With regard to acceptable flaw size limits, the specific allowable flaw size depends upon flaw shape. Therefore, the nondestructive inspection procedure must be capable of detecting both flaw size and shape. Data such as that shown in Fig. 9 can be used to develop an acceptable flaw size and shape curve for the specific component and loading conditions of interest. Fig. 10 presents the acceptable flaw size and shape curve for the pressure vessel being considered in this example. Initial defects with dimensions which fall below the maximum acceptable defect size curve (cross-hatched area) will not grow to failure in 2000 cycles of loading (safety factor of two on life). The defect size and shape curves for failure and 1000 cycles of life are also included in Fig. 10. Data such as that shown in Fig. 10 combined with adequate nondestructive inspection techniques provides the optimum interaction of fracture mechanics and nondestructive inspection technologies.

The example problem presented here does not illustrate all of the considerations that can be and are employed in the fracture mechanics approach to the development of realistic nondestructive inspection procedures. Specifically, no attempt was made to evaluate the influence of multiple defects or defects of different types, no consideration of crack growth in a hostile environment was included, and only one loading condition was considered. However, the basic aspects of evaluating the influence of flaw size and shape on fracture behavior have been demonstrated and these techniques need only be modified slightly to incorporate other variables into the consideration.

Summary

It has been shown that existing linear elastic fracture mechanics technology is directly applicable to the development of realistic nondestructive inspection requirements. The technology provides a quantitative approach to the evaluation of the interaction between material properties, stress conditions, and defects and their combined effect upon the integrity and performance of the structure. Proper consideration of these factors can be used to develop an overall fracture control plan which will ensure the desired level of integrity for the required lifetime of the structure.

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DISCUSSION[4]

P. L. Pfennigwerth[5]

The author is to be congratulated upon presenting in one paper a comprehensive treatment of the major facets of applied fracture mechanics. Fracture mechanics technology has been concisely summarized, including fundamental concepts of stress intensity factor and fracture toughness, fracture toughness testing, cyclic crack growth, defect characterization, and failure criteria. It is inevitable that a paper of such broad scope should emphasize the overall problem and not give detailed treatment to each subdivision of the technology.

Fracture mechanics is indeed a powerful analytical method. It enables the engineer to give a quantitative scientific basis to the evaluation of defected structures, replacing to a great extent use of "best engineering judgement." However, it is important that certain reservations and limitations regarding the fracture mechanics method always be closely associated with prescriptions for its use. Unless these reservations and limitations are clearly kept in mind, there is danger that uninitiated and/or overly exuberant practitioners will apply the method to situations for which it is not valid.

To guard against this unfortunate occurrence it is important that papers such as the author's clearly state limitations as well as strengths of the method. For example, nowhere in the paper is it directly stated that fracture mechanics is based upon linear elastic analysis. Only in the region of the crack tip is deviation from this ideal model acknowledged, and this is via the plastic zone correction for local plastic flow. Otherwise, a completely linear stress analysis is required. This requirement is not revealed in the sample problem because the popular pressurized cylinder sustains the same "nominal" hoop stress whether elastic or plastic. A thicker walled cylinder (say with diameter to wall thickness ratio of 5) will have a significantly higher hoop stress at the inner wall than at the outer wall, and the classical Lamé solution should be used. Similarly, when the pressure vessel experiences thermal transients, there will be additional nonuniform thermal stresses produced. General practice is to introduce these into the analysis on an elastic basis even though such peak thermal stresses may indeed be fictional as a result of plastic material behavior.

The author's Figs. 4–6 and the associated discussion should prove useful to many readers. They provide a simple means for assessing the approximate equivalence of various flaw geometries. Here again, fracture mechanics provides a rational basis for making evaluations which were hitherto based almost solely upon judgement. However, by attempting such broad coverage, the author has bypassed situations in which the fracture mechanics analysis is incomplete or ambiguous.

For example, the stress intensity factor formulations presented are all based upon an assumption that the flaw is small compared with the section thickness. It is well-known that for flaw depths of over half the section thickness there is a significant "back face magnification" effect which makes the cited equations unconservative. The author's example problem avoids this issue be-

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cause the problem parameters have been selected to give critical flaw sizes less than 46 percent of the vessel wall thickness. For higher toughness (and lower strength) materials calculated critical flaw sizes will be a much larger fraction of wall thickness. The basic principles remain the same, but the specific analysis becomes more complicated and the results are more ambiguous. Similarly, if an internal flaw lies near a surface, there will be an interaction tending to produce break-through of the flaw at a stress level lower than that predicted by the cited relationships.

Similarly, there should be some limitations placed upon use of fracture mechanics when the structure does not behave as a linear elastic body. There currently are no clear-cut answers to these "sticky" questions, and additional work, both experimental and theoretical, is required to resolve them. The best that can be done is to honestly present these limitations so that users are clearly aware of areas in which fracture mechanics evaluations should be viewed as tentative.

The author's example problem illustrates the overall method for a specific, simplified application. Fig. 10 illustrates the interrelationship between flaw length and flaw depth. A curve giving acceptable defect sizes has been shown to follow logically from the criterion that there be a calculated margin of 2 on cycles to failure. Several assumptions inherent in this procedure should be emphasized, however. Equation (3), used to calculate the number of cycles to grow a flaw from an initial depth, a_i, to a critical depth, a_{cr}, incorporates the assumption that flaw shape does not change during growth and that depth does not increase to a value which requires back face magnification correction. These generally justifiable assumptions should be clearly stated to avoid misuse of the results. (Also, the use of LN to denote $\log_e$ in the second form of Equation (3) is unfortunate in view of the defined symbol N for cycles.)

The philosophy of failure evaluation plays a strong role in any fracture mechanics evaluation. The author's paper presents what appears to be a "best estimate" analysis. The crack growth rate curve given in Fig. 2 appears to be a best fit to the test data. In design applications it would be desirable to incorporate some margin to account for data scatter, possible differences between test material and component material, etc. Similarly, it is implied that the fracture toughness used to evaluate critical flaw size in the example problem is an average value, not a minimum specified value or a measured value. This aspect is particularly important for ferritic materials which undergo a brittle-ductile transition with temperature. If the assessment of critical flaw size is to be made at a temperature corresponding to the region of rapid increase in fracture toughness, additional precautions must be taken to ensure that fracture toughness is conservatively selected. Lastly, the "acceptable defect size" curve of Fig. 10 has not been related to maximum acceptable defect *indications* resulting from a nondestructive inspection. Some margin is required to account for the ambiguity between flaw indication and actual flaw size, a parameter seldom known exactly in applications to equipment components.

In view of these uncertainties, it would be dangerous to assume that the author's illustrative safety factor of two on cyclic life will generally be adequate. (For example, the standard ASME B&PV Code, Section III fatigue curves are constructed with minimum margins of 2 and 20 on stress and on cycles, respectively.)

In another paper [13] the author has presented a similar analysis of an A533-B steel pressure vessel in which a margin of 1.5 on stress is shown to lead to a margin of 6.0 on cycles to failure. If the stress-lifetime trade off is assumed to be an exponential relationship (as is frequently found to be true of fatigue behavior), an equivalence for various margins can be found from

$$(\text{stress margin})^n = (\text{life margin}).$$

The exponent for the above example is found to be $n = (\log 6)/(\log 1.5) = 4.42$. Thus, a margin on stress of 2.0 is approximately equivalent to a margin on life of 20. If this relationship holds for the example of the present paper, also, the margin of 2.0 on cycles would be equivalent to a margin of only 1.17 on stress.

Additional Reference

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Author's Closure

The author would like to thank Mr. Pfennigwerth for his valuable comments and appreciates his concern regarding the current limitations of existing fracture mechanics technology. However, this paper was prepared specifically to serve as a basic introduction to the subject and also to illustrate the potential of this technology in the area of nondestructive testing. Obviously, it was impossible to include a detailed discussion of each aspect of the technology. For further discussion concerning the limitations as well as the advantages of this design concept, the author refers the reader to the excellent references appended to the paper.