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Dynamic Response of Cylindrical ACS Support Structures to Core Energy Release

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Abstract

The code SAFE/RAS is applied to the analysis of a new design concept for the above-core structures when subjected to the loads of a core disruptive accident. The analysis involves the determination of the postbuckling response of a thin cylinder loaded both axially and vertically. The effects of variation of cylinder thickness and fluid-structure interaction are investigated.

1. Introduction

The computer code SAFE/RAS [1] has been developed for the transient analysis of fluid-structure systems with severe nonlinearities. Both two-dimensional and three-dimensional fluid-structure systems can be considered. Material and geometric (large displacements and strains) nonlinearities are treated. Two major features have recently been included for enhancing the computational efficiency of this computer program: (1) a subcycling feature, which permits different timesteps to be used in different parts of the mesh, so that the more flexible elements in the mesh can be integrated at a much larger timestep than the stiffer elements; and (2) special reduced quadrature schemes and stabilization schemes which permit the minimum number of quadrature points consistent with optimal convergence to be used in each element.

Although the subcycling feature is quite simple in principle, its effective implementation in a general purpose code requires careful design. We have found that care must be taken to prevent large changes of timesteps in a particular element and that automatic procedures for allocating elements to different timesteps must be developed if the procedure is to be effective. These items will be discussed in the presentation.

We will describe here the application of SAFE/RAS to the analysis of some new concepts for the supports for the above-core structures (ACS) of a breeder reactor, with emphasis on a new concept in LMR design for ACS supports. In this new concept a single large radius cylinder is used, as shown in Fig. 1, where it is identified as the upper internal structure. In earlier designs, such as Clinch River, four thick columns were used to support the ACS. The advantages of a single cylinder are reduced cost of fabrication, increased lateral stiffness which enhances seismic resistance, and easier access to the fuel. Codes such as SAFE/RAS enable the performance of these designs to be evaluated for hypothetical accidents where severe vertical loads arise. The response of these two designs may be substantially different because the buckling and postbuckling behavior of a large radius, thin cylinder differs substantially from that of beams with cylindrical cross-section.

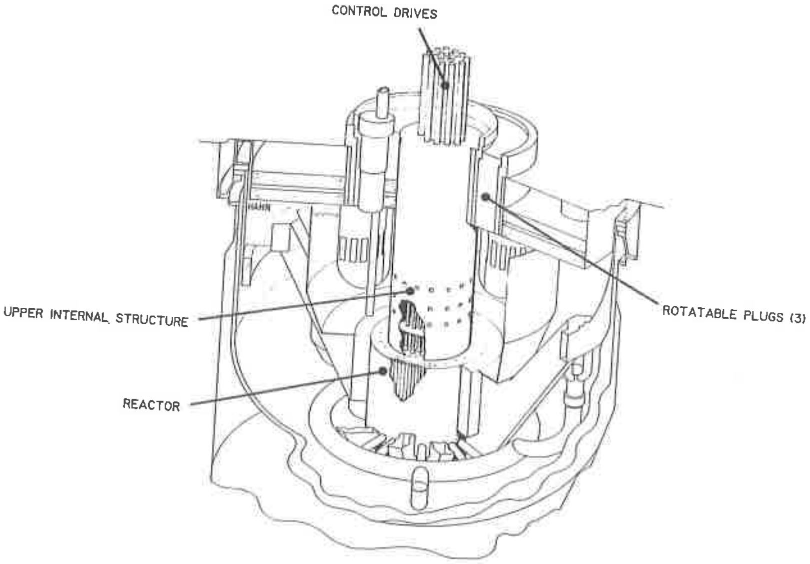

Fig. 1. LMR Design with Cylindrical ACS

The behavior of these support columns may also be influenced substantially by fluid-structure interaction (FSI). The buckling of these supports and subsequent deformation in the post-buckling regime requires substantial displacement of the fluid and hence may enhance the apparent strength of the columns.

2. Analysis Without Fluid Structure Interaction

A comparison of the performance of these two designs was first made without including fluid-structure interaction. Various dimensions were considered. The dimensions of the two designs are given in Table I. The thinnest cylinder considered here has a cross-sectional area equivalent to that of design A. The support structures are loaded vertically by a load taken from SRI [2] scale model tests and simulates a 992-MW-s energy release. The plastic yield strength of the material is 240 MPa, and its ultimate stress is 620 MPa at 18% strain. The load on design B consists of the vertical load due to the pressure on the bottom surface and a pressure on the lateral surface. The pressure time histories are different because the pressure on the side of the support differs from that in the core; the pressure time-histories are piecewise linear and given in Table I.

The model for design B is shown in Fig. 2. It consists of 1280 quadrilateral 4-node shell elements. The entire row of nodes on the bottom of the cylindrical vessel are slave nodes which are attached to a single master node; the master node includes an additional mass of 4000 kg which corresponds to the mass supported by the column. This mass has a significant effect on the response of the column since it mitigates the effects of the large initial pressures but then maintains a large axial (vertical) force on the cylinder after the pressures have diminished.

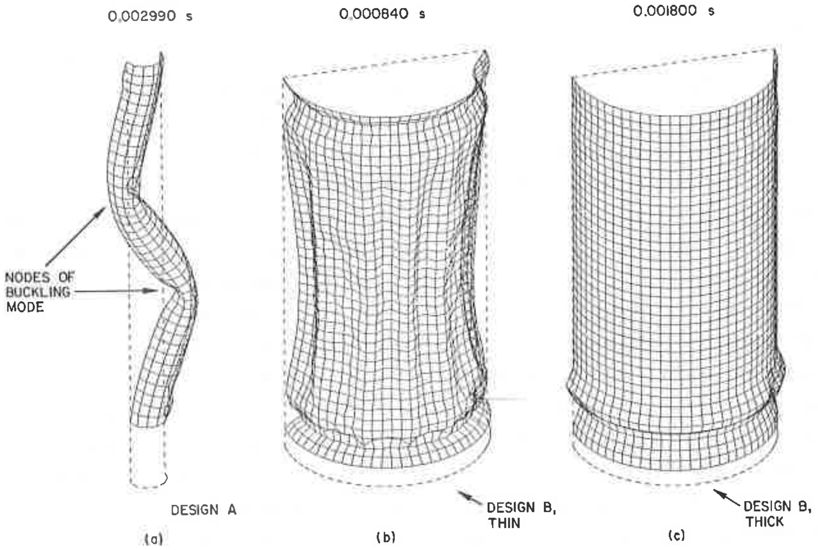

Fig. 2. Failure Modes of Designs

The element chosen for this analysis is a four-node quadrilateral with one quadrature point per element [3]; a consistent spurious mode procedure is used to control the hourglass modes of this element [4]. This element is very efficient: 1280 elements require 2.4 CPU seconds per time step on an IBM 3033. The analysis was performed with explicit time integration. The stable time step for this problem is 38.3 μs which is set by the membrane response of the element. The problem was run with a time step of 30.0 μs; 2500 time steps were required for the solutions.

Results are given in Table II and Fig. 2. It can be seen that while design A buckles laterally with a large change in its cross section, design B exhibits a symmetric nodal buckling into almost a diamond-shaped pattern (see Fig. 2b). It is seen that the cylinder with an equivalent cross-sectional area (1.651 cm thickness) as that of the four columns cannot withstand the pressure; it is shown in Fig. 2b early in the simulation, and subsequently it fails dramatically. When a wall thickness of 2.4765 cm is used in design B, the axial displacement is approximately equal to that of the four-column support. The design B cylinders with greater wall thicknesses deform as shown in Fig. 2c. Thus the single cylinder apparently requires extra material for axial stiffness as compared to design A, but the advantages of fabrication, seismic resistance, fuel accessibility, etc., may compensate for the extra material.

3. Analysis With Fluid-Structure Interaction

Fluid-structure interaction probably plays a much larger role in design B, the single cylinder support, than in design A. In design A failure is strongly influenced by the loss of flexural stiffness that is brought about by the collapse of the cross-section, i.e. the change of cross-section of the column at the nodes of buckling modes, see Fig. 2a. Since the fluid is entirely outside the column in design A, it has little bearing on the strength of the design.

On the other hand, in design B, the fluid occurs both on the inside and outside of the cylinder. As can be seen from Fig. 2b, the failure mode of the thinner versions of design B involve a significant decrease of the volume inside the cylinder. Since the sodium is almost incompressible, it must be vented out of the cylinder if failure is to occur. If the venting is slow, or if it causes the pressure inside the cylinder to rise substantially, then this failure will be prevented by fluid-structure interaction. However, when an equivoluminal failure mode, in which the volume inside the cylinder is unchanged, is possible, then the situation is more complex. If an equivoluminal failure mode is possible with a little additional force, then little benefit will be obtained from fluid-structure interaction. If it requires considerable additional force, then FSI provides benefits.

In order to examine the effect of fluid-structure interaction on the failure of design B, a fluid model was inserted into the cylinder. A venting model was included. The fluid elements in this model were larger than the shell elements so that four shell elements fit on each fluid element surface. The ratio of stable time steps in the fluid to the shell is 4.4, so that the subcycling feature proved particularly advantageous; the fluid element time step was calculated using a precise upper bound for the maximum eigenvalue of the hexahedral element which has recently been derived by Flanagan and Belytschko [5]. Since there are 1920 fluid elements, subcycling saves a factor of 1.8 in computation time.

Preliminary results for this model indicate that the effects of fluid-structure interaction are significant for the 1.651 thickness design B cylinder. The cylinder fails, but in a much less dramatic manner than without fluid-structure interaction.

Deformed configurations of the two simulations without and with fluid-structure interaction are shown in Figs. 3 and 4, respectively. As can be seen from the simulations with and without FSI, the failure mode changes markedly. The presence of the fluid prevents the type of circumferential failure mode characterized by the collapse of the shell inward. However, as can be seen from Table II, the benefits of FSI on reducing axial deformation are small, because the cylinders are quite thin and can fail in very local modes which do not bring fluid-structure interaction into play.

References

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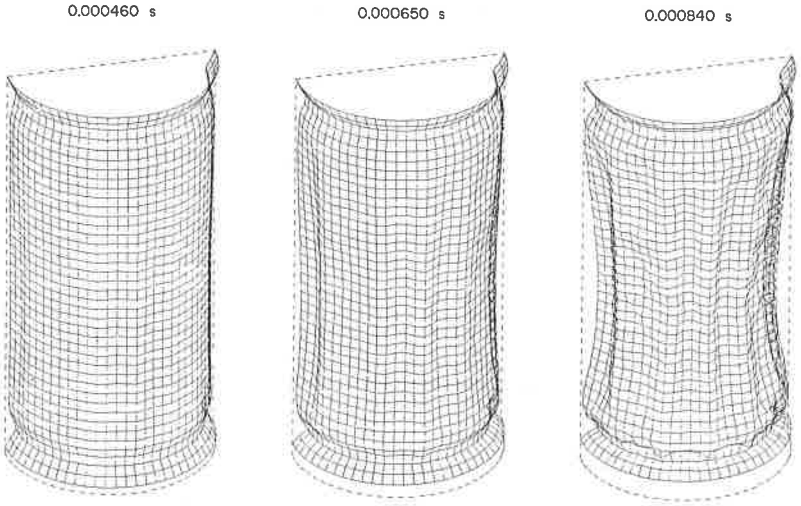

Fig. 3. Deformed Configurations of 1.651 Thickness Cylinder Without Fluid-Structure Interaction

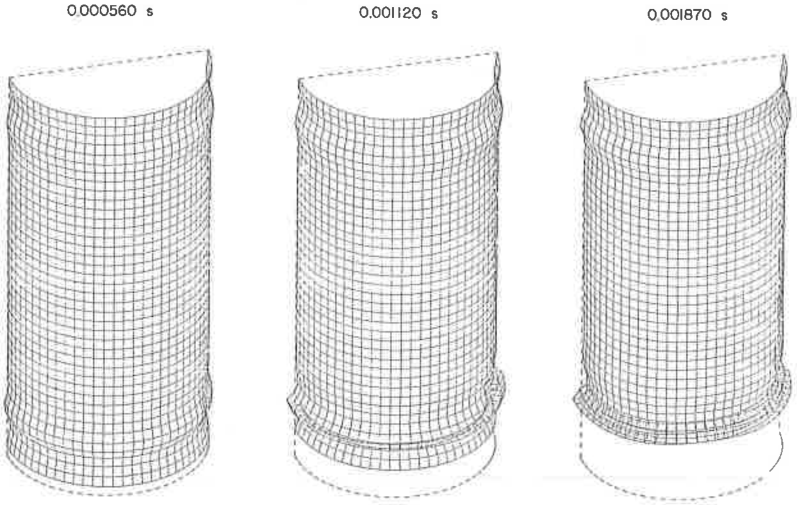

Fig. 4. Deformed Configurations of 1.651 Thickness Cylinder With Fluid-Structure Interaction

Table I. Surface Pressure Time-Histories

Bottom Surface		Lateral Surface	
Pressure (MPa)	Time (ms)	Pressure (MPa)	Time (ms)
34.47	0.4	9.65	6.0
0.0	3.0	2.41	12.0
24.13	4.4	5.17	18.0
13.79	5.0	0.0	20.0
5.52	18.0	2.07	26.0
0.0	36.0	0.0	32.0
0.0	100.0	0.0	100.0

Table II. Dimensions and Deformations of Above-Core Structures

Dimensions and Material Properties

Design A - Column Support		Design B - Cylindrical Support	
Wall thickness, cm	2.540	Wall thickness, cm	1.651 to 3.302
Column diameter, cm	33.02	Cylinder diameter, cm	203.2
Cross-sectional area, cm^2	263.5	Cross-sectional area, cm^2	1054.0 to 2108.0
Column length, cm	406.4	Cylinder length, cm	406.4

Young's Modulus - 1.93 x 10^5 MPa
Density - 8888 kg/m^3

UIS Mass
Diameter - 294.64 cm
Height - 281.94 cm
Young's Modulus - 7.17 x 10^4 MPa
Mass - 4000 kg

Deformations

Design	Wall Thickness (cm)	Maximum Axial Displacement (cm)		Time of Maximum Axial Displacement (ms)	
		Without SFI	With FSI	Without FSI	With FSI
A	2.540	58.3		60.0	
B	1.6510	fails	fails	---	---
B	2.0638		78.9		75.0
B	2.4765	62.0	43.1	66.0	67.5
B	2.8892	16.5		36.0	
B	3.3020	7.4		18.0	