

Finite Element Analysis (FEM) of spent fuel rod for study of effect of uniaxial tensile stress on crack propagation and structural stability

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Abstract— Nuclear fuel rod are utilized in nuclear reactor for nuclear energy generation. After generation it is important to determine the structural stability of nuclear fuel rod for safe storage and transport of the nuclear fuel rods to the decommissioning facility. Due to intense stress and temperature in the reactor there is a probability of crack in nuclear fuel shell which have to be analyzed. There are analysis available for intact shell under different loading condition which provides useful information. In this FEA we are evaluating structural stability of the shell with crack length of a , $2a$ and $3a$ to understand the effect of crack length on the shell. (a is factor $(1/10)$ of wall thickness)

Keywords— Nuclear fuel rod, finite element analysis, structural stability, nuclear power generation, fracture mechanics, crack propagation

I. INTRODUCTION

This study will assess the risk of loss of structural integrity of transportation casks and fuel cladding after extended storage. The main goal of this study is to determine whether the cask functions such as containment, shielding, and criticality are preserved during cask transportation after extended storage. Although it is known that fuel rods discharged from NPPs have a small percentage of rod cladding defects, the behavior of fuel cladding and the structural elements of assemblies during transportation after long-term storage is not well understood. If the fuel degrades during extended storage, it could be susceptible to damage from vibration and impact loads during transport operations, releasing fission-product gases into the canister or the cask interior (NWTRB 2010). Degradation of cladding may occur due to mechanisms associated with hydrogen embrittlement, delayed hydride cracking, low temperature creep, and stress corrosion cracking (SCC) that may affect fuel cladding and canister components after extended storage of hundreds of years. Over extended periods at low temperatures, these mechanisms affect the ductility, strength, and fracture toughness of the fuel cladding, which becomes brittle.

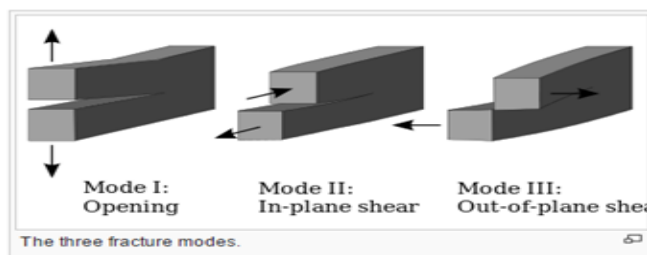


Figure 1

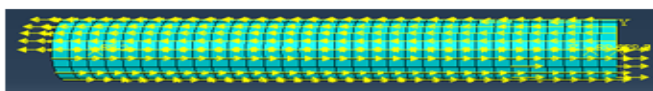


Figure 2
In plane shear

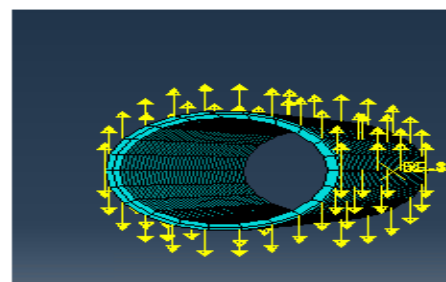


Figure 3
Opening Mode

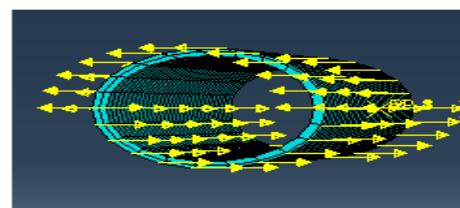


Figure 4
Out of plane shear

II. PROCEDURE

FEA model have been developed for cylindrical shell. The shell has outer wall diameter of 0.229 inches and inner diameter of 0.196 inches. The length of the fuel rod is 72 inches but to understand the structural stability 2 inch portion of the rod has been modeled which resembles the middle part of the rod, which is most critical for the analysis. Instead of zirconium steel property has been used so that in the case of making physical prototype, it can be compared and effect can be analyzed. There are pallets in the shell but for the simplicity of the experiment the pallets are ignored and only shell is considered for the analysis.

From the prior simulations proper mesh size has been determined for the analysis of fuel rod. Insertion of crack has been done for sizes a, 2a and 3a to understand the effects of crack length. Here in this study only the effects on 2a and 3a are only discussed since the effects of crack size a is not very significant with resultant stresses and it is very similar to size 2a. Since there is a symmetry in the load and the middle portion of the rod is free to rotate and displace in the reactor to replicate the effects loads are applied in the given direction to understand the effects of structural stability.

As shown in the figures 2, 3, 4 loads applied in the directions of opening mode, in plane shear and out of plane shear to understand the effects of crack. The effects of the loads should be analyzed to see the effects of different crack size. to apply the load, all nodes on the upper half of the cylinder and lower part of the cylinder are made as a set and concentrated loads has been applied to see the effect due to crack length. The results have been analyzed using von misses stresses to understand the effect on the shell.

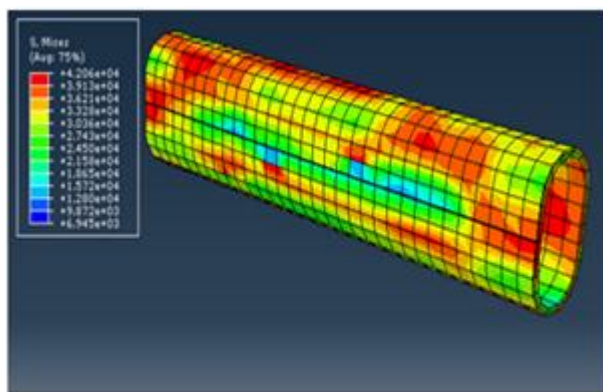


Figure 11
Opening mode (Side View)

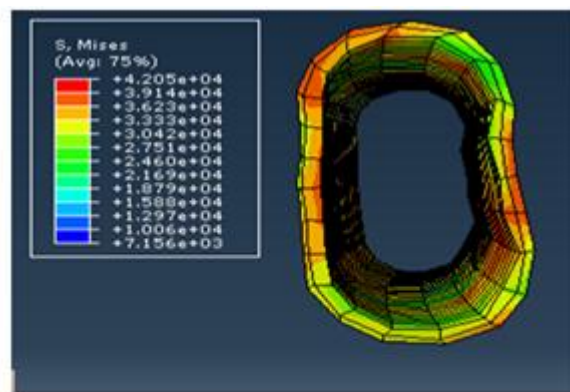


Figure 12
Opening mode (Top View)

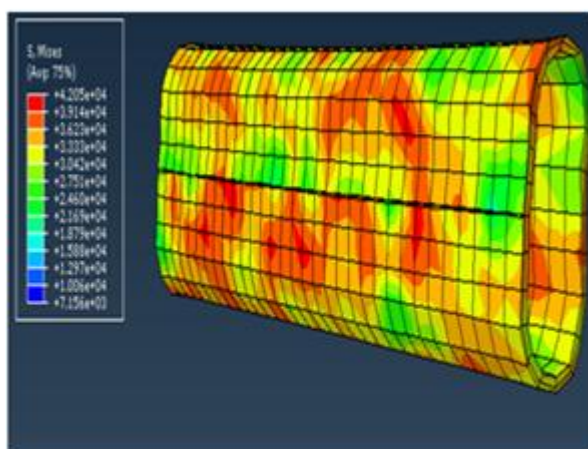


Figure 13
In plane shear mode (Side View)

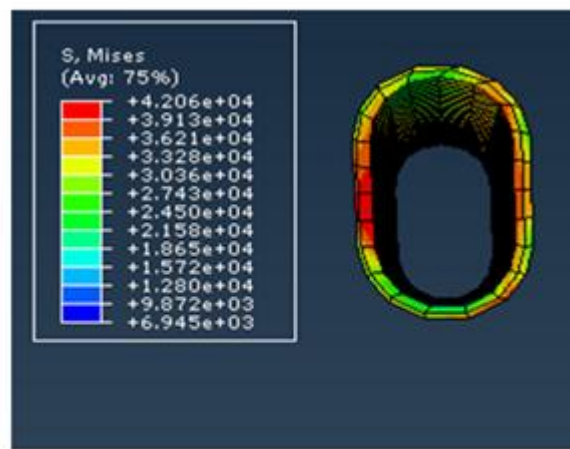


Figure 14
In plane shear mode (Top View)

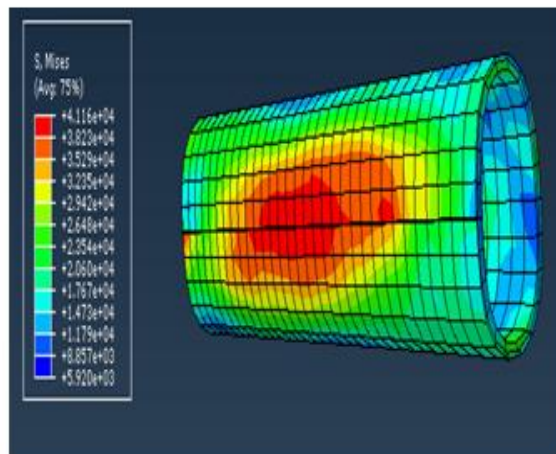


Figure 15
Out of plane shear mode (Side View)

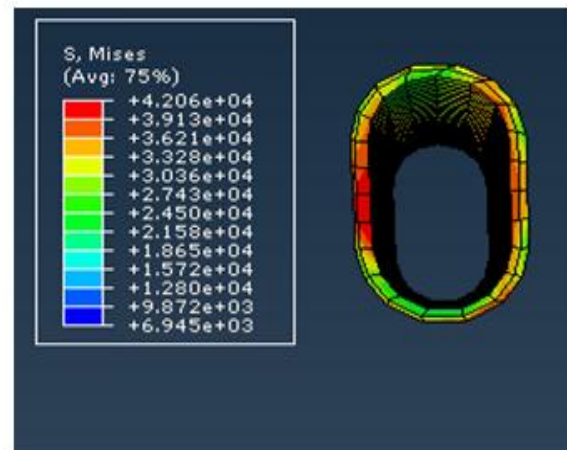


Figure 16
Out of plane shear mode (Top View)

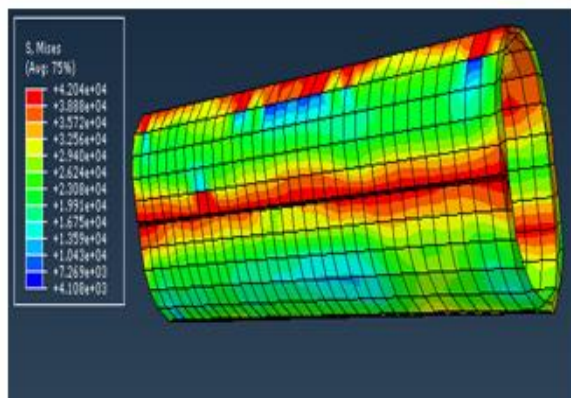


Figure 5
Opening mode (Side View)

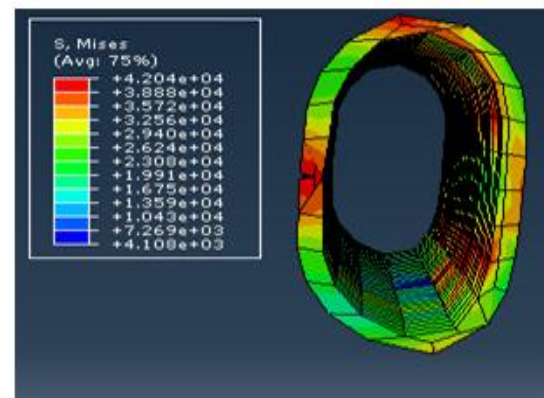


Figure 6
Opening mode (Top View)

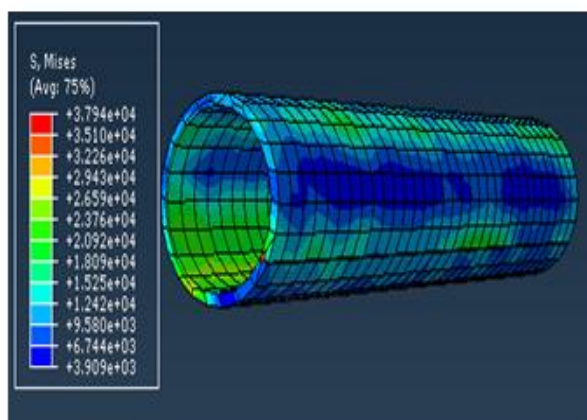


Figure 7
In plane shear mode (Side View)

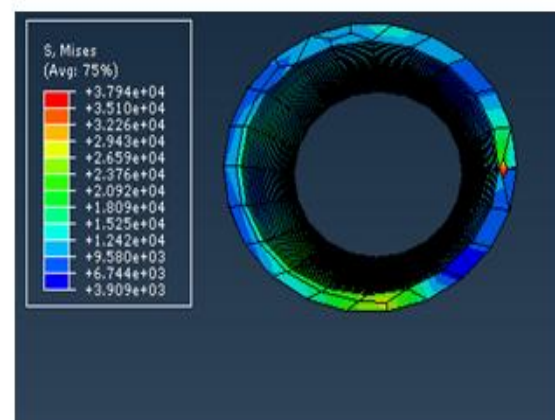


Figure 8
In plane shear mode (Top View)

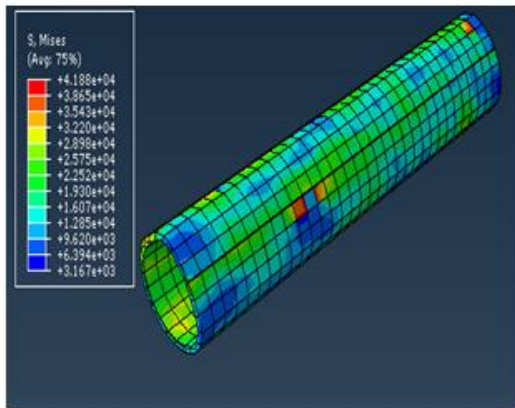


Figure 9
Out of plane shear mode (Side View)

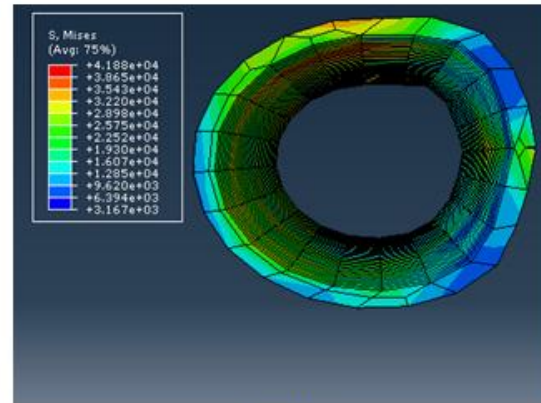


Figure 10
Out of plane shear mode (Top View)

III. RESULTS

As shown in figure results for all mode application has been obtained for both case 1 (crack length= $2a$) and case 2 (crack length= $3a$). If we compare figures 5, 7, 9 we can understand the difference on the von misses stresses due to application of load characteristics. Also as expected case 2 (crack length= $3a$) has mode deformation compared to case 2 (crack length $2a$). As we can see in case 1 the stresses are significant but there is not very much deformation of failure or the shell, while in the case of case 3 the deformation is very significant and it seems to be heading towards structural unstable condition of the fuel rod.

As we can see application of stresses in opening mode (mode-1) tensile stresses causes deformation in the tensile direction, in case 3 there is a change of shape is observed and deformation and rotation can be measured and evaluated. In the case of in plane shear stress (mode-2) the stresses are applied in the transverse direction and as we can see maximum stress effects can be observed at in the middle of the shell in the radial direction. While in the case of out of plane shear mode (mode-3) the maximum stresses are observed in the middle of the cylinder in the circumferential direction. As we can see there it is clear that in the case-3 (crack length $3a$), the effects of stresses are significant and concentrated very intensely as compared to case-2 (crack length 2).

For all the cases analyzed there are crack propagations but crack size $3a$ may not deform the rod during seconds, just because of the given load, but crack will surely increase the further crack propagation which may further lead to the failure of the component. Also, case 2 is significantly damaged, so there should be consideration of crack length while designing parameters of fuel rod and for given wall thickness and outer wall diameter, the crack length should not exceed $3a$ crack limit for its structural stability to stay intact. To understand the stresses and deformation at a point of interest, the von misses stresses should be analyzed and also there are displacement plots and contours which provides better understanding of the effects of stresses on the shell with crack initiation or preexisting cracks.

IV. CONCLUSIONS

To determine structural stability of the shell finite element analysis model can be used. Here just middle portion of shell is considered for the simplification, to have accurate analysis, complex geometry should be modeled. From the result of the experiment we can understand that for the given outer diameter and wall thickness, crack length should be less than $3a$ for given load conditions. For detailed analysis stress contours of von misses and deformation plots should be analyzed. Also from von misses we can see that in opening mode, most critical stresses are in the center of the shell in the radial direction. In the case of in plane shear mode, most critical stresses are in the center of the shell in the radial direction as well. In the case of out of plane shear mode, most critical stresses are in the center of the shell in the circumferential direction. The analysis is very helpful in understanding the effects of crack size on the shell and also the stresses and deformation due to crack for given wall thickness and outer diameter of the shell.

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