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CRACK PROPAGATION IN A FUEL CLADDING WITH A LOCAL BULGING CAUSED BY INTERNAL PRESSURE

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SUMMARY

A fracture analysis has been made of a fuel cladding which has a local bulging due to internal pressure. An axial through-crack is presumed to exist at the apex of the bulge and is permitted to extend according to a linear fracture criterion based upon the value of K_{IC}. As the crack extends, the state of stress in the cladding is computed by a finite element code and the length and opening shape of the crack are continuously monitored.

Because of the bulge, the hoop stress distribution in an uncracked, but bulged cladding tube, displays a local maximum near the junction of the bulge and the cladding and a local minimum at an intermediate position on the bulge. For very long bulges the minimum occurs near the inflection point. The initial through-crack may thus have its tip located near the maximum or near the minimum circumferential stress values and consequently the initiation and subsequent motion of the crack are stongly affected by the size of the bulge and the ratio of the crack length to the bulge length.

This initial state of stress is altered by the thinning of the cladding which is associated with the increased cladding area caused by the bulge. Depending upon the size of the bulge and its shape, this thinning may accentuate the minimum and maximum stress values and thus affect the dynamic history of the crack.

This paper reports the results of a numerical study of the dynamic crack motion for a parabolically shaped bulge with varying thickness. Crack opening shapes and stress intensity factors are given as functions of crack length and time. The results are compared to those for a through crack propagating axially in a pressurized pipe of constant thickness without a bulge.

1. Introduction

The application of fracture mechanics to ensure the safe and reliable operation of reactor structural components has been spurred by the successful use of fracture mechanic principles in predicting the safe-fail and fail-safe lives of aerospace structures containing surface flaws or through the thickness cracks. Over the past several years the authors have been applying these principles to various structures to study the nature of crack growth and to determine the conditions under which small flaws will not propagate. In this paper, we discuss the results of one study into the fracture behavior of fuel elements.

The major components of the fuel element are the cladding tube and the fuel pellets contained within it. The structural behavior of the element may be complicated by swelling, irradiation growth and cracks in the pellets which distort the cladding tube and in the presence of plastic instabilities may cause a local bulging, termed ballooning. This distortion may be accompanied by the formation of a through axial crack, and it is of interest to determine the conditions under which this crack is of stable size.

In this work, the bulging problem in a thin walled cladding tube of Zircalloy II (12.3 mm O.D, 0.75 mm thickness) is analyzed and its fracture behavior in terms of crack initiation, propagation and arrest are described. The axial through crack, located at the apex of a bulge, was driven by a constant pressure applied to the inner surface of the cladding tube. Although under actual conditions, the pressure will diminish due to leakage through the crack, the assumption of a constant pressure simplifies the analysis and the interpretation and gives an upper bound to the problem.

The paper is divided into two parts: 1) the static analyses of an axisymmetric and a non-axisymmetric bulge for better understanding of the state of stress which could cause rapid crack propagation, and; 2) the study of the dynamic crack propagation of an axial through crack.

2. Modeling of the Structure

The bulge was located as shown in figure 1 and was either a spherical cap or a portion of the paraboloid

$$r_b{}^2 = r_b{}^2(0)\ [1 - \frac{y}{L}] \qquad (1)$$

where $r_b(0)$ is the bulge radius at the plane of axial symmetry of the bulge (y = 0). Based upon the data of reference [1], an initial bulge radius, r_b, equal to one-half the cladding tube radius, r_c, centered at $\Delta = r_c/2$ and a bulge length, L, of one-half the diameter were chosen. The bulge was faired into the cylindrical section of the cladding tube at the intersection of the surfaces. The structure was then divided into a set of four node quadrilatural shell elements. The cladding tube was taken to be 4 diameters long with only the right hand side analyzed because of symmetry. An outgoing wave condition was imposed at the right end of the mesh to model the infinitely long tube in the manner used in reference [2]. A constant pressure was applied to the inner and outer surfaces of the pipe and the dynamic motion of the tube was calculated upon a sudden removal of the outer surface pressure. Both static and dynamic analyses were done with the SAP IV finite element program [3], and some additional verifying dynamic calculations were done with SLADE-D [4].

3. Static Analysis

As a preliminary to the dynamic computations, a series of static calculations were made to establish a satisfactory finite element mesh and to investigate the character of the stress fields in this odd shaped tube. The stress intensity factor for an axial through crack, of length equal to the bulge length, was calculated for different element sizes until the value was within 10% of the reported value [5]. This mesh, which modeled the length of the bulge by 10 elements, was used in all subsequent calculations.

3.1 Axisymmetric Bulge

The initial calculations for a spherically shaped bulge showed the normal circumferential stress, $\sigma_{\theta\theta}$, away from the bulge and the expected stress for a sphere at the apex of the bulge. The circumferential stress did show an unusual axial distribution so a series of computations were made for an axisymmetric bulge (i.e. a bell shaped distortion) of the shapes shown in figure 2 with radii of R_B and R_c. The circumferential stress profile is illustrated on figure 3. When the central portion of the bulge was part of the curved surface, the circumferential stress at the apex was very low. As a constant radius straight central section was added, the circumferential stress in this central section began to rise until it reached the value appropriate to a tube of radius R_B. The circumferential stress distribution shown on figure 3 for the different shapes implies that the propagation of an axial crack is subject to a strong variation of driving forces. Cracks which originate in the center of a long bulge will arrest because of the decaying stress field unless they have developed sufficient kinetic energy to run through the minimum stress. Slowly extending cracks will automatically arrest. Cracks in short bulges with no constant radius section or cracks whose tips are to the right of the minimum stress will experience an increasing stress field and will accelerate but will arrest shortly after reaching the original cylindrical portion of the cladding because of the low stresses. Computations were also performed for a tube with restrained ends to evaluate the effects of the axial tension generated by the pressure. No significant effects were noted.

3.1 Non-Axisymmetric Bulge-Static Case

For the localized bulge calculations, the bulge material was assumed to be thin since the original bulge is generally created by constant volume plastic deformation. The thickness reduction was assumed to be a maximum at the apex of the bulge and was varied linearly in the axial and circumferential directions to give a zero reduction at the junction of the bulge with the original cladding. Figure 4 illustrates the circumferential stresses along the midline of the spherical and parabolic bulges for thickness reductions of 25% and 10% respectively. Although the apex values are increased because of thinning, the basic pattern is the same, showing a rapid reduction in stress ahead of the bulge and indicating that the axial cracks will arrest shortly after penetrating into the original cladding. The combination of the thinning and the relatively straight central portion of the parabolic shaped bulge (in comparison to the strong curvature of the spherical bulge) produced an almost constant circumferential stress field.

4. Dynamic Analysis

The dynamic motion of the crack for the 10% thinned parabolic bulge was calculated by monitoring the crack opening δ and permitting the crack to extend one element-width whenever the value of K_I as calculated by the elastic relationship

$$K_I = \frac{\delta G}{4(1-\nu)} \sqrt{\frac{2\pi}{\Delta}} \qquad (2)$$

(where Δ is the distance from the crack tip to the point at which δ is measured) exceeded the critical value K_{IC}. This method has been successfully used [2,6,7] to model both elastic and ductile axial and circumferential cracks.

Figure 5 illustrates the variation of K_I versus time for a crack of fixed length when the outer surface pressure is suddenly released and the crack is allowed to open. The values of K_I as calculated by the COD method and by the stresses measured ahead of the crack are seen to be in good agreement, for most of the first cycle of the displacement of the tube. Both have a period longer than the original cladding tube because of the increased bulge radius and the reduced stresses. As indicated by the graph, the crack has only a short time to begin to move because of the basic vibrational mode of the cladding tube and it may not attain sufficient kinetic energy to propagate past the bulge.

The propagation was modeled by permitting the crack to move whenever K_I equaled K_{IC}. Since a small crack located in a reasonably sized bulge has a lower stress intensity factor than an equal crack located in the cladding, it is obvious that unless there is an unusually high degree of thinning or severe embrittlement the crack will not grow. To permit growth and to observe the history of small cracks, a hypothetical critical stress intensity factor equal to the static value the crack would experience in the undeformed cladding was chosen. This low value would permit us to see if the crack would continue to propagate after reaching the original cladding section. The low crack velocity associated with this hypothetical value of K_{IC} of approximately $0.1\,c_2$ would give a good indication of how slow crack growth would take place. Once the crack had begun to move, its velocity was set at its initial value and the computations continued until the crack passed the bulge. Figure 6 illustrates the stress intensity associated with the moving crack and it is seen to be decreasing very rapidly. This reduction is primarily due to the zone of decreasing stress into which the crack is propagating and to reflections of the expansion wave which are impinging upon the tip. The crack opening shapes were similar to those reported for fast axial and circumferential cracks velocity $\sim .8\,c_2$ [6,7] and the radial displacement ahead of the crack had the characteristic minimum reported in [2,6,7] and experimentally observed by Shoemaker [8]. The essential difference between this and the other cases is the decreasing value of K_I in the case of the bulge which will lead to arrest and the constant K_I and no arresting for the straight pipe.

5. Conclusions

The rapid spatial fluctuation of the circumferential stresses and the continuous decay of the stress intensity factor for the constant velocity crack indicate that when the stress state is such that the cracks cannot propagate in the undeformed cladding, cracks in the bulge may grow, but are most likely to arrest when they reach the limits of the bulge even when the internal pressure is maintained at its initial value. Gas leakage, with its attendent pressure reduction, will assist in arresting the crack. Based upon these calculations, which did not include the energy dissipation due to the plastic yielding which would occur at the elevated operating temperatures, it appears that through cracks will be subject to slow, but controlled growth and there is little likelihood of significant crack extension past the bulge.

6. Acknowledgements

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7. Nomenclature

c_2	Shear wave velocity
G	Shear modulus
K_I	Mode I stress intensity factor
L	Length of bulge section
P	Internal pressure
r_b, r_c	Radius of cladding tube, bulge
R_B, R_C	Radius of bell shaped axisymmetric bulge and the original cladding tube
t	Thickness
y	Axial coordinate
δ	Crack opening
Δ	Mesh spacing

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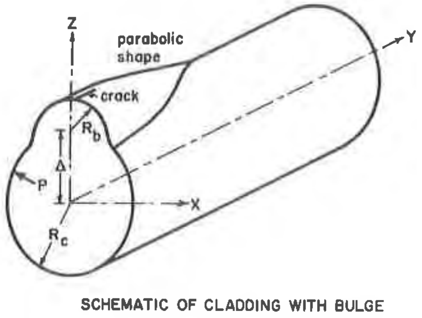

FIGURE 1
SCHEMATIC OF THE CLADDING TUBE WITH A BULGE

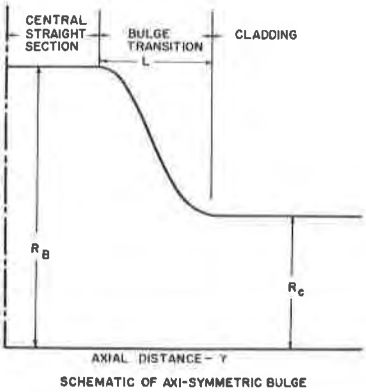

FIGURE 2 SCHEMATIC OF THE BELL SHAPED AXISYMMETRIC BULGE

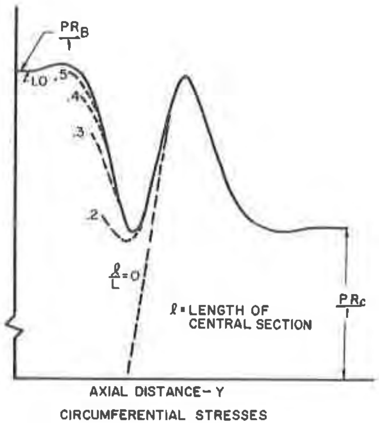

FIGURE 3

CIRCUMFERENTIAL STRESS DISTRIBUTION FOR DIFFERENT CENTRAL SECTION LENGTHS OF THE BELL SHAPED BULGE

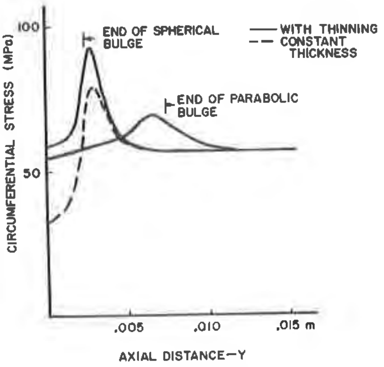

FIGURE 4

CIRCUMFERENTIAL STRESS DISTRIBUTION FOR CONSTANT AND VARYING THICKNESS BULGES

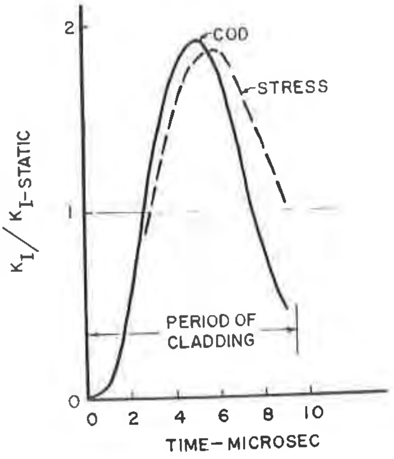

FIGURE 5

STRESS INTENSITY FACTOR FOR A SUDDENLY PRESSURIZED TUBE WITH A CONSTANT LENGTH CRACK

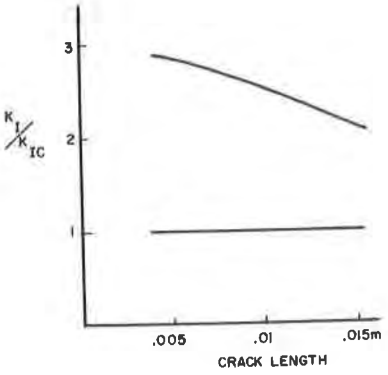

FIGURE 6

STRESS INTENSITY FACTOR AS A FUNCTION OF CRACK LENGTH FOR A CONSTANT VELOCITY CRACK