Crack Shape Factor in Plastic Collapse Evaluation of Flawed Pipes

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ABSTRACT

In an ASME Section XI evaluation of a circumferential flawed pipe, the maximum flaw depth is conservatively assumed constant over the measured length. This paper demonstrates that if the flaw is assumed to have a curved profile, a significant increase in flaw size acceptance criteria can be obtained. Crack shape factors are proposed in this paper that can be used in conjunction with the tables in ASME Code Section XI, paragraph IWB-3641 to account for the shape of a circumferential flaw.

INTRODUCTION

It has been shown in [1] that if an arbitrarily shaped circumferential flaw in a pipe section is broken into various segments as shown in Figure 1, then based on a net section plastic collapse criteria whereby the remaining ligament of the flawed pipe becomes fully plastic subsequent to failure, two sets of equations can be derived as follows:

Case 1: $\Theta_n+\beta\leq\pi$ (entire flaw is in the tension zone)

$$\beta=\pi(1-P_m/\sigma_f)/2-[\sum_{i=1}^{n-1}(d_i-d_{i+1})\Theta_i+d_n\Theta_n]/2t \tag{1a}$$

$$P_b=2\sigma_f\{2\mathrm{Sin}\beta-[\sum_{i=1}^{n-1}(d_i-d_{i+1})\mathrm{Sin}\Theta_i+d_n\mathrm{Sin}\Theta_n]/t\}/\pi \tag{1b}$$

Case 2: $\Theta_n+\beta>\pi$ (portion of flaw (segment "p") in the compression zone)

$$\beta=[\pi(t-d_p-tP_m/\sigma_f)-\sum_{i=1}^{p-1}(d_i-d_{i+1})\Theta_i]/(2t-d_p) \tag{2a}$$

$$P_b=2\sigma_f[(2-d_p/t)\mathrm{Sin}\beta-\sum_{i=1}^{p-1}(d_i-d_{i+1})\mathrm{Sin}\Theta_i)/t]/\pi \tag{2b}$$

These equations are generalizations of the net section plastic collapse equations derived for a constant depth flaw by Ranganath and Mehta [2] and also by Kanninen et al. [3, 4, 5]. The work of these authors has formed the basis for Tables IWB-3641-1 and IWB-3641-2 in the ASME Code [6] which assumes a flaw of constant depth along its length.

CRACK SHAPES

Equations (1) and (2) can be used to investigate the net section plastic collapse behavior of a circumferential flaw of any shape, the only requirement being that the flaw should be bi-laterally symmetric at its apex. To investigate the effect of a flaw with a curved profile, elliptical and parabolic flaw shapes are considered in this paper and compared to a constant depth flaw. These crack shapes are shown schematically in Figure 2. From this figure, it can be seen that if a constant depth flaw is assumed instead of the actual curved shape, a significant portion of the remaining ligament of the pipe is ignored. The relationship between d_i and θ_i for these crack shapes are as follows:

(a) Constant crack depth:

$$d_i = d_{max} \tag{3a}$$

(b) Elliptical crack shape:

$$d_i = d_{max}\sqrt{1-(\theta_i/\theta_n)^2} \tag{3b}$$

(c) Parabolic crack shape:

$$d_i = d_{max}[1-(\theta_i/\theta_n)]^2 \tag{3c}$$

The above equations, when substituted into Equations (1) and (2), provide a complete set of equations necessary to describe the net section plastic collapse behavior of a flawed pipe. For a given crack shape from Equation (3) and for specified values of P_m, P_b, and σ_f, the value of d_{max} can be determined for a given value of θ_n by solving Equations (1) and (2) iteratively.

ASME CODE EVALUATION

The basis for derivation of Tables IWB-3641-1 and IWB-3641-2 from the ASME Code [6] for flaw evaluation of austenitic stainless steels has been provided in [7]. Tables IWB-3641-1 (normal/upset/test conditions) and IWB-3641-2 (emergency/faulted conditions) were derived using Equations (1) and (2) with a constant depth flaw. For normal/upset/test conditions, a safety factor of 2.77 was assumed together with the assumption that $P_m = 0.5\ S_m$ (where S_m is the ASME Code allowable design stress intensity) and $\sigma_f = 3.0\ S_m$. For emergency faulted conditions, a safety factor of 1.29 was used in conjunction with the assumption that $P_m = 1.0\ S_m$ and $\sigma_f = 3.0\ S_m$.

When these assumptions are used in Equations (1) and (2) together with the crack shapes in Equation (3), acceptable flaw depth ratios (d_{max}/t) can be determined given a stress ratio ($[P_m + P_b]/S_m$) and flaw length. Figure 3 shows an example of a plot of the collapse line for the case where the cracked pipe is subjected to a stress ratio of 1.0 under normal operating conditions. As can be seen from this figure, there are significant differences in acceptable flaw size between the three crack shapes. Because more uncracked ligament remains by assuming a parabolically or elliptically shaped flaw, these crack shapes lead to more favorable results.

CRACK SHAPE FACTOR

Taking the flaw with constant depth as a reference, crack shape factors are determined for elliptical and parabolic shaped flaws. A plot of the crack shape factors versus fraction of pipe circumference is shown in Figure 4. To determine the acceptable flaw depth ratio for an elliptically or parabolically shaped flaw, the acceptable flaw depth ratios provided in Tables IWB-3641-1 or IWB-3641-2 are multiplied by the appropriate crack shape factor from Figure 4.

It was found in this study that the crack shape factor is independent of the applied stress ratio. In deriving Tables IWB-3641-1 and IWB-3641-2, the allowable flaw depth ratios were limited to 75% of the pipe wall thickness [7]. The product of the Figure 4 crack shape factors and the acceptable flaw depth ratios in Tables IWB-3641-1 and IWB-3641-2 should also be limited to 75% of pipe wall thickness.

DISCUSSIONS AND CONCLUSIONS

Several experimental studies of flaws in piping have shown that the flaw depth varies along the length and that flaws have curved profiles. However, evaluation of flaws in Section XI of ASME Code, assumes a flaw of constant depth. This paper has shown that if a curved profile is used to describe the shape of the flaw, there can be an appreciable increase in the flaw acceptance criteria. The choice of the constant depth flaw in the ASME Code provides simplicity in analytical evaluation and also provides conservative results which for most practical purposes are adequate. However, inservice inspection techniques are improving to the point where the entire crack profile can be reasonably described. Therefore, the shape factors presented in this paper can be used to more accurately determine the acceptability of a given flaw. The use of elliptical and parabolic crack profiles in this study is purely arbitrary. The generalized equations presented in this paper can be used to derive the appropriate shape factors for any bi-laterally symmetric crack profile.

REFERENCES

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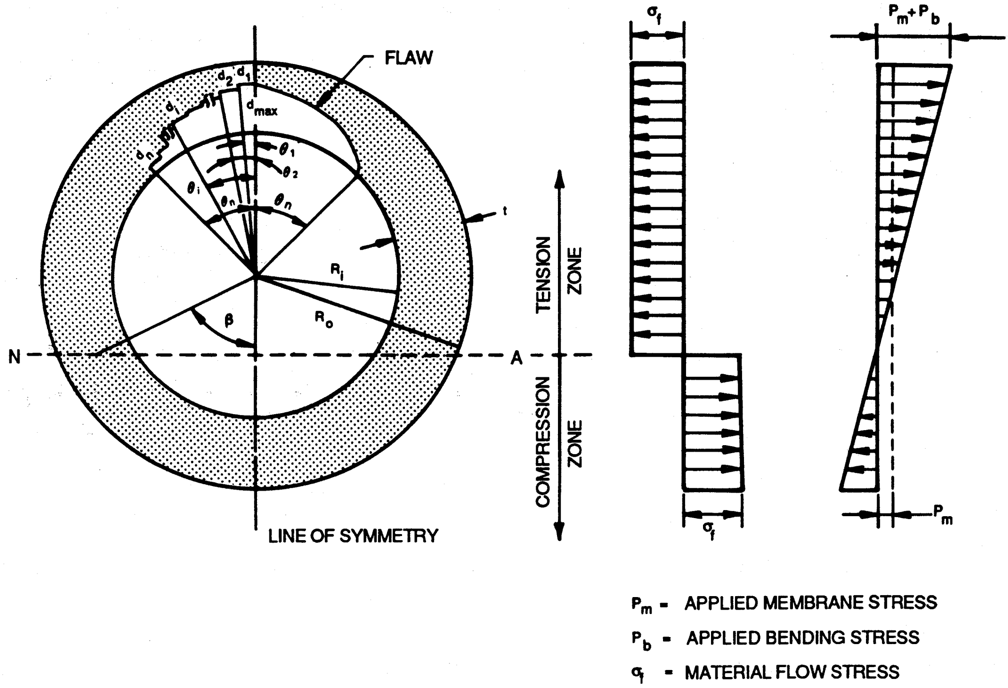

Fig. 1 Arbitrarily shaped circumferential crack geometry for net section plastic collapse analysis.

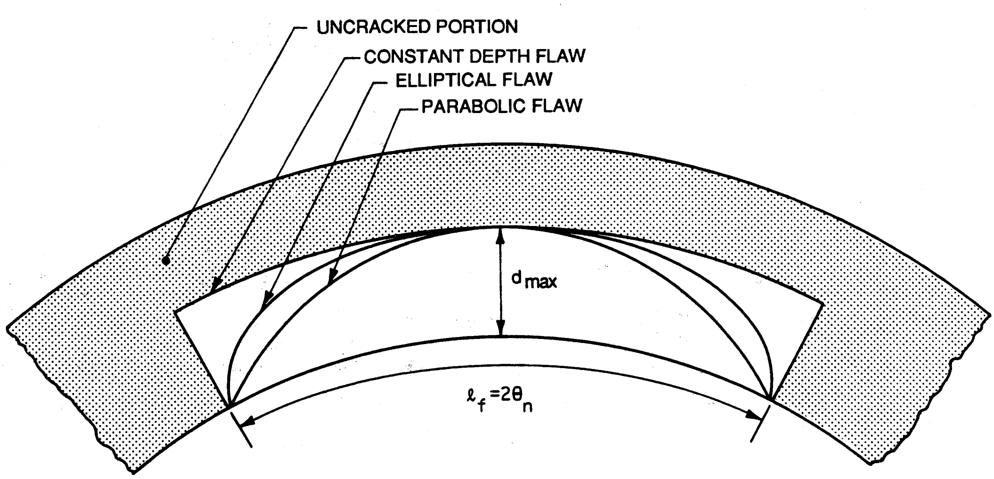

Fig. 2 Schematic illustration of various crack shapes.

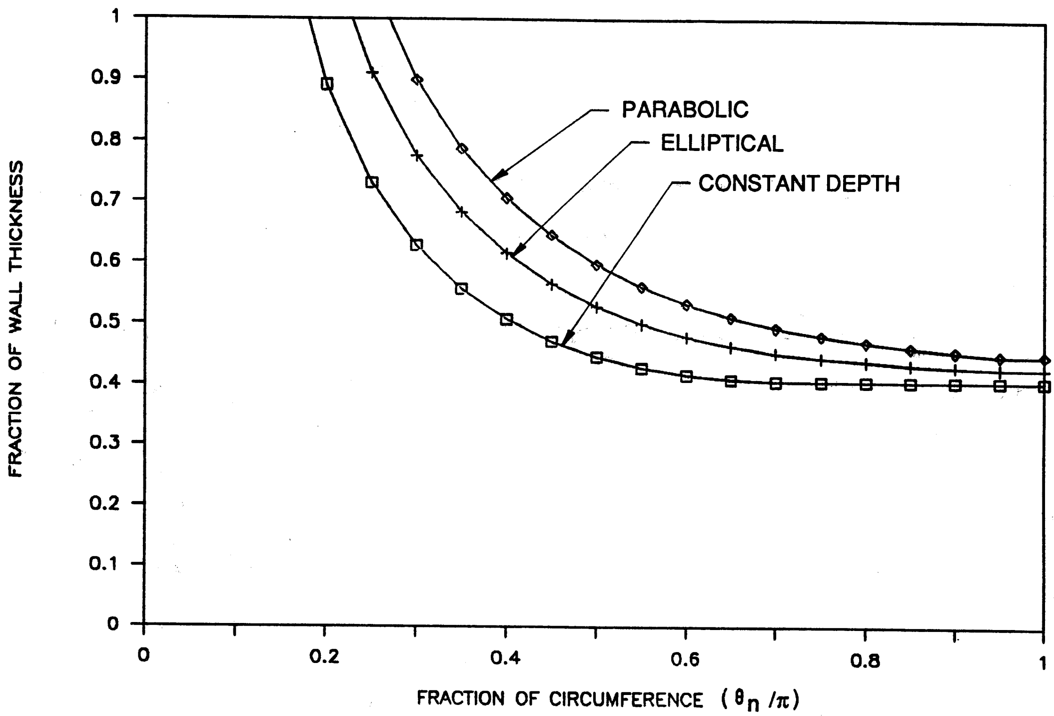

Fig. 3 Collapse line for various crack shapes under normal operating conditions and applied stress ratio = 1.0.

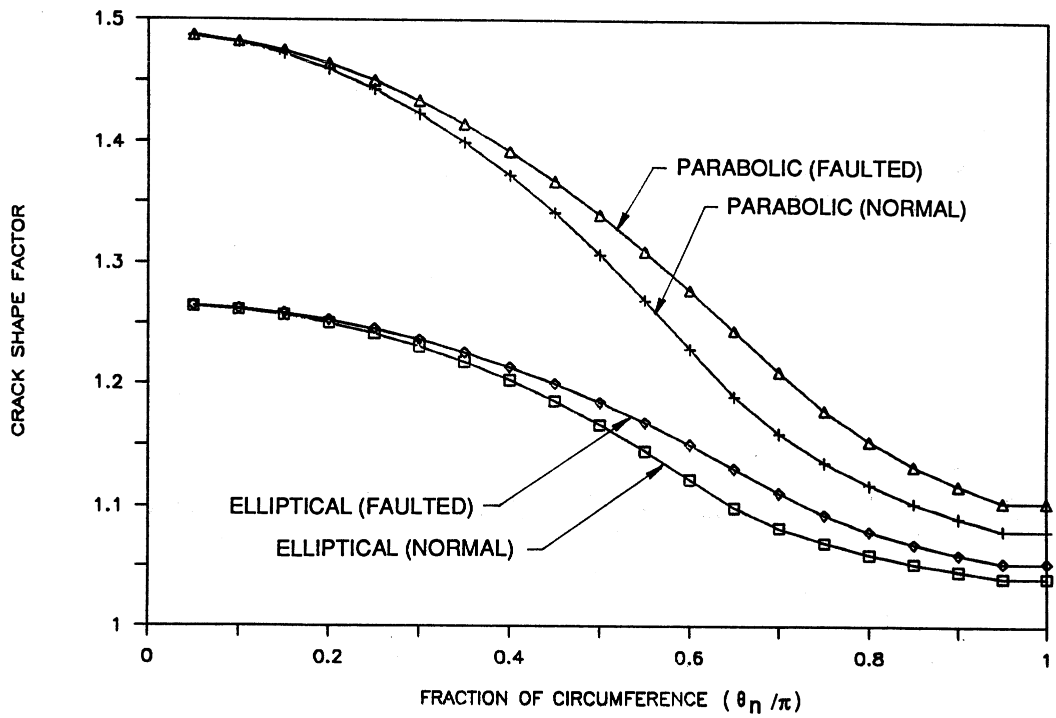

Fig. 4 Crack shape factors for normal operating and faulted conditions.