ (RSF/RSF_a)\ \text{for}\ RSF < RSF_a \quad (2a)$$

$$MAWP_r = MAWP\ \text{for}\ RSF \geq RSF_a \quad (2b)$$

$MAWP_r$ is the reduced maximum allowable working pressure, MAWP the original maximum allowable working pressure, and RSF_a is the allowable remaining strength factor (typically 0.9). For rerating storage tanks, the following expressions apply:

$$MFH_r = MFH\ (RSF/RSF_a)\ \text{for}\ RSF < RSF_a \quad (3a)$$

$$MFH_r = MFH\ \text{for}\ RSF \geq RSF_a \quad (3b)$$

MFH_r is the reduced maximum allowable fill height, and MFH the original maximum allowable fill height.

API RP 579 uses a local stress approach to assess wall loss and corrosion flaws. The approach is based on the effective cross-sectional area of the flaw and the tensile flow strength of the material. It has been established based on the results of extensive FEA and numerous full-scale burst tests of pressure vessels and piping.

API RP 579 uses engineering fracture mechanics to assess crack-like flaws. Most often, a general failure assessment diagram (FAD) is applied to crack-like flaws, as illustrated in Figure 3. Linear elastic stress analysis is used to compute the toughness ratio (K_r) and the load ratio (L_r) for a component with a crack-like flaw. K_r is the ratio of the linear elastic stress intensity factor (K_I) to the material fracture toughness (K_{MAT}), while L_r is the ratio of the reference stress (σ_{ref}) to the material yield strength (σ_{ys}). For a given flaw and load, the value of K_r as a function of L_r is plotted on the FAD. No failure is predicted for points below the failure assessment envelope, whereas failure is likely to occur for points at or above the assessment envelope. Calculations are repeated for other conditions to see where they fall with respect to the envelope or to determine the critical conditions (a point on the failure envelope) at which failure is predicted to be more likely to occur.

The calculated value of remaining life (RL) is generally not a precise value of the expected time to failure. Instead, it is a conservative estimate that is used to set the inspection interval and provide safe operation until the next inspection. One of two approaches may be used. The maximum allowable working pressure (MAWP) or the maximum fill height (MFH) may be computed based on a corrosion allowance or RL may be computed based on the wall thickness. For general metal loss, the effective corrosion allowance (CA_e) is computed as follows:

$$CA_e = t_{loss} + CR \times \textit{time} \quad (4)$$

Where t_{loss} is the amount of metal loss at the time of inspection, CR is future corrosion rate, and *time* is future operating time. Alternatively, RL is computed as follows:

$$RL = (t_{am} - K\ t_{min})/CR \quad (5)$$

Where t_{am} is the average thickness at time of inspection, t_{min} is minimum allowable thickness, and K is a factor that equals 1 for Level 1 assessment and RSF_a for Level 2 assessment.

Documentation of the results is an important part of fitness for service assessment. API RP 579 gives the following recommendations for documentation:

1. It should be sufficient to repeat the assessment at a later date, for example 5 years later.
2. It should include the original design data and the maintenance and operating history.
3. It should include all inspection data that were used in the assessment.
4. It should include assumptions and analytical results, including
   - 4.1 version, section, and level of API RP 579 and other documents used in analysis
   - 4.2 future design and operating conditions (temperature, pressure, environment, ...)
   - 4.3 calculations of minimum required thickness or MAWP
   - 4.4 calculations of remaining life and inspection interval
   - 4.5 mitigation and monitoring recommendations that are conditions for continued operation
5. All documents should be stored with inspection records.

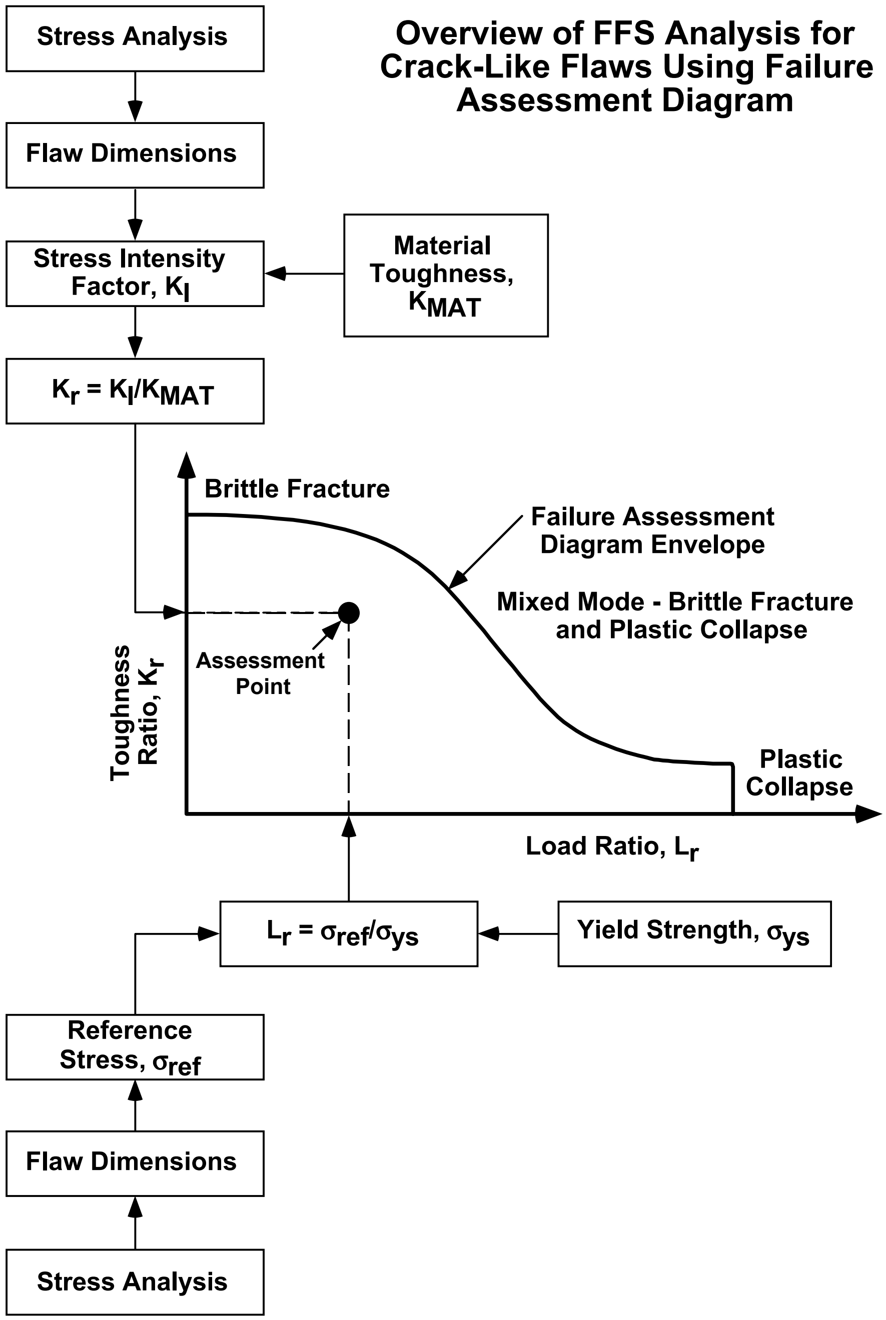

Figure 3. Use of General Failure Assessment Diagram (FAD) for Crack-Like Flaws.

The general assessment procedure recommended by API RP 579 has the following eight steps:

Step 1 Identify the type of flaw and the material damage mechanism.
Step 2 Determine the applicability and limitations of the assessment procedures.

Step 3 Define the data requirements. Those data needed for all assessments are given in Section 2, while those data needed for a specific type of flaw and damage mechanism are given in the section containing the evaluation procedure for that type of flaw and damage mechanism.
Step 4 Apply the assessment techniques and acceptance criteria.
Step 5 Evaluate the remaining life or the limiting flaw size and establish an inspection interval based on results of the evaluation.
Step 6 Apply the required remediation methods to the extent possible and practical.
Step 7 Employ in-service monitoring procedures when remaining life and inspection interval cannot be adequately established.
Step 8 Document all information used and decisions made in Steps 1 through 7, and store the documentation with inspection records.

These eight steps should be included in each fitness for service assessment of a specific flaw and component combination.

Assessment Examples

Two examples of fitness for service assessment are presented. The first one is a corrosion flaw evaluated following the procedures in Section 4 of API RP 579, and the second one is crack-like flaw evaluated following the procedures in Section 9 of API RP 579.

Evaluation of Corrosion Flaw

A region of corrosion is discovered in the wall of a pressure vessel. The corrosion is in base metal and does not cross any welds. The following parameters apply:

The maximum operating pressure (p) is 270 psig at 100 F.
The inside diameter (ID) is 60 in., so the inside radius (R) is 30 in.
The wall thickness is 0.55 in. where there is no corrosion loss.
The future corrosion allowance (FCA) is 0.05 in.
The material is ASTM A516 Grade 70 steel, so the allowable stress (S_a) is 17500 psi.
The weld efficiency factor (E) is 0.85.
The minimum distance of the flaw from a major structural discontinuity (L_{msd}) is 40 in.
Critical thickness profiles (in inches) were measured on 1-in. intervals:
Longitudinal: 0.55, 0.50, 0.51, 0.41, 0.49, 0.52, 0.51, 0.55
Circumferential: 0.55, 0.50, 0.41, 0.48, 0.51, 0.55
The minimum measured thickness (t_{mm}) is thus 0.41 in.

The task is to determine if the vessel is acceptable continued operation by means of a Level 1 assessment.

First, compute minimum required wall thickness values as follows:

$$t^{c}_{min} = \frac{p(R + FCA)}{S_a E - 0.6p} = \frac{275(30 + 0.05)}{17500(1.0) - 0.6(275)} = 0.477 \text{ in.} \quad (6a)$$

$$t^{L}_{min} = \frac{p(R + FCA)}{2S_a E + 0.4p} = \frac{275(30 + 0.05)}{2(17500)(1.0) + 0.4(275)} = 0.235 \text{ in.} \quad (6b)$$

Thus, the minimum wall thickness (t_{min}) is 0.477 in. Thickness profiles were obtained. However, there are less than 15 thickness readings and general metal loss was not confirmed, so the point-thickness-reading method cannot be used.

Next, determine the length for thickness averaging (L) by computing the remaining thickness ratio (R_t) as follows:

$$R_t = (t_{mm} - FCA)/t_{min} = (0.41 - 0.05)/0.477 = 0.755 \text{ in.} \quad (7)$$

Obtain the factor Q from Table 4.4 of API RP 579 using $R_t = 0.755$ and $RSF_a = 0.9$ or compute Q as follows:

$$Q = 1.123[\{(1 - R_t)/(1 - R_t / RSF_a)^2 - 1]^{0.5} = 1.123[\{(1 - 0.755)/(1 - 0.755/0.9)^2 - 1]^{0.5} = 1.28 \quad (8)$$

$$L = Q(ID(t_{min}))^{0.5} = 1.28(60(0.477))^{0.5} = 6.85 \text{ in.} \quad (9)$$

Now, determine the longitudinal extent of the corrosion flaw (s), as follows:

$$s = 5(1.0) + \left(\frac{0.477 - 0.45}{0.50 - 0.45}\right)(1.0) + \left(\frac{0.477 - 0.46}{0.50 - 0.46}\right)(1.0) = 5.97 \text{ in.} \quad (10)$$

Since the minimum required thickness for longitudinal stress = 0.235 < 0.41 - 0.05 = 0.36, the circumferential extent of the flaw (c) is not required.

Because s < L (5.97 < 6.85), check the criteria of Paragraph 5.4.2.2.d of API RP 579:

$R_t = 0.755 > 0.20$ *Okay*
$t_{mm} - FCA = 0.36 > 0.10$ *Okay*
$1.8(Dt_{min})^{0.5} = 9.63 < L_{msd} = 40$ *Okay*

In addition, check the criterion of Paragraph 5.4.2.2.g of API RP 579 for c. Using Figure 5.7 of API RP 579, $R_t = 0.755 > 0.20$ at c/D = 0.08 *Okay*.

Based on the results of this Level 1 assessment per API RP 579, the corrosion flaw is found to be acceptable.

Evaluation of Crack-Like Flaw

A plate of SA 516 Grade 70 steel has an edge crack with a depth (a) = 0.50 in. The plate thickness (B) = 1.25 in., and the plate thickness (W) = 5.00 in. It is in service at a temperature (T) = 100°F and is subject to a maximum axial load (F) = 240 kips. No material properties data are available. There are no bending loads and no cyclic loads or environmental exposure (non-growing crack). The problem is to determine if the flaw is acceptable and the maximum safe applied axial load by Level 2 assessment.

From ASME Code Section II.D, the minimum yield strength of the plate material is 38 ksi. The minimum fracture toughness (K_{Ic}) is estimated using methods given in API RP 579. From Table 3.3 of API RP 579, Curve B applies to this steel. From Figure 3.3 of API RP 579 (ASME Code Section VIII, Division 1, Paragraph UCS-66), the reference temperature (T_{ref}) = 40°F for this case. Then, from Paragraph F.4.4.1.c of API RP 579, an estimate of K_{Ic} is computed as follows:

$$K_{Ic} = 33.2 + 2.806 \exp[0.02(T - Tref + 100)] \quad (11a)$$

$$K_{Ic} = 33.2 + 2.806 \exp[0.02(100 - 40 + 100)] = 102 \text{ ksi}\sqrt{\text{in.}} \quad (11b)$$

Next, determine the reference stress (σ_{ref}), using Equation D.27 of API RP 579. The primary membrane stress (P_m) = 240/(1.25 x 5.00), and the primary bending stress (P_b) = 0. It follows that

$$\sigma_{ref} = \frac{P_b + (P_b^2 + 9P_m^2)^{0.5}}{3(1-\alpha)} = \frac{P_m}{(1-\alpha)} = \frac{240}{(1.25\times 5.00)(1-\alpha)} \quad (12)$$

From Equation D.28 of API RP 579, $\alpha = a/W$; thus,

$$\sigma_{ref} = 240/[5(1.25)(0.9)] = 42.7 \text{ ksi} \quad (13)$$

From Tada, et al.,[8] the stress intensity factor (K_I) is

$$K_I = Y\, P_m\, (\pi a)^{0.5} \quad (14)$$

Where $Y = 1.122 - 0.231(a/W) + 10.550(a/W)^2 - 21.710(a/W)^3 + 30.382(a/W)^4$

For a = 0.5, W = 5, and P_m = 240 kips,

$$Y = 1.122 - 0.231(0.1) + 10.550(0.1)^2 - 21.710(0.1)^3 + 30.382(0.1)^4 = 1.186 \quad (15)$$

$$K_I = 1.186(240/[5(1.25)])(p0.5)^{0.5} = 57.1 \text{ ksi}\sqrt{\text{in.}} \quad (16)$$

Finally, determine L_r and K_r as follows:

$$L_r = \sigma_{ref}/\sigma_{ys} = 42.7/38.0 = 1.12 \quad (17)$$

$$K_r = K_I/K_{ic} = 57.1/102 = 0.559 \quad (18)$$

When these results are plotted, the evaluation point falls above the Level 3 FAD as shown by the uppermost square symbol in Figure 4. Thus, the crack-like flaw is NOT acceptable.

A spreadsheet was made to perform these same calculations as a function of applied load, and the results are shown by the other square symbols plotted in Figure 4. If this were part of a Level 2 assessment, the maximum acceptable load would be 171 kips using the Level 2 FAD. Alternatively, partial safety factors and the Level 3 FAD could be used. If this were part of a Level 3 assessment, the maximum acceptable load would be 222 kips.

Conclusion

This paper has reviewed the basic concepts of fitness for service assessment and the history of the methodology developed and implemented in API RP 579. Two examples were presented to illustrate application of the API RP 579 techniques.

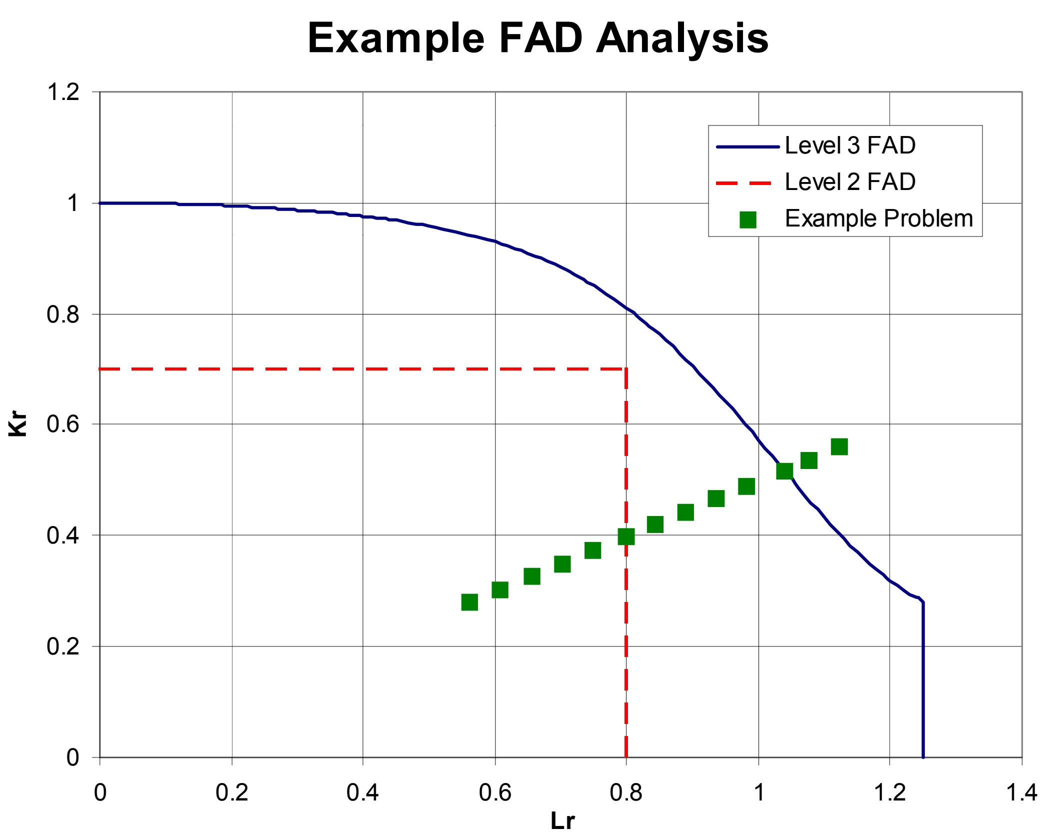

Figure 4. Failure Assessment Diagram (FAD) for Crack-Like Flaw Example.

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