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Clarification On Definition Of Membrane-to-Gradient Stress Ratio Used In The Development Of ASME Code Section XI Appendix L Flaw Tolerance Procedures

NUCLEAR

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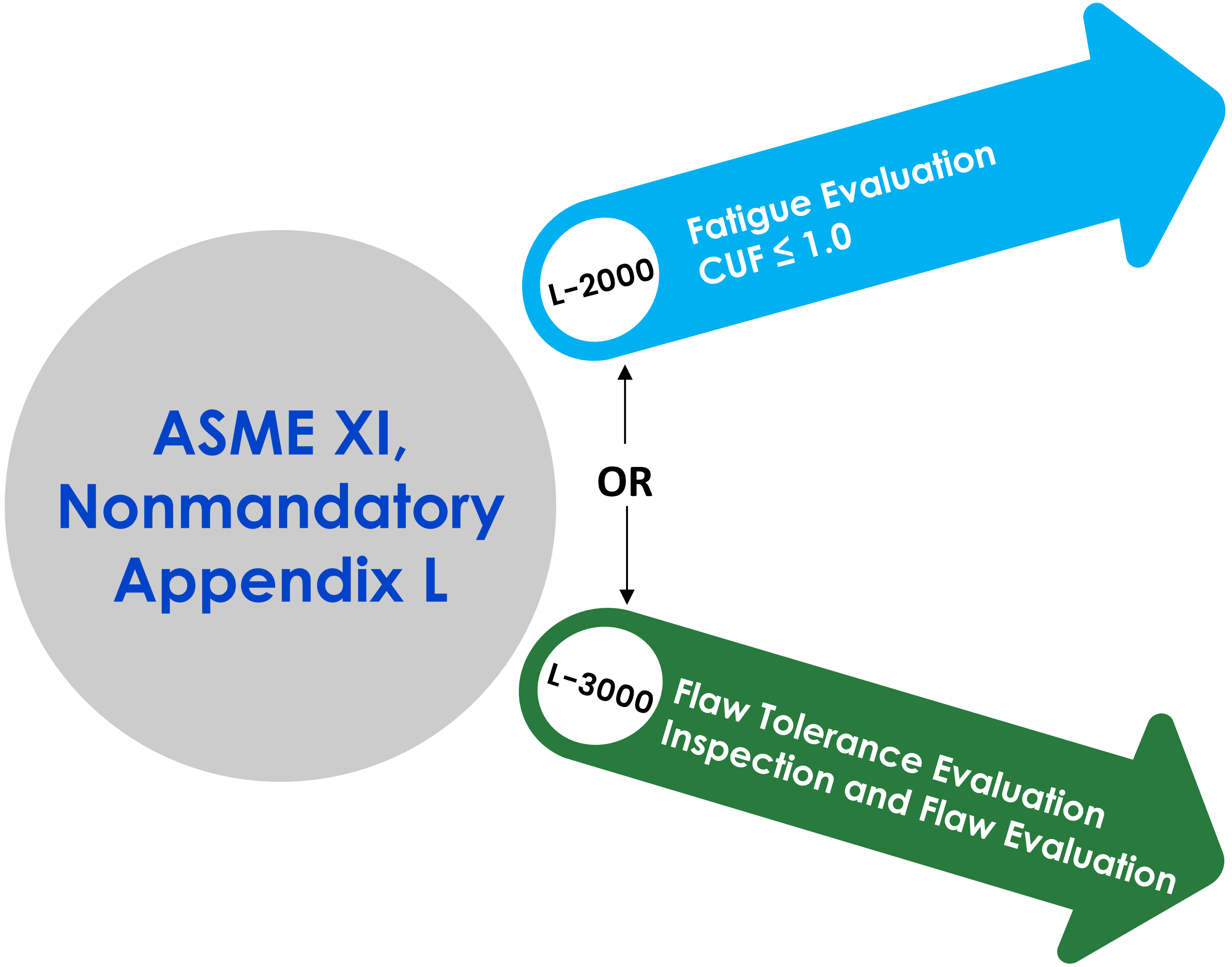
Overview of Appendix L

ASME Code, Section XI, Nonmandatory Appendix L provides procedures for performing cumulative usage factor (CUF) and fatigue flaw tolerance analytical evaluations



Enabling words in IWB-3740:

(a) Nonmandatory Appendix L provides analytical evaluation procedures that may be used to assess the effects of thermal and mechanical fatigue concerns on component acceptability for continued service.

(b) Nonmandatory Appendix L provides analytical evaluation procedures that may also be used when the calculated fatigue usage exceeds the fatigue usage limit defined in the original Construction Code.

L-3000: Flaw Tolerance Evaluation

Flaw tolerance evaluation eliminates the need to calculate and monitor CUF

As a result, it is a highly attractive option for components that are already in the Section XI inspection program

1 Inspection

Verify the absence of any flaws exceeding the applicable standards in Table IWB-3410

2 Flaw Tolerance

Postulate a hypothetical flaw, determine stresses, and perform a flaw tolerance evaluation to define the allowable operating period

3 Monitoring

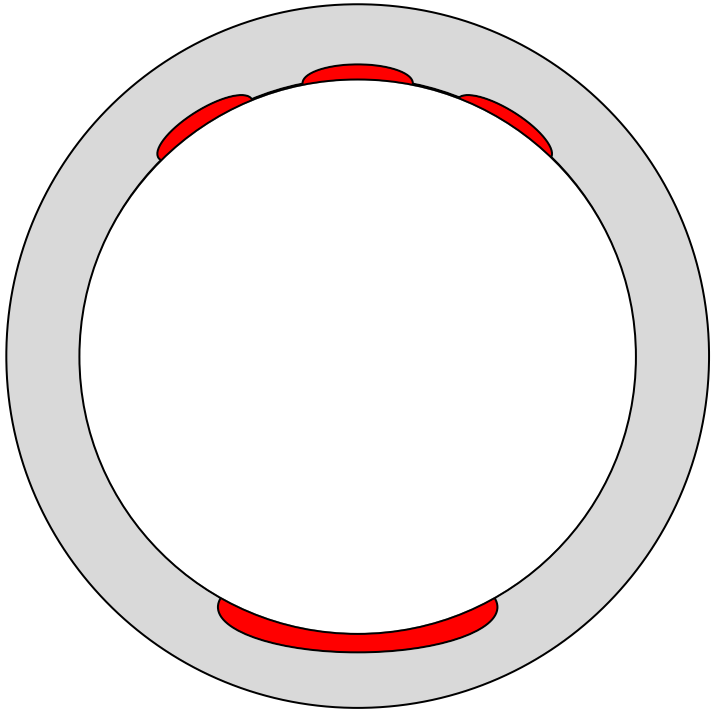
Continue operation and inspect at a frequency determined in the flaw tolerance evaluation

ASME XI, Nonmandatory Appendix L

EPRI

Equivalent Single Cracks (ESCs)

- The Appendix L flaw tolerance procedure accounts for the possibility of crack initiation and growth at multiple locations around the component circumference by employing the concept of an equivalent single crack (ESC)
  - The Appendix L ESCs have aspect ratios that yield leakage probabilities consistent with multiple crack behavior



Challenges With Appendix L

Through application of Appendix L, there have been several obstacles identified by users

To address these challenges the Task Group on Appendix L was re-established

- Lack of detail on how to calculate ESCs
- ESC tables are based on outdated fracture mechanics rules (2006 timeframe)
- Application to components other than straight piping isn't defined
- No technical basis was provided for axial flaws

Membrane to Gadient (M-G) Stress Ratio

Lack of detail on how to calculate ESCs

- The cyclic M-G stress ratio, identified as $\Delta\sigma_m/\Delta\sigma_g$, is an important parameter in the Appendix L ESC calculations
  - Accounts for the evolution of the flaw aspect ratio due to the effect of stress gradient through the component wall thickness
  - Users stated that it is not clear how to calculate the cyclic stress M-G ratio for many applications

A small M-G ratio (low cyclic membrane stress and high cyclic gradient stress) has significantly higher stress at the surface compared to the deepest point evaluated through the section thickness, which will lead to more crack growth at the surface and promote multiple adjacent cracks to coalesce

Current Technical Basis for Appendix L

- Based on a detailed review of original Appendix L technical basis documents, the cyclic M-G stress ratio for the Appendix L ESC tables is based on:

  - Decomposed total stress value ($\Delta\sigma_0$) at the component internal surface into membrane ($\Delta\sigma_m$) and gradient stress ($\Delta\sigma_{g0}$):

$$\Delta\sigma_0 = \Delta\sigma_m + \Delta\sigma_{g0}$$

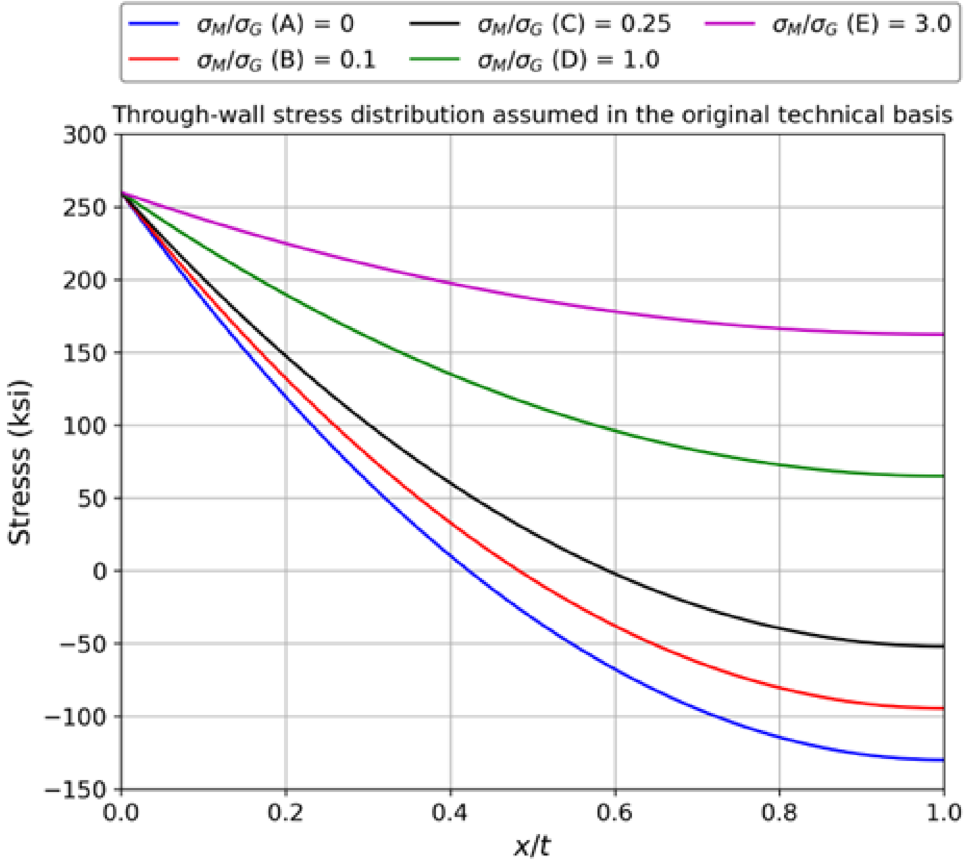
  - The through-wall gradient stress ($\Delta\sigma_g$) is assumed to follow a quadratic equation

$$\Delta\sigma_g = \Delta\sigma_{g0}\left[1 - 3\left(\frac{x}{t}\right) + \frac{3}{2}\left(\frac{x}{t}\right)^2\right]$$

Current Technical Basis for Appendix L

- The original calculations to develop the Appendix L ESC tables used $\Delta\sigma_0$ = 260 ksi and six values of cyclic M-G stress ratio:

$\Delta\sigma_m / \Delta\sigma_{g0}$ = 0, 0.1, 0.25, 1, 3, and ∞ (i.e., no gradient stress, or all membrane stress)



Challenge with Applying Available Stresses

- While the M-G ratio definitions crafted in the development of Appendix L are intended to be compatible for use with existing NB-3200 and NB-3600 stress reports, they are based on the use of surface stresses
  - This is because the underlying evaluations were focused on calculating CUF
  - However, there are still challenges in applying stresses from NB-3200 and NB-3600 stress reports to Appendix L evaluations

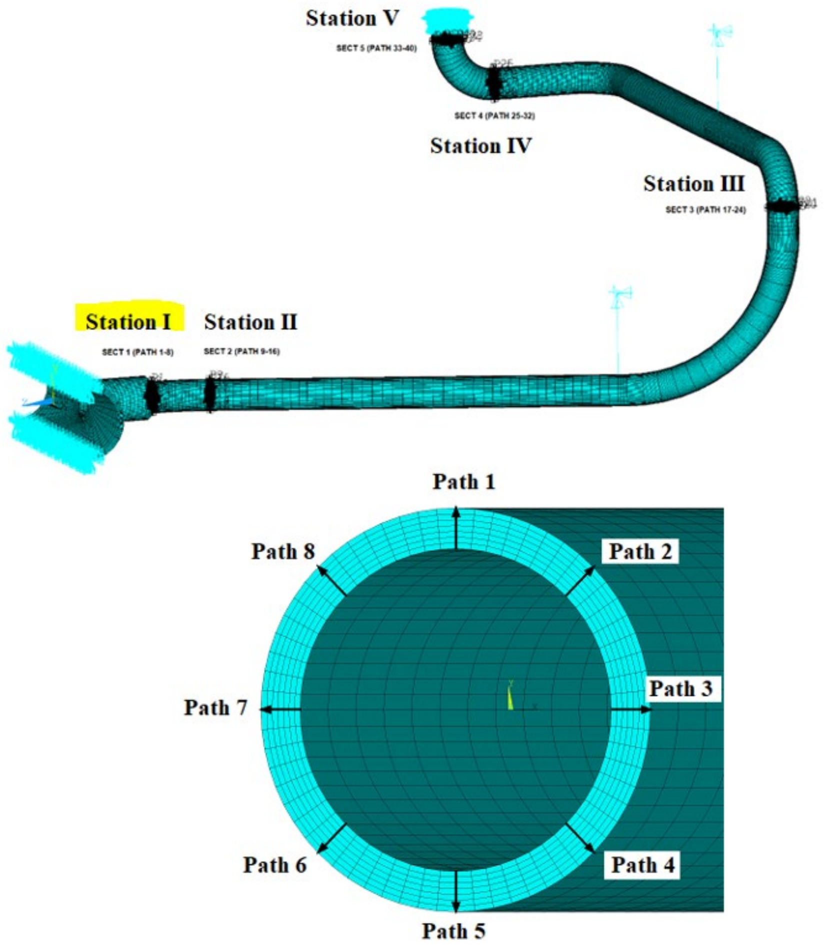


Image courtesy of Structural Integrity Associates

Improved Guidance Suggestion

- The M-G ratio is based on the through-wall variation of stress, which is more appropriate for use in a crack growth evaluation
- An improved procedure to calculate the M-G stress ratio is suggested for a given cyclic stress input across the component wall thickness
  - When the generic stress is characterized by a fourth order polynomial stress distribution consistent with Section XI Appendix A:

$$\Delta\sigma(x) = \Delta\sigma_0\left[B_0 + B_1\left(\frac{x}{t}\right) + B_2\left(\frac{x}{t}\right)^2 + B_3\left(\frac{x}{t}\right)^3 + B_4\left(\frac{x}{t}\right)^4\right]$$

  - The statically equivalent membrane and bending stress would be given by the following equations from API 579-1:

$$\Delta\sigma_m = \Delta\sigma_0\left(B_0 + \frac{B_1}{2} + \frac{B_2}{3} + \frac{B_3}{4} + \frac{B_4}{5}\right)$$

$$\Delta\sigma_b = \Delta\sigma_0\left(-\frac{B_1}{2} - \frac{B_2}{2} - \frac{9B_3}{20} - \frac{6B_4}{15}\right)$$

Conclusions

- It is not clear how to calculate the cyclic stress M-G ratio for many applications, especially from finite element analyses
  - Has noteworthy consequences because the determination of the cyclic M-G ratio has a significant impact on the selection of the ESC for use in an Appendix L flaw tolerance evaluation

- This paper provides clarification, and identifies ongoing, further studies underway that will clarify the calculation of M-G ratios:
  - Original Appendix L authors were focused on the use of available Section III Design Stress Reports which concentrated on computing CUF, so they made use of surface stresses
    - The use of the surface stress does not characterize the more appropriate cross-sectional stress distribution
    - An equivalent membrane-bending stress ratio for a generic through-wall cyclic stress profile was developed
      - The proposed equivalent membrane-bending stress ratio idea presented in this paper is preliminary; further work is needed to fully establish and verify the approach

- The final EPRI Technical Report on this work will be published by the end of 2025

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