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On predicting the interaction of crack-like defects in ductile fracture

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ABSTRACT

Closely-spaced cracks in structures can interact with each other; the presence of one crack can change the strain energy release rate at another crack nearby. Since this interaction is enhanced by the onset of plasticity, elastic analysis alone should not be used for judging whether interaction between cracks will have a significant effect on the integrity of a structure.

1. Article body

A problem encountered frequently in structural integrity assessment is the need to assess structures containing multiple crack-like defects. In pipes and pressure vessels, closely-spaced crack-like defects can occur due to hot cracking of welds or from progressive modes of crack growth such as stress corrosion cracking or fatigue. Integrity assessment procedures including BS7910 [1], R6 [2], ASME B&PVC Section XI [3] and API 579-1 [4] contain criteria for determining whether a set of defects will interact with one another. In an assessment, the ability to show that the initiation of fracture at one defect is not affected by the presence of others can be very beneficial: it removes the need to conservatively re-characterise the crack system as a single enclosing crack or to model the interaction between cracks explicitly.

Criteria for determining whether this type of interaction is significant for fracture initiation are typically established using linear elastic fracture mechanics. Specifically, they may be based on linear-elastic modelling of interacting pairs of cracks and/or experimental observations of fatigue crack growth [5–7]. Normally, it is assumed that the maximum stress intensity factor which occurs anywhere on either crack tip line is the critical parameter for fracture initiation. When the proximity of two cracks increases this maximum stress intensity factor by an 'unacceptable' amount, 10% for example, interaction is judged to have a significant effect. The critical stress intensity factor can be affected by the size, shape, relative position and loading of the cracks [8], [9]. However, simple and conservative rules for acceptable crack proximity can be formulated based on results for selected crack pairs.

For a component subjected to a given set of constant surface tractions (i.e. 'primary' load [2]), interaction causes a proportionally larger enhancement of the Strain Energy Release Rate (SERR) under elastic-plastic conditions than in material that is purely elastic:

$$\left.\frac{G^{int}}{G}\right|_{el.-pl.} \geq \left.\frac{G^{int}}{G}\right|_{el.} \quad (1)$$

where G and G^{int} are SERRs for single and interacting cracks respectively, and the subscripts *el.* and *el.* $-pl.$ denote elastic and elastic-plastic material respectively. This can alternatively be expressed in terms of crack tip field parameters (pure Mode 1 loading assumed):

$$\left.\sqrt{\frac{J^{int}}{J}}\right|_{el.-pl.} \geq \left.\frac{K_I^{int}}{K_I}\right|_{el.} \quad (2)$$

where J and J^{int} are J-integrals for single and interacting cracks respectively, while and K_I and K_I^{int} are their stress intensity factors. When interaction criteria are formulated using linear elastic analysis but applied to cracks in elastic-plastic materials, there is a risk that the effect described by Equation (2) could cause unintentional non-conservatism. This is illustrated in the following example, representing a typical situation in which interaction criteria are employed.

Consider the cylindrical pipe with an inner diameter of 400 mm and an outer diameter of 500 mm shown in Fig. 1a. It is assumed to be long, but with closed ends. The pipe contains a pair of identical and co-planar internal semi-elliptical surface cracks in the axial-radial plane. The cracks each have a depth a of 25 mm and an overall width $2c$ of 100 mm, giving an aspect ratio $\frac{a}{c}$ of 0.5. Free from any residual stress or thermal gradient, the pipe is subjected to increasing internal pressurisation which causes both hoop and axial stress in the pipe wall; pressure also acts on the faces of the internal cracks. The pipe material's stress-strain curve follows a Ramberg-Osgood relationship [10] approximating the properties of A533B Class 1 ferritic pressure vessel steel at 20 °C [11] (Young's modulus: E = 210 GPa, Poisson's ratio: $\nu = 0.3$, yield stress: $\sigma_0 = 450$ MPa, hardening exponent: n = 7.6, yield offset parameter: $\alpha = 0.9333$). It follows incremental plasticity theory with a von Mises yield locus and an isotropic hardening law. Here,

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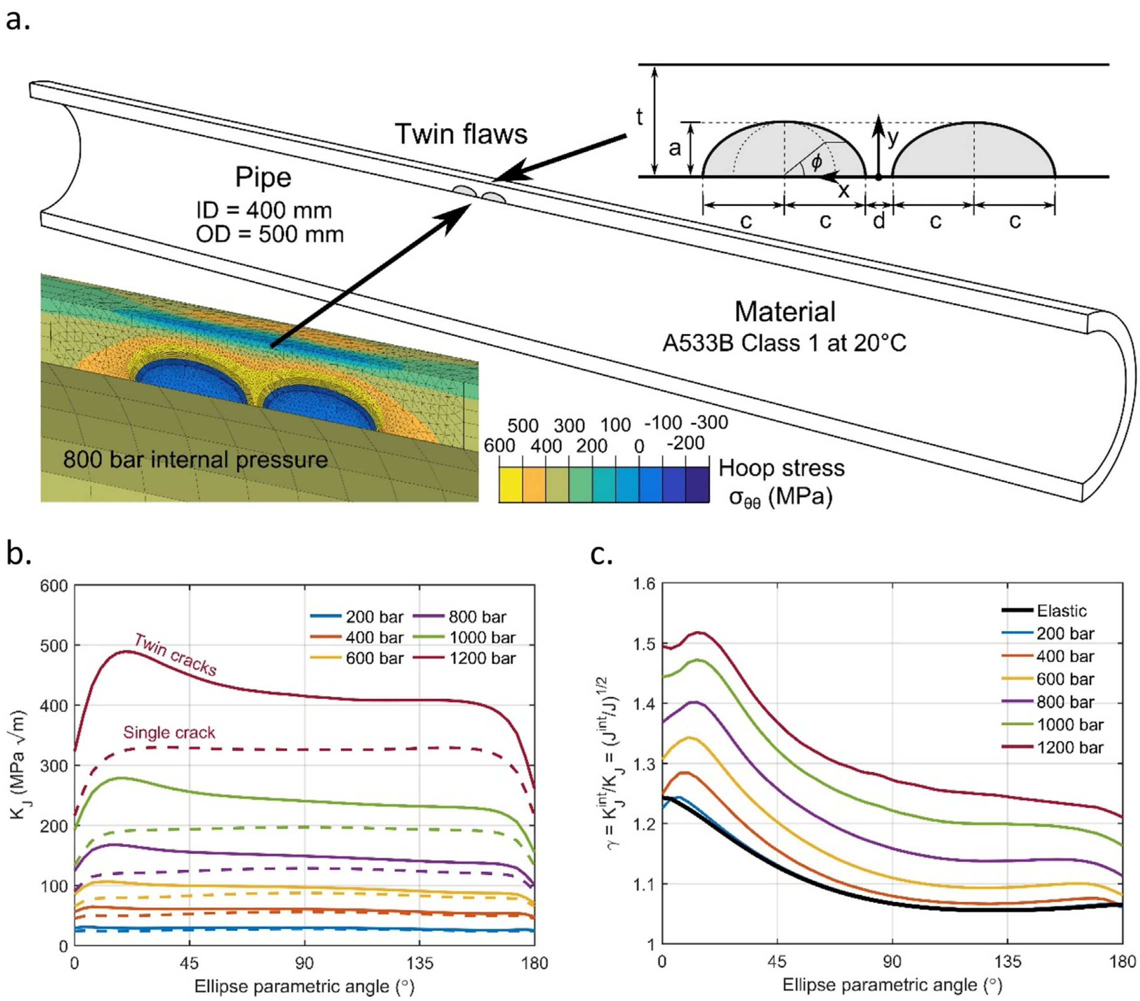

Fig. 1. a.) Analysis of a pressurised pipe containing twin internal surface cracks. b.) Elastic-plastic equivalent stress intensity factor $K_J = \sqrt{\frac{JE}{1-\nu^2}}$ for a single crack and for twin cracks separated by d = 0.25c (i.e. 12.5 mm). c.) Interaction factor.

finite element analysis was used to determine the deformation of pressurised pipes containing single cracks and twin cracks and hence to calculate the J-integrals for each case. Limit load analysis was also performed using a rigid-plastic material, also with $\sigma_0 = 450$ MPa and a von Mises yield locus.

Fig. 1b & c illustrate that two closely-spaced cracks in the pipe wall produce more severe crack tip loading than a single crack. Furthermore, the cracks interact more strongly under increasing levels of applied pressure as the material between them experiences increasing plasticity. This conflicts with earlier suggestions that the interaction effect is either unaffected or weakened by the onset of plasticity [12–14], but agrees with the prediction by Xuan et al. of enhanced interaction under creep conditions [15]. A 'global' interaction factor, i.e. the increase in the maximum crack driving force anywhere on the crack tip line, can be defined as [9]:

$$\gamma^G = \frac{\max_{\phi} K_J^{int}(\phi)}{\max_{\phi} K_J(\phi)} = \sqrt{\frac{\max_{\phi} J^{int}(\phi)}{\max_{\phi} J(\phi)}} \tag{3}$$

where ϕ denotes the position on the crack tip line (see Fig. 1a). For the twin-flawed pipe under internal pressure in Fig. 1, the global interaction factor is 1.107 at 200 bar of internal pressure, but increases to 1.484 at 1200 bar. The maximum SERR occurs along the region of the crack tip line closest to the other crack (eg. at $\varphi = 19.7^\circ$ for 1200 bar) indicating that in a ductile material, tearing would initiate close to the internal surface and cause the cracks to coalesce as the internal pressure is increased. This is consistent with the experimental results of Bezensek and Hancock [16] which showed that in twin co-planar surface cracks under three-point bending, ductile tearing consistently initiated in the 're-entrant' region between them. Closer proximity of the cracks to one another and increasing material hardening modulus increase the interaction under inelastic conditions as shown in Fig. 2.

The observation that stronger crack interaction occurs under elastic-plastic conditions than under linear elasticity is significant for the formulation of interaction criteria. For example, the criterion used to judge significant interaction for this crack geometry in BS7910 and R6 is:

$$\begin{aligned} &d \le \min(2c_1, 2c_2) \quad for \quad \tfrac{a_1}{c_1} > 1 \;\; and \;\; \tfrac{a_2}{c_2} > 1 \\ &d \le \max\left(\tfrac{a_1}{2}, \tfrac{a_2}{2}\right) \quad for \quad \tfrac{a_1}{c_1} \le 1 \;\; and \;\; \tfrac{a_2}{c_2} \le 1 \end{aligned} \tag{4}$$

where a_1, c_1 and a_2, c_2 are the depth and half-width of the first and second cracks respectively, and d is the inter-crack spacing. The example shown in Fig. 1 lies at the limit of this criterion. For a wider crack spacing d, the cracks would not be re-characterised as a single large crack or be subjected to detailed analysis. Subsequent steps in the integrity assessment could be carried out considering the two defects individually. In this situation, unintentional non-conservatism could arise: firstly because the defects' elastic-plastic interaction generally