

THE DYNAMIC RESPONSE OF CRACKED HEXAGONAL SUBASSEMBLY DUCTS

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The hexagonal subassembly ducts (hexcans) of current Liquid Metal Fast Breeder Reactor (LMFBR) designs are typically made of 20% coldworked Type 316 stainless steel. Prolonged exposure of this initially tough and ductile material to a fast neutron flux at high temperatures can result in severe embrittlement. Under these conditions, the unstable crack propagation of flaws, which may have been introduced during fabrication or transportation of the hexcans, is a problem of interest in LMFBR safety analysis. The abnormal overpressurization resulting from certain interactions within a subassembly, or the rupture of one or more fuel pins, may be sufficient to overload an otherwise subcritical crack in an embrittled hexcan.

Studies of cracked hexcans under static loading conditions have been performed previously by means of simple models, a weight function technique and a finite element analysis. In the event of an abnormal situation occurring in a subassembly, however, the applied loads on the hexcan walls will be time-dependent. Due to vibrational effects, the resulting stress field in the hexcan wall may or may not be more severe than the statically loaded case.

This paper examines the dynamic elastic response of flawed and unflawed fast reactor subassembly ducts. A plane-strain finite element analysis was performed for ducts containing internal corner cracks, as well as external midflat cracks. Two worst case loading situations were considered: rapid uniform internal pressurization and suddenly applied point loads at opposite midflats. The finite-element code CHILES, which can accommodate the stress singularities that occur at crack tips, was given dynamic capabilities through the inclusion of a consistent mass matrix and step-by-step time integration scheme. The SAP IV code was also employed for eigenvalue analysis and modal response. Although this code does not contain singular elements in its element library, dynamic stress intensity factors were calculated by a technique requiring only ordinary isoparametric quadrilaterals.

The dynamic response of the hexcan is changed due to the presence of cracks. The twelve-fold symmetry of the problem is destroyed and lower-frequency flexural modes are introduced. The contributions of these lower modes to the response increases with increasing crack depth. The number and nature of these modes depends on the number and positioning of cracks in the hexcan wall. It appears from the situations considered that a wide range of results can be obtained depending on the cracked geometry and loading considered. In no case, however, has a value of the dynamic stress intensity factor been greater than three times the stress intensity factor for the corresponding static problem. This ratio of three could be employed as a conservative dynamic amplification factor for the hexcan geometry considered, but since a limited parametric study has been performed, the application of the factor should be judicious.

1. Introduction

At the goal fast neutron fluences which LMFBR hexcans must sustain ($\sim 10^{27}$ n/m²), it is expected that linear elastic fracture mechanics (LEFM) will be applicable to any cracks which may be present in the duct walls. In order to predict whether or not unstable crack propagation and, therefore, hexcan failure, will occur, it is necessary to characterize the stress field surrounding the tip of a crack. Within LEFM, this amounts to the determination of the stress intensity factor, a measure of the strength of the crack-tip stress singularity. When this factor reaches a critical value, which is a material property known as the fracture toughness, a crack can become unstable and propagate in a brittle manner.

Stress intensity factors for a large number of problems have been computed in recent years using a wide variety of analytical and numerical techniques. One of the most versatile of these for problems with complicated geometries is the finite element method. The hexcan geometry studied in this paper is quite complex as is evident from Fig. 1. Stress intensity factors for this hexcan having internal corner cracks have been computed previously using the finite element code CHILES [1]. This analysis was performed for two different static loading conditions, viz., uniform internal pressure and concentrated loads at opposite midflats, perpendicular to the plane of the corner crack. Reliable estimates of the stress intensity factor for cracked subassembly ducts under various static loads and with different crack geometries can be easily determined. This information, along with knowledge of the critical stress intensity factor for the hexcan material, enables one to predict whether a given cracked hexcan will fail by brittle fracture under a given static load.

If an abnormal dynamic event such as rapid hexcan overpressurization or fuel pin failure should occur, however, inertia effects must be taken into consideration. The crack-tip stress intensity factor could conceivably be much higher than that obtained for the corresponding static analysis. Knowledge of the vibrational response of cracked hexcans is important in determining whether contact with surrounding hexcans will occur, a situation which could lead to possible core damage. The finite element method appears to be the logical choice for dealing with the complex hexcan geometry and dynamic loading conditions. In this paper, we present the results of a finite element analysis of the dynamically loaded cracked hexcan problem for several cracked hexcan configurations and loading situations.

2. Finite Element Analysis

In order to describe the high stress gradient surrounding a crack tip, special "singular" finite elements have been developed which incorporate the characteristic inverse square root singularity. The aforementioned computer code CHILES, which employs the singular element formulation of Benzley [2], appeared to be a natural point of departure for the dynamic study. After providing CHILES with a consistent mass matrix and an implicit step-by-step time integration scheme to accommodate the hexcan dynamics, however, several difficulties became apparent.

An important consideration in the analysis is the extent to which higher-frequency vibrational modes are filtered out due to the selection of the time step. A well-known rule of thumb states that one would like to choose a time step to be at most 1/10th of the period of the highest frequency of interest. In a problem such as that of the hexcan, however, it is not clear how this should be done. The natural frequencies of the structure are not known a priori. Even if they were, the number of modes which must be taken into account is unknown. For thin walled structures like the hexcan, the contributions of the modes does not necessarily decrease monotonically with increasing frequency. Clearly, a bad choice of time step will

alter one or more frequency components of possibly substantial amplitude. When the various frequency responses are combined, reinforcement and cancellation of real and filtered frequencies might result in a total response which is quite different from reality. Choosing an arbitrarily small time step is cost prohibitive.

One solution to the dilemma is a modal superposition analysis of the problem. This procedure requires, first, the determination of the eigenvalues and eigenvectors of the problem, then the solution of the decoupled equilibrium equations for each mode and, finally, the superposition of the responses of the eigenvectors. The SAP-IV structural analysis program [3] was acquired for this purpose. Although no crack-tip singular elements are available in the SAP code, results for cracked bodies can be determined using ordinary elements.

The technique employed depends on one knowing a priori the corresponding static stress intensity factors for the dynamic situations considered. As mentioned earlier, this is the case for the problems at hand. Then, the quantity of importance is the dynamic stress intensity amplification factor, L_I , which is defined as the ratio of the dynamic stress intensity factor to its static value. It has been shown that L_I can be determined by dividing the dynamic crack opening displacement of the node closest to the crack tip on the crack surface by its static value using ordinary elements [4]. This method yields extremely good results for L_I , especially for thin walled structures like the hexcan. Since most of the cost in the procedure is the one time determination of the eigenvalues and eigenvectors, very small time steps can be used economically and more modes can be conveniently added to assure the inclusion of all significant responses.

Figure 2 illustrates a typical finite element mesh used for our analysis; this particular one is for the case of two diametrically opposite corner cracks. Symmetry considerations require the use of only one-quarter of the hexcan. Although this grid is cruder than the one used previously for static analysis, it does provide stress intensity factors within 2-3% of those reported in [1] when used with CHILES.

3. Results of Analysis

Figure 3 illustrates the first six vibrational modes of an uncracked hexcan using the SAP-IV code. Mode 3 is typically called the "breathing" mode and is the only one excited by a step uniform internal pressure. The introduction of cracks in the duct walls, however, destroys this twelvefold symmetry. Consider the aforementioned case of a hexcan containing two diametrically opposite corner cracks of half the wall thickness deep. The lower frequency mode shapes for this geometry differ only slightly from those of the uncracked hexcan, but larger differences appear with increasing frequency. The first three, however, have been found to be the only ones which contribute significantly to the response for this case. Figure 4 shows the participation of each mode in the outward radial displacement of the cracked corner and the midflat parallel to the plane of the cracks. Clearly, the first mode is as important as the third, with the second making a smaller contribution. This participation has, as expected, been found to be a function of crack depth and spatial loading. For example, consider the same cracked hexcan but now subjected to step concentrated loads applied at opposite midflats perpendicular to the plane of the cracks. Figure 4 also shows the participation of each mode for this loading situation. Again, only the first three modes are significantly excited but for this case mode 1 is very dominant with modes 2 and 3 making only minor contributions to the overall response. This is due to the fact that the cracked geometry and loading both favor mode 1 in this case, whereas with uniform internal pressurization, the geometry

favors mode 1 while the loading favors mode 3. Clearly, a wide variety of responses can result, depending on the number and locations of cracks and the type of loading postulated.

With respect to the applicability of LEFM to the cracked hexcan problem, the determination of L_I is of prime importance. Figures 5 and 6 illustrate the time dependence of this factor for the step uniform internal pressure case and the step concentrated midflat load case, respectively. The participation of mode 3 in L_I is much larger than would be expected from an examination of the radial displacement response curve. Figure 6 shows values of L_I below zero and subsequently much higher than two. Negative values of L_I indicate crack closure, which has not been accounted for in the model; therefore, results after L_I becomes negative should be considered less than reliable.

The effects of changing the time dependence of the loading conditions from step functions to pulses were also studied for this hexcan geometry. The time dependence employed was a triangular pulse of 1 ms. rise time and 5 ms. decay. Figure 7 illustrates the variation of L_I with time for the pulsed uniform internal pressure loading. The response appears to follow the loading exactly. Figure 8 shows L_I for the case of pulsed midflat concentrated loads. Obviously, dynamic effects are of much greater consequence for this spatial loading.

4. Conclusions

The above finite element analysis has been performed for a particular hexcan geometry having one or two internal corner or external midflat cracks subjected to the loadings mentioned. Substantial variations occur in mode shape, number and degree of modes participating, and displacement and L_I response. A value of L_I of greater than three has not been encountered, however, and it appears this may be used as a conservative value in describing the dynamic effects as far as the stress intensity factor is concerned for the hexcan geometry studied.

5. Acknowledgments

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- Fig. 1. Cross-section of an LMFBR hexcan, showing dimensions used in computations.
- Fig. 2. Finite element mesh employed to model one-quarter of a hexcan.
- Fig. 3. First six natural modes of vibration of an uncracked hexcan.
- Fig. 4. Modal participation of a hexcan having two diametrically opposite corner cracks of depth half the wall thickness. Subfigure (a) illustrates outward radial displacement of cracked hexcan corner (solid) and midflat (dash) subjected to step uniform internal pressure considering only the first mode. (b) first two modes considered. (c) first three modes considered. (d)(e)(f) same as (a)(b)(c) except for the case of step concentrated loads applied at midflats.
- Fig. 5. Time history of L_T for step uniform internal pressure case.
- Fig. 6. Time history of L_T for step concentrated midflat load case.
- Fig. 7. Time history of L_T for pulsed uniform internal pressure case.
- Fig. 8. Time history of L_T for pulsed concentrated midflat load case.

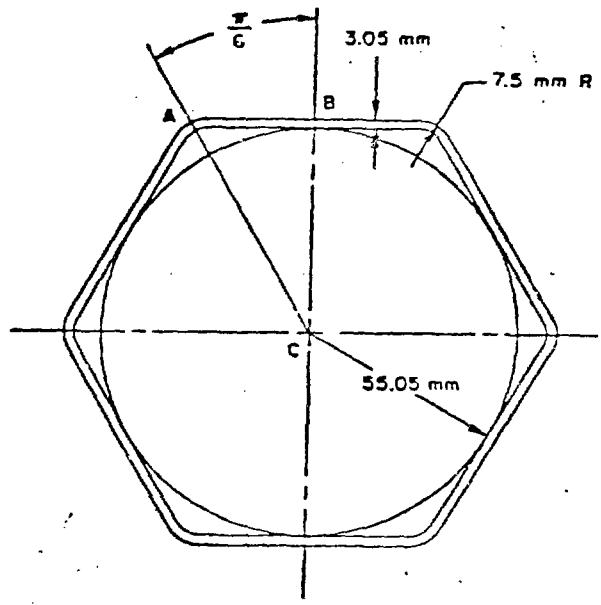


FIG 1.

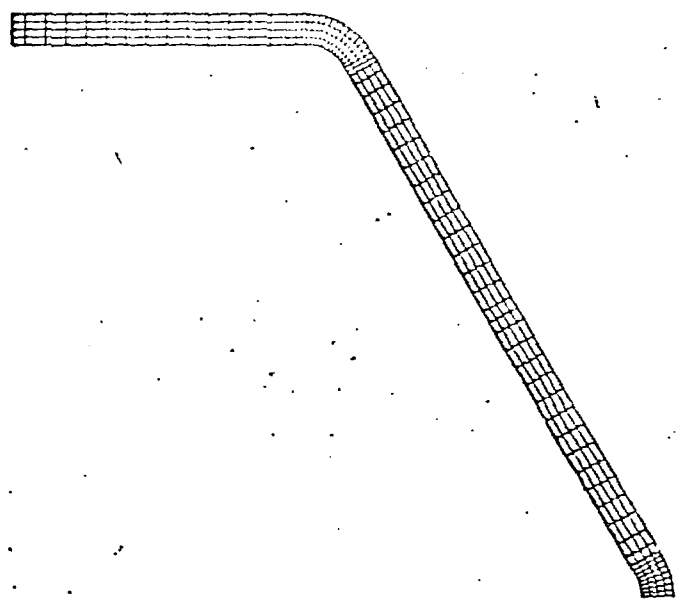


FIG 2.

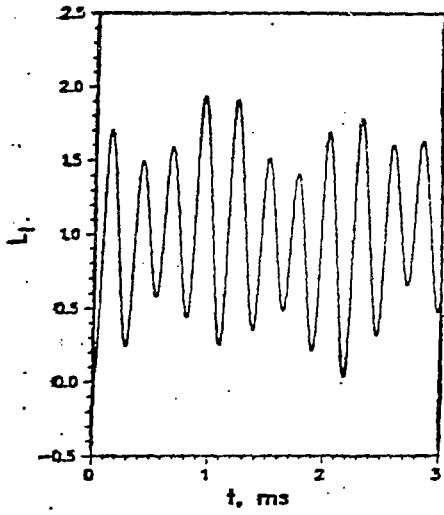


FIG 5

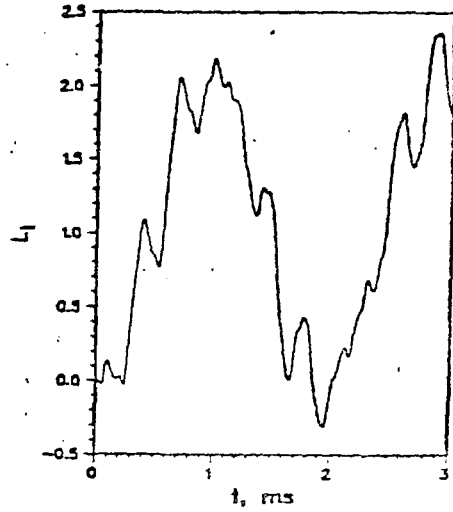


FIG 6

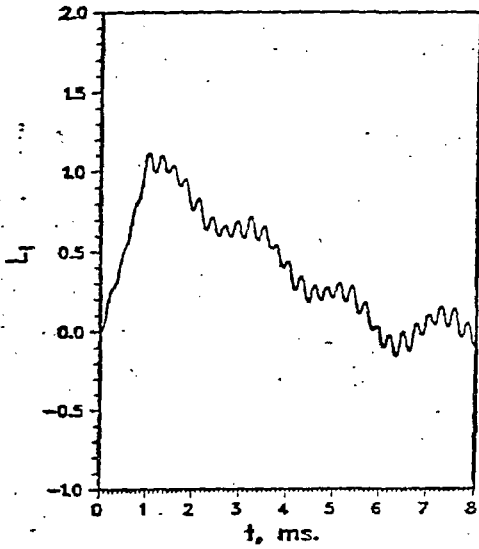


FIG 7

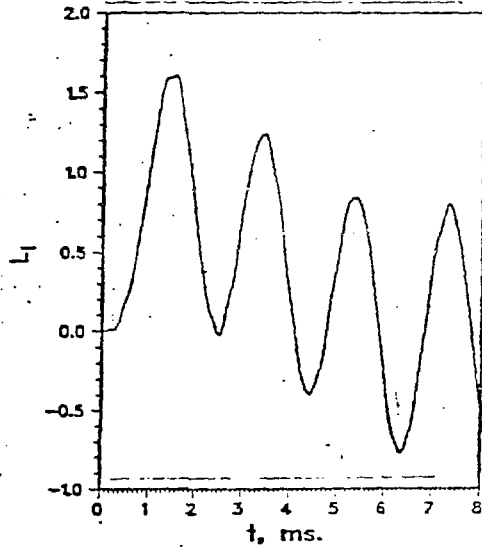


FIG 8

