Dynamic Stability under Fluid-Structure Interaction

P. DESCLEVE
Framatome, Lyon, France

A. COMBESCURE
CEA, CEN Saclay, Gif-sur-Yvette, France

ABSTRACT

The strength of the internal structures of a sodium cooled reactor must be evaluated under seismic conditions and in the case of thin shells surrounded by narrow fluid gaps the stability under fluctuating external pressure must be demonstrated. During the construction of the Creys-Malville plant design methods have been developed to include the influence of geometrical defects on buckling under constant pressure, the effect of dynamic loadings has been studied in various tests and has been shown to be important. The overall accuracy of the seismic analysis is evaluated and results obtained on a 1/30 scale simplified model of a reactor vessel are described. Recent developments have been made for the non linear dynamic analysis of quasi-axisymmetric shells coupled with a fluid, the theory is presented and a simplified method is proposed to include the dynamic effect in the mechanical evaluation of internal structures.

1 INTRODUCTION

Under static pressure the experimental collapse of an axisymmetric imperfect elastoplastic shell can be rather accurately predicted. Under dynamic conditions using the same methodology may be adequate for a sphere but is overconservative for a cylinder since the pressure can reach a value well above the calculated static stability limit.\(^1,2\)

The object of this paper is to summarize the methodology used during the construction of the Creys-Malville plant, to describe briefly some of the calculations and tests made for stability evaluation and to present a method for introducing dynamic effects at the design level.

2 METHOD USED FOR SUPERPHENIX 1 INTERNAL SHELLS

2.1 Mechanical analysis

The seismic response of the reactor-block is calculated with a linear model including fluid-structure interaction and the dynamic properties of intermediate heat exchangers, pumps and core. The modal time history method is used and the dynamic pressure generated in the fluid gaps separating the inner shells is evaluated with time. Then the most severe conditions for a given structure must be determined for application to the more refined non linear model requested by a stability evaluation. As a general rule the instant giving during the seismic transient, the maximum stresses in the area of inception of buckling, is selected for the pressure loading specification. To assess the adequacy of this procedure two questions will be examined: accuracy of the pressure field calculation and evolution of the loading distribution under high seismic excitation.


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2.2 Questions raised by the seismic loading determination.

The pressure accuracy can be directly assessed from a comparison of frequency measurements and calculations made on fluid coupled systems. Satisfactory results have been obtained in this respect, for example the typical error on frequencies is 2 to 5%, therefore the error on the pressure field is less than 10%. Under SSE level no significant frequency shift is observed and this conclusion holds. 3,4

Loading distribution inside the reactor vessel under high seismic excitation is however a point of concern since some structures like thermal baffles may exhibit a reduced stiffness and cliff edge effects cannot be ruled out. A sensitivity analysis has been made for SPX1: with perfectly flexible cylindrical shells in the upper part of the vessel it was found that the stresses in the bottom head would increase by 45% but would still remain below an acceptable limit. In the core itself the stresses would not be modified.

2.3 Influence of the shape of a shell on dynamic buckling.

The influence of the structure shape has been studied by the CEA-DEMT in several experiments.

With concentric hemispherical shells it was shown that dynamics effects can be neglected. The instability is of the bifurcation type, associated with a high frequency mode of vibration.

For thin cylinders with geometrical defects, large non-linear deformations are necessary to reach the limit. Furthermore the frequency of the mode associated with buckling is low when compared to the frequencies of the modes associated with pressure fluctuations, for SPX1 the ratio is 1/3 and in experiments close to one. This means that inertia are more important than restoring forces and as verified by tests, that higher loads can be accomodated under seismic conditions.

2.4 Test on a 1/30 scale model.

The model is like a simplified reactor vessel with a rigid core support. The cylindrical shells are made of aluminium to decrease their mechanical resistance. The system was placed in a shaking table driven by an electrodynamic actuator. During a sine sweep test the most important frequencies calculated between 24 and 300 hz were found to be 2% accurate only one experimental result was 10% low. The horizontal motion of the reactor upper deck was applied with a time scale factor of 1/23 for maximum efficiency. The table acceleration was increased by steps up to a value equivalent to twice the SSE conditions, evaluated by comparison to the buckling limit of the internal shells.

Peak pressures where found proportional to the table acceleration and close to the calculated values, however the frequency content was more complex than predicted by the simple linear theory. The maximum differential pressure on the internal vessel as a function of the table acceleration is shown on Fig.1. No buckling was observed and after the test the eigenfrequencies were not modified. It was concluded that the internal baffles which are not submitted to a permanent pressure could not fail by buckling in case of an earthquake. 5

The influence of a permanent pressure, as in the case of the deversoir, has been studied with concentric cylinders under resonant conditions. In some experiments a saturation has been observed at high excitation level with pressure fluctuations approaching one bar. An equivalent level has not been reached in the test reported above and this effect cannot be anticipated for a full size reactor vessel.

3 TRANSIENT FINITE ELEMENTS CALCULATIONS

3.1 Background

The starting point is the non-linear shell element developed for the buckling analysis of imperfect axisymmetric vessels. This 2 nodes element is based on a Fourier series expansion of the
variables. An inextensional defect is taken into account as an initial displacement parallel to the
Euler bifurcation mode. A fluid and a coupling element have been added for step by step non linear
analysis. In comparison with a 3D mesh this approach reduces the computer time. The choice of the
Fourier components to be retained in the analysis depends on the initial defect and the possible
harmonics of the loading system. For example a large initial defect on a Fourier component n with
an axisymmetric loading requires the basis 0, n, 2n, 3n for an elastic material and at least 0, n, 2n, 3n
for an elasto-plastic case.

3.2 Fluid formulation

The hypothesis correspond to a negligible compressibility and no viscosity effects. A Lagrangian
formulation is used with a penalty function to enforce the rotational constraint and suppress the
zero-energy modes of deformation. The four nodes isoparametric element has one point of
integration in the meridional plane and Simpson points along the circumference. 6
For fluid-structure coupling, Lagrange multipliers with pressure at the boundary nodes as extra
variables or special elements with a stiffness along the normal to the structure are available.

3.3 Transient analysis

Starting from an incremental static solution the implicit method is easily implemented. With
non-linearities the equilibrium can be reached by Newton iterations. A mixed implicit-explicit
method is well adapted to seismic calculations and may be less expensive but the time step is
limited by the stability condition. The criteria of numerical stability are well established for the
linear case and should be satisfied as a minimum requirement. In the non-linear large displacement
case, oscillations can be reduced by an algorithm introducing numerical damping of high frequencies
and a small number of Newton iterations may still be necessary. 7

3.4 Example

Analysis of a steel ring surrounded by a water annulus.

- Inside radius : 1 m
- Outside radius : 1.050 m
- Shell thickness : 0.0025 m
- Height : 0.052 m
- Steel modulus : 1.95 E11 Pa
- Density : 7850 kg/m3
- Water modulus : 4.00 E9 Pa
- Density : 1000 kg/m3
- Fixed boundary
- Poisson ratio : 0.3

In the Fourier decomposition harmonics 0, 6 and 12 are used. The metal ring has an initial defect
of 0.001 m on harmonic 6. The first eigenfrequency is 11 Hz and corresponds to the buckling mode.
A fluctuating pressure of up to three times the Euler pressure is applied at 33 Hz by the fluid on
harmonic 6. The radial displacement of the shell for twice this limit is shown in Fig. 2, the
maximum occurs in the first cycle of the transient and is close to the value obtained in a static
calculation with 60% of the Euler pressure.

4 PROPOSAL FOR THE EVALUATION OF DYNAMIC STABILITY

The calculation described above would be too expensive to be applied to the seismic analysis of a
whole reactor vessel. For the design against buckling it is therefore proposed to use a simplified
method and increase the static limit by an amplification factor α which is the ratio between the
dynamic or fluctuating and the equivalent static pressure. This factor would be evaluated with a
diagram, Fig. 3. In the case where it must be verified that a given value is acceptable an
alternative procedure would be to use directly the result of a calculation performed on a simple
structure and an axisymmetric transient load: one shell element with a geometrical defect,
surrounded by a water annulus. The methodology is the following.

1. Compute the buckling load and the corresponding eigenshape by a standard static elastic
analysis of the structure. This involves the determination of the circumferential mode \( n \) giving the lowest bifurcation pressure.

2- Determine the frequency to be associated with the buckling mode by the Rayleigh quotient method or by using directly the reactor seismic model as for the frequency associated with the pressure fluctuations. The ratio of these two frequencies is \( R \).

3- Read the amplification factor \( u \) on the diagram as a function of \( R \) or perform a calculation with a ring model having the same cross-section as the structure. In that case the buckling load and the associated frequency are calculated for the circumferential mode \( n \). Then using the ratio \( R \) the frequency of the harmonic pressure fluctuation is known. A transient analysis is performed with the above buckling load multiplied by the required factor \( u \).

The same method can be used when the load contains a permanent component but in this case it must be verified that the structure remains elastic or that progressive deformation is avoided.

5 CONCLUSIONS

Tests performed during the construction of the Creys-Malville plant demonstrate that the internal structures of a sodium cooled reactor can withstand higher pressures than predicted by a static analysis based on maximum transient values.

A methodology has been presented to evaluate the dynamic buckling limit of an elastic shell in fluid and to design for dynamic stability.

More developments are necessary to generalize the hypothesis and include the effects of thermal stresses and plasticity.

Experiments on a large model would be necessary to qualify the method: measure damping, check the accuracy of stress calculation in the core support structure and other critical parts of the reactor vessel, finally evaluate the influence of large components and other non axisymmetric effects.

REFERENCES


Figure 1: Test of a 1/30 scale model
Figure 2: Dynamic stability calculation of an annulus

Figure 3: Efficiency diagram of the dynamic pressure