Determination of R/t limits for ASME Code Case N-494 FAD curve procedure

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ABSTRACT

A comprehensive study of failure assessment diagrams for circumferentially surface-cracked austenitic stainless and ferritic steel pipes was conducted with the use of the finite element method (FEM). While the majority of the analyses were conducted using the line-spring/shell finite element method, some three-dimensional finite element analyses, conducted independently, are also reported in this paper. Comparison of the predictions of the line-spring/shell and three-dimensional analyses reinforce the validity of the former approach for surface cracked pipes. The results indicated that the ASME Code Case N-494-2 applicable for ferritic steel piping appears reasonably conservative even for pipes with mean radius-to-wall thickness ratios of 20, whereas the results showed that the newly adopted Code Case N-494-3 for austenitic stainless steel piping requires a limit for pipe with mean radius-to-wall thickness ratios larger than 15. For consistency, the limitation of $R_m/t \leq 15$ was incorporated in the approved final version of Code Case N-494-3, for both ferritic and austenitic pipes. Because these Code Cases are applicable only to Class 1 primary nuclear piping, which typically has values of $R_m/t \leq 15$, this is not a significant limitation.

1.0 INTRODUCTION

Failure Assessment Diagrams (FADs) have offered a simple and useful methodology in the engineering assessment and evaluation of the integrity of flawed pressure vessels, piping and related equipment. The idea of this simple methodology originates from the work, known as R6 procedure, of Harrison et al. (1976). A FAD for a given flawed structure typically involves estimation of an assessment curve or line in a two-dimensional space defined by some form of normalized stress, denoted $S_p$ and some form of normalized crack-driving force, denoted $K_n$. This curve or line is thought to demarcate the safe and unsafe regions in the considered space for the given structure, thereby providing a very useful tool in deciding on the continued operability of the equipment or component in question. The original R6 procedure, which was based on the Dugdale strip yield model, was shown to be inadequate.
in its representation of geometry and strain-hardening effects of the material (Bloom and Malik, 1982). This led Bloom and Malik (1982) to formulate a procedure for developing FAD curves based on the GE/EPRI J-estimation scheme for surface-cracked pipes, assuming Ramberg-Osgood behavior of the material, developed by Kumar et al. (1981). The resultant assessment approach was coined the deformation plasticity FAD (DPFAD) (Bloom, 1983). Following the study of Akhurst and Milne (1983), which demonstrated that the GE/EPRI estimation scheme, and thus the DPFAD method, was quite sensitive to the fit of the stress-strain data to the Ramberg-Osgood equation, Bloom (1996) modified the DPFAD approach to take into account the actual true stress-true strain behavior of the material, which he termed the piecewise FAD approach (PWFAD).

This paper examines the effect of pipe geometry on FAD curves for austenitic stainless steel and ferritic steel piping. Circumferential (constant depth) surface cracked pipes are considered in this study. To this end, FAD curves were generated using the results from line-spring/shell finite element model. In addition, the FEM FAD curves are compared with the ASME Code Case FAD curves.

2.0 EQUATIONS USED IN DEVELOPING THE FAD CURVES

The abscissa, $S_r$, of the FAD for combined bending and tension is given by,

$$S_r = \frac{P_m}{P_m'}$$

the membrane stress, $P_m = p \frac{R_o^2}{R_o^2 - R_i^2}$

where $P_m' = \sigma_y \gamma \Gamma_m$

and $\gamma = -\frac{\pi}{8} \frac{P_b}{P_m} + \sqrt{\left[\frac{\pi}{8} \frac{P_b}{P_m}\right]^2 + 1}$

and the bending stress, $P_b = \frac{M R_o}{I}$

where $\Gamma_m = \frac{A_{nc}}{A}$

$p$ = internal pressure,

$M$ = applied bending moment,

$\sigma_y$ = yield strength,

$R_o, R_i$ = outer and inner radii

$A, A_{nc}$ = total area of the pipe cross-section (including the crack), and uncrazed cross-

sectional area of the pipe.

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In the case of pure tension, \( \gamma = 1 \). In the case of pure bending, \( S_r \) is given by,

\[
S_r = \frac{\pi}{4} \frac{P_b}{\alpha \Gamma_m}
\]

(3)

The ordinate, \( K_r \), is given by

\[
K_r = \sqrt{\frac{J}{J}}
\]

(4)

where, \( J \) in the \( K_r \) term, is the applied \( J \) value.

It is noted here that the definitions of membrane and bending stresses used here are consistent with ASME Code Case N-494-2. These definitions entail some degree of conservatism in that they overestimate the actual membrane and bending stresses. In the GE/EPRI estimation scheme, the actual membrane stress and the bending stress based on thin-shell theory were used. Another important consideration involves the fact that in determining the elastic contribution to \( F_1 \), functions developed by Zahoor (1990) are recommended in ASME Code Case N-494-2. These \( F_1 \) functions are independent of \( R_m/t \) ratios of the pipe and realistically have a limited range of applicability, i.e., for \( R_m/t \) ratios between 5 and 10. It will be shown later that use of these \( F_1 \) functions further accentuates the effect of \( R_m/t \) ratios of the cracked pipe on the resulting FAD curves.

**3.0 COMPARISON OF FEM FAD CURVES WITH ASME CODE CASES**

Recently, based on Bloom’s work (1995), ASME Section XI evaluated a newly proposed Code Case, N-494-3, for a lower bound FAD curve for austenitic stainless steel piping. This code case assumed a lower bound true stress-true strain behavior of a TP304 austenitic stainless steel, and used the GE/EPRI estimation procedure for a cracked pipe with \( R_m/t = 10 \), \( \theta/\pi = 0.25 \), and \( a/t = 0.5 \), subjected to pure tension, to establish the FAD curve. The stress-strain curve was from the same pipe used in the finite element analyses, i.e., from Battelle TP304 Pipe A23. In this section, the FAD curves developed using the finite element results for pure bending as well as pure tension are compared with the proposed ASME Code Case N-494-3 for validation purposes. In addition, the effect of pipe \( R_m/t \) ratios on the resulting FAD curves are examined for austenitic stainless as well as ferritic steel piping.

In constructing the FAD curves based on the finite element analyses for pure tension and pure bending, the abscissa, \( S_n \), is calculated based on Equations 1 to 3. In calculating \( S_n \) for pure bending, the value of applied bending moment, \( M \), from the FEM analyses was directly used, while for pure tension, the pressure, \( p \), was calculated from the applied tensile load, \( N \), from the FEM analyses. The total crack-driving force, \( J \), from the FEM analyses was used with its elastic part calculated using Zahoor’s \( F_1 \) function and the definitions of membrane
and bending stresses as given in Equation 2. The FAD curves developed in this manner are consistent with Code definitions.

3.1 Comparison of FAD Curves for Austenitic Stainless Steel Piping with $R_m/t = 10$

A comparison of FAD curves (using the TP304 Pipe A23 stress-strain curve) for pure tension is shown in Figure 1. It can be seen that the FEM FAD curve yields a slightly increased regime of safety in comparison with the proposed Code Case N-494-3. Thus, for the case of pure tension, and for $R_m/t = 10$, the proposed Code Case N-494-3 FAD curve compared well with the FEM FAD curves, albeit slightly conservative.

In the case of pure bending, a comparison of FAD curves is shown in Figure 2. For the region near fully plastic, ($K < 0.5$), the proposed Code Case N-494-3 appears to be slightly more conservative than the FEM FAD curves. In the transition regime ($K$ values between 1 and 0.5), the Code Case is less conservative when compared with the results of line-spring/shell analyses and Bass’s three-dimensional analyses, whereas a better agreement is found between the FAD curves from the Code Case and Gilles’s three-dimensional analyses. It should also be noted that in the transition regime, the FEM FAD curves for pure bending lie below the Code Case FAD curve, while the reverse is true for pure tension. Thus, the FEM FAD curves for pure bending appear to provide a lower bound in comparison with the FEM FAD curves for pure tension especially in the transition regime.

3.2 Effect of $R_m/t$ Ratio on FAD Curves for Austenitic Stainless Steel and Ferritic Steel Piping

It was shown in the preceding subsection that the FEM FAD curves for pure bending provided a lower bound compared with that for pure tension. In addition, for the considered crack geometry in a pipe of $R_m/t$ of 10, the proposed Code Case N-494-3 FAD curve provides a reasonably conservative approach, except in the LEFM-EPFM transition regime where the Code Case FAD curve was slightly higher for the case of pure bending. In order to examine the effect of $R_m/t$ ratio on the FAD curves, additional line-spring/shell calculations were performed assuming the same crack geometry for the same TP304 (Pipe A23) material, as well as for a ferritic steel. In the case of ferritic steel, an incremental stress-strain curve was used in the analyses. This curve approximates a Ramberg-Osgood law with $n = 4.2$, but blends with the elastic behavior at the yield strength. It should be noted again that the line-spring/shell analysis considers incremental theory of plasticity, as opposed to deformation plasticity.

The FEM FAD curves for pure bending and for several $R_m/t$ ratios using the TP304 (Pipe A23) material are shown in Figure 3. For the sake of comparison, the proposed Code Case N-494-3 curve is also shown in the figure. It can be seen that while FEM FAD curve for $R_m/t = 5$ lies above the proposed code case FAD curve, the FEM FAD curve for $R_m/t = 20$ lies significantly below the proposed code case curve. This is not surprising considering the fact that the proposed code curve uses the GE/EPRI $h_1$ function for $R_m/t = 10$. It is noted that
Figure 1. Comparison of FAD curves for pure tension loading for A23 austenitic stainless steel material. Approach 1 is used in developing FAD curves from FEM results ($R_{oc}/t = 10$, $\theta/\pi = 0.25$, $a/t = 0.5$, and actual Pipe A23 stress-strain curve)

Figure 2. Comparison of FAD curves for pure bending for A23 austenitic stainless steel material. Approach 1 is used in developing FAD curves from FEM results ($R_{oc}/t = 10$, $\theta/\pi = 0.25$, $a/t = 0.5$, and actual Pipe A23 stress-strain curve)
Figure 3. Comparison of FEM FAD curves with different $R_m/t$ values and Code Case N-494-3 FAD curve. Approach 1 is used in constructing FAD curves from FEM results ($\theta/\pi = 0.25$, $a/t = 0.5$, pure bending, actual stress-strain curve of Battelle Pipe A23)

Mohan et al. (1997) reported a significant increase in the $h_f$ function value for a pipe with $R_m/t = 20$. Another important consideration is the fact that the Zahoor's $F_1$ function as used in the ASME Code is strictly not applicable for $R_m/t$ values greater than 10. The effect of $R_m/t$ ratio on FAD curves for ferritic steel piping, shown in Figure 4, is quite significant as well. However, in this case, the Code Case N-494-2 curve lies slightly below the FEM FAD curve for $R_m/t = 20$. Thus, the effect of $R_m/t$ ratio on the FAD curves is quite significant for both austenitic stainless steel and ferritic steel piping materials. The Code Case N-494-2 curve for ferritic steel pipes was conservative enough to account for this effect, for pipes with $R_m/t$ up to 20, while Code Case N-494-3 curve for austenitic steel piping was not. Hence, an $R_m/t$ limit for the proposed Code Case N-494-3 austenitic pipe FAD curve was recommended.
4.0 SUMMARY AND CONCLUSIONS

A comprehensive study was undertaken to examine effects of pipe geometry and definition of stresses on resulting FAD curves. In addition, the FAD curves constructed using FEM analyses were compared with the relevant ASME Code Cases. The analyses were restricted to a fixed constant depth circumferential surface flaw with $a/t = 0.5$ and $\theta/\pi = 0.25$. In the majority of the cases, the line-spring/shell finite element method was used to determine the crack-driving force. It was shown by Mohan (1996), that within its range of applicability, the line-spring/shell method does provide an excellent approximation of the crack-driving force for circumferentially surface-cracked pipes and elbows subjected to pure as well as combined pressure plus bending conditions. Additional verification of this fact is provided in this paper through comparisons of the predictions of the line-spring/shell method with that of the three-dimensional finite element method. The latter calculations were conducted independently by Bass (ORNL) and Gilles (Framatome).
Comparisons of FAD curves for a lower-bound austenitic stainless steel piping material using FEM analyses and Code Case N-494-3 show that the latter is conservative for the case of pure tension while it is slightly less conservative in the transition region for bending.

For the austenitic stainless steel material considered in this study, it is shown that the FAD curve for pure bending lies lower than that of pure tension, thus providing a lower bound. The results of the effect of $R_m/t$ on FAD curves for austenitic piping indicate that the proposed Code Case N-494-3 FAD curve should be limited to pipes with of $R_m/t$ ratios less than 15. However, for ferritic steel piping, the Code Case N-494-2 FAD curve appears to be conservative enough even for an $R_m/t$ value of 20. The $R_m/t$ of 15 was subsequently employed in the new Code Case N-494-3 for both austenitic stainless steel and ferritic steel piping, for consistency purposes.

ACKNOWLEDGMENTS

The authors are grateful to Mr. P. Gilles, Framatome (France) for his help in also conducting the independent three-dimensional finite element calculations. R. Mohan and G. Wilkowski express their gratitude to Mr. D. Scarth, Ontario-Hydro, Canada for his interest and involvement in this work as well as the rest of the ASME Section XI Working Group on Pipe Flaw Evaluations. Fruitful discussions with Prof. D. M. Parks, MIT, and Dr. P. Burgers, HKS, are acknowledged by R. Mohan.

REFERENCES


