MECHANICAL DESIGN CONSIDERATIONS FOR A COLLAPSIBLE FUEL CLADDING

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SUMMARY

The design of fuel elements for the pressurised heavy water reactors being built in India is based on thin zircaloy cladding of collapsible type dictated by the use of natural uranium dioxide fuel material. A thin cladding will be deformed from the beginning of irradiation by either the external coolant pressure or by a change in pellet outer geometry. In order to establish reliable design criteria for satisfactory performance during the life time, a thorough understanding of the behaviour of such fuel elements is necessary. In this paper, the following problems related to structural stability associated with the use of thin-walled cladding are examined:

(i) *Longitudinal Ridge Formation:*

The dominant collapsed mode for the cladding tube is found to be an oval with a single lobe in the transverse section, the shape depending on the diametral clearance between the pellet and the sheath. The unsupported area of the sheath increases with increased diametral clearance. At the onset of collapse, the unsupported length is assumed to be arc of an ellipse. This arc is analysed as a curved plate with calculated initial curvature and the end conditions i.e. the tip of the oval is assumed as a hinge on rollers. Critical diametral gap and sheath material properties and thickness are related to the formation of a permanent longitudinal ridge. Experimental observations show good statistical correlation with the predictions of the analytical model.

(ii) *Circumferential Ridge Formation:*

Circumferential ridging at pellet interfaces commonly observed in irradiated fuel, have been analysed on the basis of hourglass shape by Veeder, AECL-2660 (1967). In our model, however, it is predicted that circumferential ridging could form even in the absence of a temperature gradient, as is observed during out-of-pile autoclave tests. Pellet thermal expansion together with the collapse under external pressure cause firm contact between the pellet and sheath. The frictional forces set up cause high local strains at the interface. A non-linear axisymmetric analysis by finite element technique was carried out and it was found that the resulting local strains in the unsupported region were sufficient to make the material yield and thereby cause a circumferential ridge. Ridge profiles obtained in the out-of-pile tests as well as irradiated fuel elements are compared with the model predictions.

(iii) *Collapse into Axial Gaps*

Collapse into axial gaps between adjacent pellets or between pellets and end-plugs is also analysed. Calculations by classical formulae indicate that the critical pressure is overestimated by a factor of about 2.5.

For short cylinder length, the collapse is initiated by yielding rather than elastic instability. The theory developed by Donnell, J. Appl. Mech. (Dec. 1956), based on finite deflections including geometrical imperfections was found most appropriate. Experimental results were found to be in agreement with that calculated from theory.

The mathematical models for structural stability of thin-walled cladding tubes thus formulated have been used in evolving the revised fuel cladding specifications.

1. Introduction

The design of fuel elements for the pressurised heavy water reactors, now being set up in India, is based on thin zircaloy cladding of the collapsible type. This has been necessitated because of natural uranium being the fuel material. The wall thickness to diameter ratio of the cladding has been so chosen that the sheath would collapse under the external coolant pressure. The net strain on the cladding is controlled by a combination of suitable diametral clearance and yield strength of the cladding material.

The adoption of such non-rigid cladding poses a number of problems to designers as well as during manufacturing of fuel elements, required to perform at high heat ratings of 500 W/cm and burnup exceeding 10,000 MWD/TeU. Three problem areas typically applicable to collapsible cladding design are examined in this paper. The first aspect related to longitudinal ridge formation is important in the early days of reactor operation when the maximum diametral clearance is available without cladding getting the support of internal fission gas pressure build-up or swelling of UO_2 pellets. While the limitations in reactor operation caused by longitudinal ridge have been examined [1] , the fuel design parameters which are responsible for such collapse mode are examined in this paper. The second aspect is related to circumferential ridge formation, particularly at pellet inter-faces, which are commonly observed in irradiated fuel elements. Such ridges could also be formed during autoclave cycle of fuel manufacture. The tip of the ridge could act as a site for crack initiation resulting in possible premature fuel failure. The last consideration is related to collapse into axial gaps which is caused between adjacent pellets or between pellet and the end plugs in the sealed element.

The mathematical models for the three collapse modes outlined above are evolved. A comparison is also made with out-of-pile test simulations in some of the cases.

2. Longitudinal Ridge Formation

2.1 General

An estimate of the critical pressure at which a thin tube will collapse can be obtained from the classical collapse formulae. A thin-walled tube will have t/R ratio smaller than 0.07 and one can use the formula based on elastic collapse theory as presented by Timoshenko [2] .

$$P_c = \frac{E_r}{4(1 - \nu_e^2)} \left(\frac{t}{R}\right)^3 \qquad (1)$$

This classical formula predicts the critical collapse pressure reasonably well in the temperature range 20-300°C.

As predicted by eq. (1) above, the cladding in question having t/R ratio of 0.05 will collapse on to the pellets at relatively low pressure of 28 kg/cm^2 (the reactor coolant pressure is 100 kg/cm^2). As the pressure is increased, the tube will be forced into contact with the pellets, initially at points or along lines. At higher pressure, these points or lines become arcs of contact. Finally, arcs tend to become unstable and spring out. Subsequently, yielding starts and the plastic flow manifests itself in the form of a longitudinal residual ridge on the cladding.

2.2 Method of Analysis

The problem becomes one of collapse of a thin tube having a rigid core placed inside, with known clearance in the radial direction. The primary mode of collapse (Fig.1) is found to be an oval with a single lobe in the transverse section. The shape of the oval, its radius of curvature at point A and the unsupported arc length 2 x AB at the onset of collapse are dependant on the diameter of the pellet and the initial diametral clearance between the pellet and the sheath. The arc length AB is analysed for stability under the external coolant pressure, using the following correlation [2] :

$$q_o = \gamma_4 \frac{EI}{l^3} \qquad (2)$$

where l is the span length AB and γ_4 is a function of (a/l).

From the calculations, it is seen that the arc AB is not stable for practical values of diametral clearance and coolant pressure. In the next step, therefore, the position of point B is shifted towards A and the shape of the deformed profile is recalculated and checked against stability criterion of eq. (2). This iterative procedure is continued till the stable profile shape is established. The strain at the tip point A is then calculated using the following correlation:

$$\epsilon = \frac{t}{2} \left[\frac{1}{R_2} - \frac{1}{R_1}\right] \qquad (3)$$

where R_2 = radius of curvature at point B and
R_1 = original radius of curvature of the tube.

It is seen from the calculations that for low diametral clearances ($\leqslant 0.13$ mm), as are being obtained in the production fuel, the strain along the ridge remains within the recoverable limits, while a permanent ridge is predicted for higher values of diametral clearance exceeding 0.2 mm.

3. Circumferential Ridging

3.1 General

Circumferential ridging at pellet interfaces are most commonly observed on irradiated fuel rods. Veeder [3] has analysed the thermo-elastic behaviour of the UO_2 pellets and calculated the ridge height resulting from the hourglass shape. However, hourglassing alone does not fully explain the ridge heights actually observed with both dished and non-dished pellets. It was thus realised that thermal hourglassing was not the only mechanism responsible for ridge formation.

Ridal and Bain [4] have shown by experiments that chamfering the pellets did not eliminate nor even reduce ridging. They also concluded that axial loads imposed on the end plugs by the coolant pressure does not play an important part in the formation of ridge during irradiation of UO_2 fuel elements in pressurised water. Cold-working of zircaloy-2 sheathing reduced slightly, but did not eliminate circumferential ridging.

3.2 Finite Element Formulation

An isoparametric eight-noded quadrilateral element to suit the axisymmetric conditions presented in reference [5] together with isoparametric six-noded joint element is used for the finite element method of stress analysis. Reduced (2 x 2) integration scheme is used for evaluation of element stiffness matrix. From the known temperature variation in the radial direction and pressure acting on the surface, displacement and stress values are calculated at gauss points and nodal points using quadratic shape function. The debonding between the cladding and pellet is incorporated by eliminating joint elements which go in tension state of stress. This allows the tendency to form the circumferential ridge.

The material nonlinear analysis follows standard steps given in reference [5] . Using step by step process of iteration, the final displacements and stresses are calculated at gauss points as well as at nodal points.

For the joint element the relative nodal displacement Δu and Δv as given in eq. (4) are used. Using the shape functions in eq. (5) usual stiffness matrix is computed.

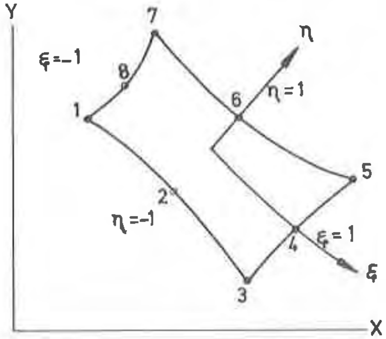

Fig.2: Isoparametric eight-noded element for UO_2 and sheath.

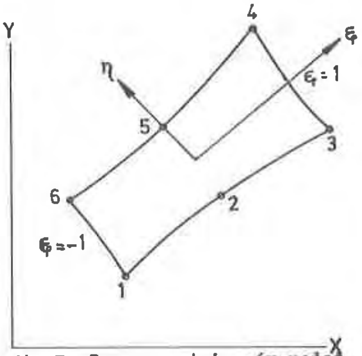

Fig.3: Isoparametric six-noded joint element.

$$\begin{aligned} \Delta u_1 &= u_6 - u_1 \\ \Delta v_1 &= v_6 - v_1 \\ \Delta u_2 &= u_5 - u_2 \\ \Delta v_2 &= v_5 - v_2 \\ \Delta u_3 &= u_4 - u_3 \\ \Delta v_3 &= v_4 - v_3 \end{aligned} \qquad (4)$$

$$\begin{aligned} N_1 &= -\frac{\xi}{2}(1-\xi) \\ N_2 &= (1-\xi^2) \\ N_3 &= \frac{\xi}{2}(1+\xi) \end{aligned} \qquad (5)$$

$$\begin{aligned} \Delta u &= \sum_{i=1}^{3} N_i \Delta u_i \\ \Delta v &= \sum_{i=1}^{3} N_i \Delta v_i \end{aligned} \qquad (6)$$

The mesh, boundary conditions and the node numbers are shown in Fig.4 for cylindrical fuel pellet inside cylindrical cladding.

4. Collapse Into Axial Gaps

The problem is same as study of collapse under uniform external pressure of a thin cylindrical shell having closely spaced internal stiffners. The effective dimensions of the cylinder are determined by the gap between the pellets in the axial direction and t/R ratio of the sheath. It is observed that the classical collapse formulae overestimate the critical pressure by a factor of about 2.5 and the discrepancy increases with diminishing cylinder lengths. The discrepancy could be attributed to geometrical and material imperfections, use of small defection theory and consideration of only elastic instability.

The theory developed by L.H. Donnell [6] makes allowance for these inadequacies. He showed that the critical pressure P_c can be expressed as a dimensionless factor P, by the equation:

$$P = \frac{P_c}{E} \frac{R^{3/2} l}{t^{5/2}} \qquad (7)$$

which could be plotted against $\frac{\sigma_y}{E}\sqrt{\frac{R}{t}}$ for different values of unevenness factor.

Estimation of the critical pressure from Donnell's graphical functions yielded results close to the experimental values. It is seen that the critical pressure to cause collapse into a given gap is sensitive to t/R ratio, yield strength, and unevenness factor of the cladding. It was concluded for the current production tubes, an axial gap of upto 10 mm could be considered safe for the operating pressures.

5. Collapse Test Experiments

25 half length collapse test elements were fabricated and subjected to out of pile collapse tests at 100 kg/cm^2 pressure and 315°C temperature with 24 hours soaking time. The other half length cladding tube was utilised for evaluating tensile test properties. The range of clearance maintained was as follows:

Diametral clearance : 0.05 - 0.5 mm
Axial clearance : 0.8 - 1.4 mm

The test elements were in pickled condition, with their dimensions and manufacturing tolerances etc. fully documented. The range of yield strength for the test elements was from 342 to 402 MN/M^2.

Profilometric scans including longitudinal and helical traces were taken using a linear variable differential transducer (LVDT). Scans were taken at representative positions, for which as fabricated data was obtained. A typical profilometric scan as obtained for circumferential ridge formation is shown in Fig.5.

From the results already obtained, it is observed that the tube does not suffer from change in ovality for diametral clearances upto 0.09 mm. A permanent ridge is however formed for large clearances of 0.2 mm and higher. In the intermediate range of clearances. there could be some probability of risk as indicated by a large change in ovality. Further studies are directed in this intermediate zone, particularly between 0.1 - 0.13 mm which represents the majority of cases of diametral clearance obtained in actual manufacture.

6. Conclusions

1. Formation of longitudinal ridge is principally dependant on diametral clearance, yield strength and the thickness of the cladding. Of these, diametral clearance is found to be the most sensitive parameter. In fact, it is possible to offset the effect of lower yield strength material with reduced diametral clearance.
2. The initial ovality and eccentricity of the cladding do not play an important role in the formation of longitudinal ridge.
3. Finite element formulation, explained in the paper, predicts the circumferential ridge profile as observed in the out-of-pile autoclave tests. One can use this formulation for study of in-reactor ridging behaviour by introducing further refinements, as necessary.
4. For predicting of collapse into small axial gaps, application of Donnell's theory is suggested. The critical pressure for collapse into axial gap is sensitive to thickness, yield strength and unevenness factor of the cladding tube.

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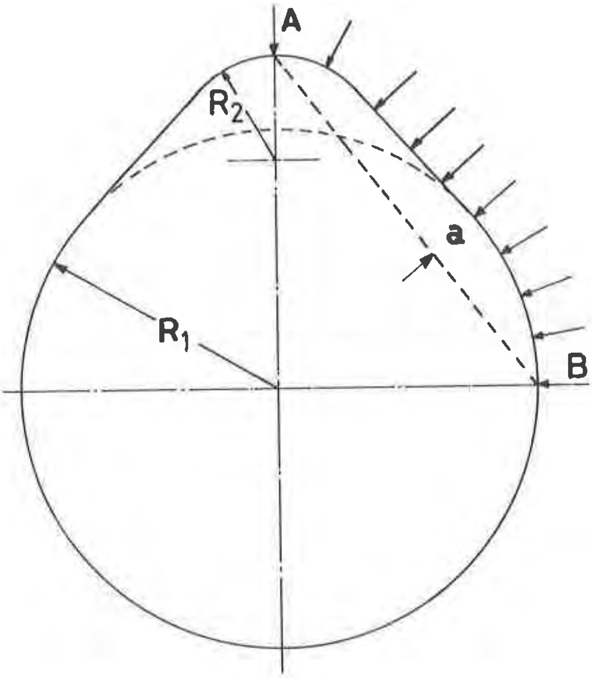
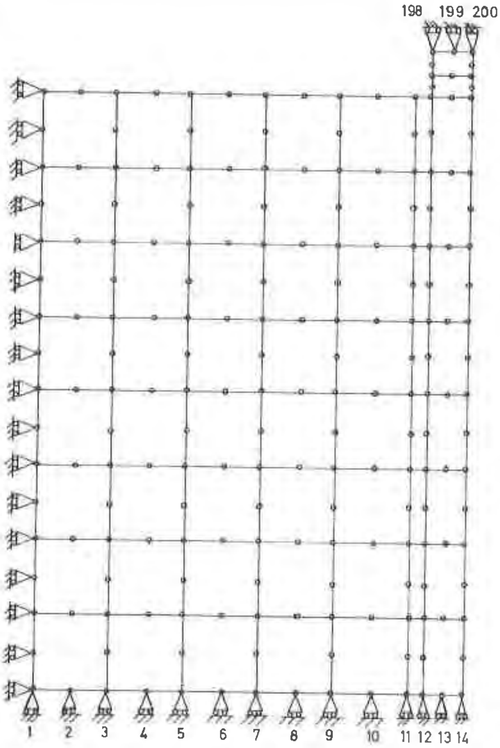


DEFORMED PROFILE OF SHEATH WITH LONGITODINAL RIDGE

FIG. 1



MESH AND BOUNDARY CONDITIONS

FIG. 4

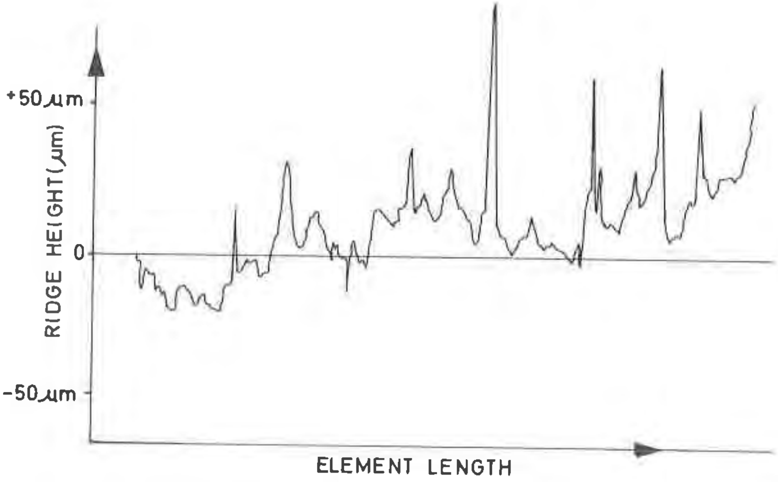


FIG 5. PROFILOMETRIC TRACE FOR CIRCUMFERENTIAL RIDGE