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# Dynamic buckling in a next generation metal coolant nuclear reactor

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**Analysis and modelling**

## ABSTRACT

**Purpose:** The aim of the paper is to investigate the buckling effects due to the seismic sloshing phenomena interesting for a next generation heavy liquid metal cooled reactor as for example the eXperimental Accelerator Driven System (XADS).

**Design/methodology/approach:** In this study the structural buckling behaviour of a reactor pressure vessel, retaining a rather large amount of liquid and many internal structures, is coupled to the fluid-structure interaction because during a postulated earthquake (e.g. Design Basis Earthquake) the primary coolant surrounding the internals may be accelerated with a resulting significant fluid-structure hydrodynamic interaction (known as “sloshing”). Finite element numerical approach is applied because neither linear nor second-order potential theory is directly applicable when steep waves are present and local bulge appear with a marked decrease in strength of structure.

**Findings:** The numerical results are presented and discussed highlighting the importance of the fluid-structure interaction effects in terms of stress intensity and impulsive pressure on the structural dynamic capability. These results allowed to determine the components mostly affected by the loading condition, in order to upgrade the geometrical design, if any, for the considered nuclear power plant (NPP).

**Research limitations/implications:** The presented research results may be considered preliminary; thus it may be useful for a design upgrading of the reactor vessel and for achieving a first evaluation of the real components capacity to bear dynamic loads in particular in the event of a severe earthquake.

**Originality/value:** From the point of view of the practical implication, it is worth to stress that the safety of liquid retaining nuclear structures subjected to a seismic loading is of great importance in regard to the hydrodynamic forces caused by sloshing and impulsive liquid motion determined by the liquid filling levels oscillatory phenomenon.

**Keywords:** Numerical techniques

## 1. Introduction

The thin-walled shell has many applications in engineering such as underground pipes and outer shells of submarines, which are usually subjected to a pressure loading. When designing those structures one should consider not only the strength problem in service, but also their buckling capacity under various pressure loadings. When thin shells are subjected to external pressure, the collapse is generally initiated by yielding, which is often the dominant factor, but the interaction with the instability is meaningful too because it could reduce the load bearing capacity by an amount of engineering significance; thus the classical elastic solution to determine buckling load, like Timoshenko and Gere approach [1], appears to be not completely adequate from a practical application point of view. Moreover some geometrical and material parameters, such as the diameter-to-thickness ratio D/t, Young's modulus as well as yield stress in the circumferential direction, may influence in a relevant way the collapse behavior.

The current paper deals with buckling issue related to a thin heavy metal coolant reactor vessel arising from the interaction between fluid-structure coupling, in particular in the event of earthquake. In fact, the safety of liquid retaining structures subjected to a seismic loading is of great importance in regard to the hydrodynamic forces caused by sloshing and impulsive liquid motion determined by the fill levels containers oscillatory phenomenon [2].

In the considered application a selected configuration was used to perform the different analysis significant for the specified field of interests in the dimension range of next-generation reactor eXperimental Accelerator Driven System (XADS).

## 2. Structure and model description

The analysis of the liquid sloshing is thus very important in many engineering applications as in the field of Nuclear Power Plants (NPPs) structures, to evaluate the real capacity of dynamic loads bearing and related safety levels as NPP integrity of structures, systems and components must be ensured in particular also in the event of a severe earthquake [3]. Heavy metal primary coolant, which characterizes pool type NPPs, responds to seismic dynamic motions and some rather “violent” waves can form and impact into the tank walls [4].

In the considered XADS reactor, the reactor vessel contains a large amount of heavy primary coolant that is the lead-bismuth eutectic (LBE) and may become more susceptible to the seismic sloshing. XADS reactor type, showed in the Fig. 1, is characterized, from a mechanical point of view, by the relevant coolant and their own weight to which the structures are submitted. The reactor vessel (RV) is filled with about 2000 tons of liquid LBE that have to be transferred through the annular structure to the reactor building foundations making them the most critical objects in the mechanical components design, in particular during seismic conditions.

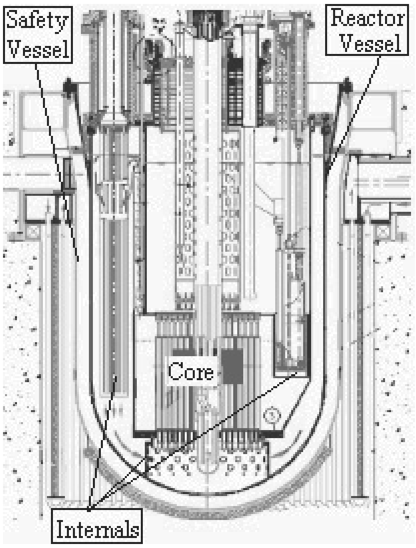


Fig. 1. XADS reactor assembly

In this paper a preliminary analysis is carried out to evaluate the influence of the dynamic loads, derived from the seismic sloshing that may arise severe enough to cause serious damage of the considered reactor vessel, due to buckling phenomenon, more relevant than in light water reactor. The first task in the proposed structural modelling approach is to develop suitable fixed-base finite element (FEM) models of the XADS reactor structure and its main internals, in as much detail as it is necessary to define adequately the seismic response at all desired locations for both system and fluid. To the purpose of determining the dynamic (or seismic) buckling the first step has been to study the above mentioned sloshing waves effects. Therefore seismic analyses accounting for the fluid-structure interaction have been carried out adopting the Time History approach to determine the pressure behaviour inside the reactor [5] to compare with those obtained with the appropriate buckling simulation on the same structure. It must be pointed out however that realistic prediction of both phenomena are made particularly difficult by non-linear nature of each considered phenomena and by the large number of parameters affecting them, such as tank geometry, liquid-fill height, etc. for sloshing, or the diameter to thickness ratio, as well as yield stress in the circumferential direction, etc. for buckling.

### 2.1. Sloshing phenomenon

Generally the analytical approaches, even if explored by several investigators (e.g. Faltinsen), are not adequate to describe and predict in a realistic way sloshing motions and their hydrodynamic effects, due to the non linear characteristics of the oncoming steep waves. It is very difficult to determine theoretically the intensity of impulsive pressure when the mass of heavy coolant impact on the internals and reactor vessel walls, as a result of sloshing, hence numerical evaluation and assessment are necessary [6].

To the purpose of this study a system constituted with three mutually interacting components were considered: the reactor vessel, the submerged structure, as, for example, the core barrel and its support and the fluid too.

The reactor vessel is composed of a cylindrical shell with a hemispherical bottom head. Its upper part is divided into two branches by a “Y forged piece”: the inner cylindrical branch supports the reactor cover and the outer conical one that transfers the whole weight of the RV to an annular support. The reactor roof ensures component support, reactor cover gas containment, and the biological protection. As afore-mentioned due to the reactor vessel height (Fig. 2), the large dead weight of lead and free surface of the heavy molten coolant, seismic loading and sloshing may become very important. The present paper investigates numerically free surface sloshing in RV with a focus on moving tanks mainly due to horizontal excitation, having peak ground acceleration and duration equal to 0.6 g and 12 seconds respectively (applied at the support of the considered reactor) and assuming the fluid inside the vessel as incompressible, not viscous and irrotational. The basic assumptions for both fluid and structure problems are the following ones:

- The fluid has an elastic, linear, isotropic behaviour;
- The RV, Safety Vessel and Internal structures have a linear elastic perfectly plastic as well as isotropic behaviour;
- The fluid and structure exchange mechanical energy at the fluid-structure interface.

Seismic loading, due to LBE sloshing effect, may produce stresses exceeding the allowable limits in localized parts of the reactor Internals.

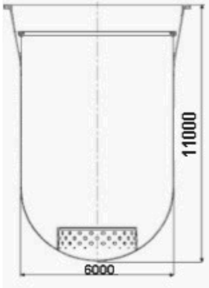


Fig. 2. Reactor vessel – vertical section

It maybe worthy to note that in the carried out preliminary analyses the fluid movement inside the vessel is due to the ground accelerations (impulsive pressure) as well as to the liquid surface displacement (fluid pressure) and tank deformation (due to the fluid pressure itself) [7].

## 2.2. Buckling formulation

Buckling phenomenon occurs when most of the strain energy, which is stored as membrane energy, can be converted into bending energy required by large deflections. As for the theoretical solution, cylindrical shells analysis in absence of torsion and bending moments, before buckling, under a homogeneous pressure, may be performed solving the elastic differential equation:

$$\frac{D}{h}\nabla^{8}\omega + Ek_{x}^{2}\frac{\partial^{4}\omega}{\partial y^{4}} + 2Ek_{x}k_{y}\frac{\partial^{4}\omega}{\partial x^{2}\partial y^{2}} + Ek_{y}^{2}\frac{\partial^{4}\omega}{\partial x^{4}} - \\ + \sigma_{x}^{(0)}\nabla^{4}\left(\frac{\partial^{2}\omega}{\partial x^{2}}\right) - 2\sigma_{xy}^{(0)}\nabla^{4}\left(\frac{\partial^{2}\omega}{\partial x\partial y}\right) - \sigma_{y}^{(0)}\nabla^{4}\left(\frac{\partial^{2}\omega}{\partial y^{2}}\right) = 0 \quad (1)$$

where $\sigma_{x}^{(0)}, \sigma_{xy}^{(0)}, \sigma_{y}^{(0)}$ are the initial membrane stresses; $k_x$ $k_x$ are the curvatures in x, y direction; ω is the buckling deflection in the z direction; *E* is Young's modulus, $D = Eh^3/[12\,(1-\nu^2)]$ is the bending stiffness; ν is Poisson's ratio; *h* is the thickness of the shell [8].

As mentioned for the sloshing treatment, the linear analyses were inadequate to the purpose of determining the critical loads and describe the buckling phenomenon, so a nonlinear analysis is required. In the present work a nonlinear three-dimensional finite element model (MSC.MARC FEM code) was set up and used to describe adequately the bifurcation instability phenomenon. This formulation has been adopted successfully (its reliability has been widely proven by a comparison with an extensive experimental test activity) for predicting the ultimate bearing capacity load for thin shell under external pressure [9-10]. Moreover the assumption of perfect plasticity allowed a better assessment of the effects of circumferential instability.

## 3. Numerical analysis

The XADS structures models described previously, as far as the sloshing seismic effects analysis has been set up with a finite element code (MSC.MARC; the same used later for buckling simulation) while the sloshing effects were simulated by means a commercial code dedicated to shock and impulsive phenomena (Dytran), which used Eulerian hexahedron elements the primary coolant and the cover gas and Lagrangean shell elements for the reactor vessel model (Fig. 3).

The coupling between the fluid and the structure was achieved using the algorithm "ALE" (Arbitrary Lagrangean Eulerian couopling).

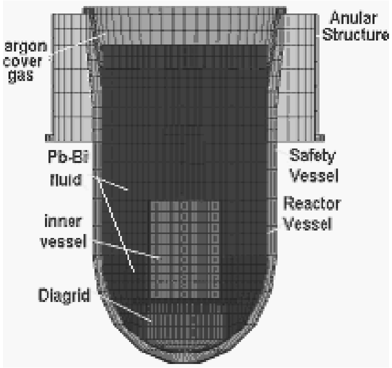


Fig. 3. XADS FEM model – vertical section

It is worthy to note that the carried out (seismic) sloshing simulations, adopting the above showed models, may be considered conservative because not all the internal structures have been set up in this preliminary model. Therefore the fluid is assumed to cover a more extensive region inside the vessel and the obtained stresses might result greater than the real ones.

It is important to highlight that XADS reactor and its internals were modeled in a different way to estimate buckling loads (Fig. 4) by using 20-node solid 3-D finite elements; because shell elements were not adequate to compute the contribution of radial compression. Furthermore, it was assumed that all variables involved in the analyses were constant along the structures length [11-12]. The carried out seismic sloshing analyses allowed helping understand the nature of the internal oscillations and of the developed impulsive wave's pressure during an earthquake.

In the following Fig. 5, the calculated numerical pressure distribution results highlighted that the maximum impulsive value depends on the level of excitation and it does not necessarily relate at the level of the first effective wave maximum eight (at about 0.45 sec.) [13]. The maximum impulsive pressure induced by the dynamic seismic loading resulted at the edge of the core support component, while in the others implemented and analyzed systems the pressure varies from 1 to about 4 MPa. After the occurrence of maximum impulsive pressure, the pressure does not increase even if the seismic excitation continues.

In the studied case the wave height become lower along with increase of internals components in the main reactor vessel. This means, as it might be found, that the presence of inner structures is favourable for stabilizing sloshing [14]. These obtained results have been compared with buckling numerical ones.

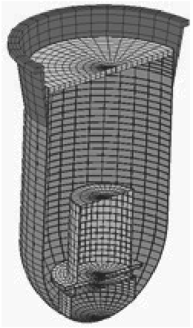


Fig. 4. Reactor vessel FEM model – vertical section

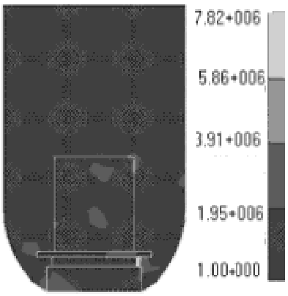
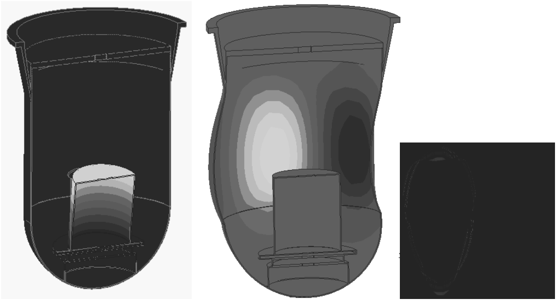


Fig. 5. Maximum pressure behaviour distribution in the fluid region

The buckling evaluation has shown that the deepening of the initial buckle was either a result of a local buckling process, characterized by a local instability and/or of progressive stress-deflection dependence. However, the reaching of a certain depth in the initial on going buckle can lead to the formation of another adjacent buckle, if the material local resistance is larger than the local stress one. The numerical results point out that collapse load level is strictly dependent from the geometrical parameter and characteristics, so the level of the first instability load is found to be less for the considered internals than that of reactor vessel one. Therefore in the following Fig. 6 (a) and (b), there are represented the deformed shapes of set up structures, which are different among each others highlighting the complexity to predict buckling phenomenon in a not simple geometry. Moreover the number of bulges or waves around the circumference is related to the reactor length. In the analyzed structures this number is corresponding to three. The obtained numerical buckling pressure values resulted to be equal to 20.37 MPa for the internals and 34.4 MPa for the reactor vessel. These loads are greater (twice for the internals) than the impulsive pressure induced by the sloshing impact waves, accounting for the seismic magnitude considered.



(a) (b)

Fig. 6. Internals (a) and RV (b) deformed shapes

Furthermore the adopted numerical approach has been validated with a rather extensive literature experimental data on buckling phenomenon with a good agreement between numerical and experimental buckling pressure values [15].

## 4. Conclusions

The present work has investigated, with very preliminary analyses, the plastic collapse behaviour due to seismic dynamic loading of the considered XADS nuclear reactor, as an example. To the purpose the effects of fluid–structure interactions on the stability in particular the sloshing ones have been accounted for.

Analysis and design of the NPP structures involve considerations not only on the available geometry but also on the capability of the most important structural members that transfer the seismic inertial loads from their application points to the internal structures. On the basis of the overall obtained results it is worth to note that the lead bismuth eutectic sloshing pressure is far from the buckling pressure values (20.37 MPa for the internals and 34.4 MPa for the RV) that determine an immediate loss of stability, confirming the structural integrity of the reactor vessel and its internals under the induced impulsive sloshing pressure.

The performed preliminary analyses highlighted the importance of the interaction between the fluid and the reactor vessel and internals both in terms of the stress level as well as impulsive pressure distribution.

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