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Experimental validation of CASTEM code for buckling problems

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ABSTRACT: For validating the buckling analysis capability of CASTEM code which is used for the buckling design of Prototype Fast Breeder Reactor (PFBR) vessels, a few experiments have been carried out at Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam. Experiments were conducted on aluminium cylindrical shells under axial compression and stainless steel cylindrical shells under external pressure and transverse shear loading. This paper presents the results of experimental and associated theoretical buckling studies performed using the code INCA.

1 INTRODUCTION

The usage of very large sized thin shell structures for FBR vessels poses the problem of buckling risk, particularly when they are subjected to compressive loads originating from the normal and seismic loads. The main vessel (MV) of PFBR is one of the important safety related component as it contains a large pool of radioactive sodium and it also acts as a medium for transmitting the core loads to roofslab. It is subjected to axial compression and transverse shear loads during the seismic events and external pressure during the decay heat removal operation. Theoretical studies towards the buckling analysis of MV have already been reported (Damodaran 1991,1993).

The prediction of buckling load calls for the detailed analysis taking into account the several complexities associated with the problem viz., the effect of initial geometric imperfection, large displacement, plasticity, dynamic nature of seismic loads and the combined action of mechanical and thermal loads. For PFBR vessels, buckling analysis have been carried out with a powerful non-linear software 'CASTEM' which takes into account all the complexities of buckling problems (CASTEM 1985). Although, this code is completely validated in CEN-Saclay, FRANCE, a few buckling experiments have been carried out at IGCAR, Kalpakkam in order to understand further the performance of the code in solving the buckling problems of thin shell structures more relevant to PFBR situations. To start with, experiments were conducted on aluminium and stainless steel models under the action of axial compression, external pressure and transverse shear loadings. The theoretical and experimental buckling studies performed on aluminium and SS models are discussed in this paper.

2 DETAILS OF EXPERIMENTAL AND THEORETICAL STUDIES

2.1 Experiments with aluminium model

Four seamless aluminium vessels of 320 mm diameter and 310 mm height were utilised for studying their elastoplastic buckling behaviour by experiment and theory. The vessel was provided with carbon steel flanges at the top and bottom edges. The initial geometric imperfection in the vessel was measured by rotating the dial gauge around the inner surface of cylinder. The typical imperfection observed for model 3 is shown in Figure 1. Dominant mode of imperfection and maximum deviation from the true circular shape was identified by the Fourier decomposition of dial gauge reading. Thickness variation along the axial and circumferential direction was measured by means of ultrasonic thickness gauge and the thickness variation observed along the axial direction for model 3 is shown in Figure 2. The stress-strain curves were determined by testing samples prepared from the lower flat portion of the vessel. It is to be noted that, with the thickness variation from 0.5 mm to 1.3 mm along the axial direction, the hardening and hence the yield strength also is expected to vary due to variation in the amount of cold work. This change in yield strength along the axial direction is taken into account in the theoretical prediction of buckling load.

The compressive load was applied to the models in universal tensile testing machine. The axi-ality of the loading was ensured by checking the axial displacements at three dial gauge locations. The test setup considered for buckling experiment is shown in Figure 3. The onset of buckling for the model was identified by the visibility of first buckle pattern in the model during the application of loading. The buckling strength of the models were evaluated by performing detailed elastoplastic large displacement analysis by modeling the vessel with 80 COMU elements of INCA code of CASTEM. The dominant imperfection mode of 4 selected from the modal decomposition of the measured imperfection with an amplitude of 0.2 mm is chosen for the analysis. The harmonic modes of 0,4,8,12,16 and 20 were considered for the displacement field in the analysis. The theoretical and experimental prediction of buckling load for the four models are given in Table 1. Figure 4 compares the axial load Vs axial deflection curves for the model 3 in both experiment and theory. Buckling modes in observed the experiment and theory are shown in Figure 5. It is found that, the INCA prediction of buckling behaviour of aluminium vessels is very good both for buckling load and mode shape.

Table 1. Buckling load for aluminium cylinder under axial compression load (t)

Model	Experiment	Theory
1	2.9 (8)*	3.01 (11)
2	2.2+ (8)	4.08 (9)
3	4.6 (11)	4.7 (12)
4	4.8 (11)	4.5 (12)

* Number in the parenthesis indicated the number of circumferential waves.

+ The model 2 was found to have local imperfection of 2.5 times vessel thickness and the axi-ality of the loading was not maintained in this test.

2.2 Experiments with stainless steel models

Stainless steel cylindrical shell models of 350 mm diameter and 0.5 mm thickness have been used for testing their buckling strength either under the action of external pressure or under the action of transverse shear load. The models were fabricated by rolling the SS 304LN sheet of 0.5 mm thickness and welding along the axial direction. These models represent the 1/40th scaled down model of PFBR main vessel with the same diameter to thickness ratio.

2.2.1 Cylinder under external pressure

Two SS models of 345 mm height have been tested for evaluating their buckling strength under external pressure. The models were inserted to the grooves provided in the top and bottom flanges and they were connected by spot welding. The black wax sealing compound was pasted on the top and bottom ends of the shell near the spot weld region throughout the circumference to assure the leak tightness. The external pressure was applied by creating vacuum inside the vessel with a rotary vacuum pump connected to the opening provided in the top flange. The onset of buckling was identified with a sudden appearance of wave pattern in the shell and the corresponding pressure gauge reading was considered as the buckling pressure. Figure 6 shows the test setup considered for this experiment.

Theoretical analysis of the model was performed in two stages with the INCA code. In the first stage, elastic bifurcation analysis was carried out and it predicted the elastic buckling pressure of 0.0413 MPa for the circumferential mode of 8. In the second stage, large displacement analysis was performed for the imperfect geometry with maximum imperfection of 0.1 mm and 0.5 mm for the two models. The theoretical and experimental results observed for the models are given in Table 2. Both the experiments have shown good comparison with the theoretical prediction of critical pressure at the buckling mode 8. The mode shapes observed for the model 2 are shown in Figure 7.

Table 2. Buckling pressure for stainless steel vessel under external pressure (MPa)

Model	Experiment	Theory
1	0.038 (8)	0.037 (8)
2	0.030 (8)	0.030 (8)

2.2.2 Cylinder under transverse shear

For studying the buckling behaviour under the action of transverse shear load, two SS models with a height of 275 mm for the first model and 185 mm for the second model were considered. The models were bolted with stainless steel flanges and its one end was fixed to a rigid frame and its other end was connected to a loading fixture. The model was kept with its axis along the horizontal direction and the shear loading was applied to the model in universal tensile testing machine. The test setup considered for the experiment is shown in Figure 8.

The theoretical analysis was carried out by performing the elastic bifurcation analysis

with COMU elements of INCA code. The effect of plasticity was considered with the quadratic interaction formula involving the elastic buckling load and yielding load. The theoretical and experimental results observed for the two models are presented in Table 3. Eventhough, there is a good comparison between theory and experiment in the estimation of buckling load, the models were found to buckle slightly in the bending mode just prior to the onset of shear buckling mode in experiment, whereas theoretical prediction has shown only the shear mode of buckling. This small discrepancy in the prediction of buckling modes in the experiment are due to some edge effects near the bottom flange. Few more experiments are being carried out to get further inside of this problem. Figure 9 shows the buckling modes predicted for model 2 by the experiment and theory.

Table 3. Buckling load for stainless steel vessel under shear load (t)

Model	Experiment	Theory
1	1.68	1.6
2	1.74	1.9

3 CONCLUSIONS

Considering the importance of buckling analysis for PFBR vessels, theoretical and experimental investigations were carried out on the aluminium and SS models under the action of axial compression, external pressure and transverse shear loading in order to validate the CASTEM code used for buckling studies. In general, the comparison between the theoretical and experimental predictions of buckling load and mode shapes are very much satisfactory. In the case of aluminium models, the comparison between the prediction of axial compressive buckling load by experiment and theory are very good. The experiments with SS models under external pressure have also shown good comparison with theory in the prediction of buckling pressure and mode shapes. In the case of shear buckling of SS models, the theoretical prediction of buckling load compared well with the experimental prediction. However, the slight bending mode was observed for the models just before the onset of shear buckling mode in experiments, whereas only the pure shear mode was observed from the theoretical prediction. The small discrepancy may be due to some edge effects near the flange. It is planned to conduct more buckling experiments in near future with the large scale SS models.

REFERENCES

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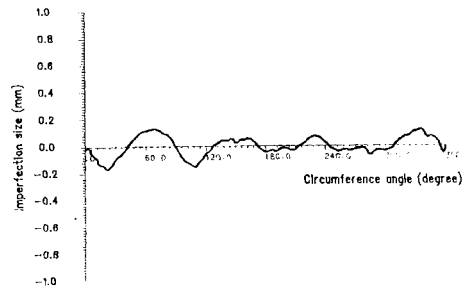


Fig. 1. Initial imperfection in aluminium model

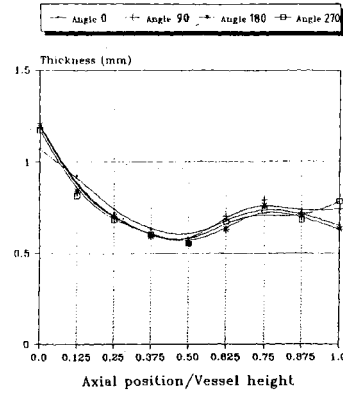


Fig. 2. Thickness variation in aluminium model

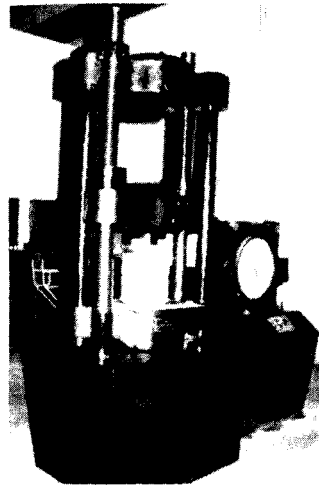


Fig. 3. Experimental setup for aluminium model under axial compression

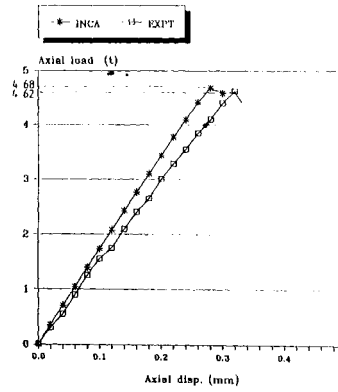


Fig.4. Load deflection curve for aluminium model

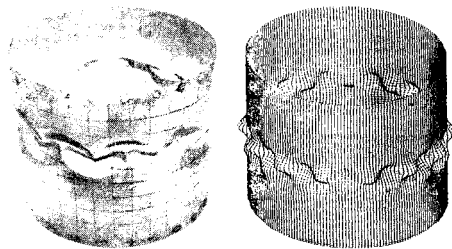


Fig. 5. Buckling modes for aluminium model under axial compression



Fig.6. Experimental setup for SS cylinder under external pressure

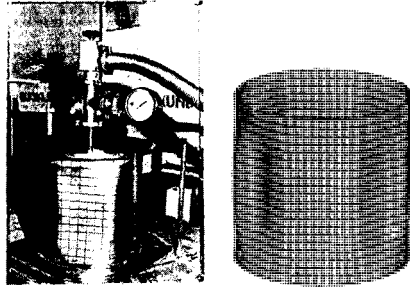


Fig. 7. Buckling modes for SS model under external pressure

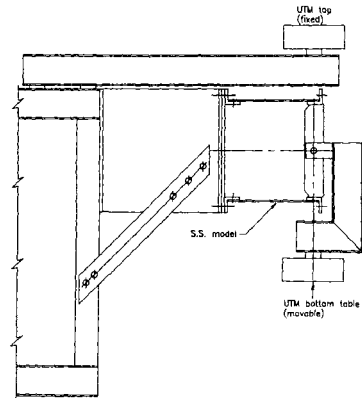


Fig. 8. Experimental setup for SS cylinder under shear load

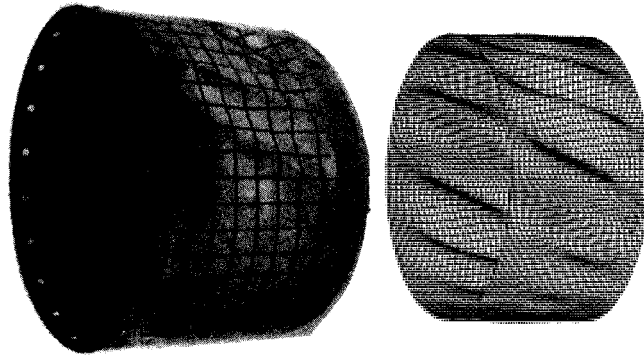


Fig. 9. Buckling modes for SS model under shear load