

TRANSIENT RESPONSE OF FAST-REACTOR CORE SUBASSEMBLIES TO PRESSURE LOADS A COMBINED ANALYTICAL AND EXPERIMENTAL APPROACH

J. DONEA, S. GIULIANI, H. HOLTBECKER, G. VERZELETTI

*EURATOM — Joint Research Centre, Commission of the European Communities,
I-21020 Ispra (Varese), Italy*

SUMMARY

The licensing of reactors involves the discussion of hypothetical accident situations in the necessary detail. The code validation programme presently performed at J.R.C. Ispra and UKAEA has the aim of developing and validating computer codes for the analysis of primary containment structures. In addition there is also a requirement for reliable tested methods of calculating the response of LMFBR core internals when subjected to large transient loads. Using these numerical tools the analyst should be able to assess the consequences of postulated local accidents and their possible propagation.

The difficulties associated with such a task are due mainly to the coupling of hydrodynamic and structural effects and to the need of an adequate modelling of the various features present in a typical subassembly design.

The intent of the paper is to describe a combined analytical-experimental programme that is being performed at J.R.C. Ispra in the field of subassembly deformation.

From the numerical side, 2D and 3D non-linear dynamic finite element codes are being developed for coupled hydrodynamics structures situations. The structural part of these codes is based on the use of flexural elements in which non-linearities arising from elastic-plastic behaviour and from large-displacement effects are accounted for. As far as the fluid flow phase is concerned, a Lagrangian code is used, since, due to the particular configuration of the subassemblies, the fluid distortions can be assumed to be relatively small. Nevertheless special hybrid elements are used on the interfaces between the liquid and the hexcan walls.

In parallel with the analytical work experiments are performed in steps of increasing complexity to that each component of the computer codes can be adequately tested. The experimental series starts with single internally loaded hexcans in which the pressures, strains and displacements are measured as a function of time. The programme continues by explosively loading hexcans surrounded by one or two rows of water filled subassemblies which are hold together by a rigid heavy ring. This configuration has well defined boundary conditions, which are necessary for code validation purposes. Experiments are also planned in which the fuel element pins and their spacers will be modelled. Comparisons between experimental and analytical results will be presented for a single internally loaded subassembly and possibly for a subassembly surrounded by a first row of water filled hexcans.

1. Introduction

The licensing of nuclear reactors involves the discussion of hypothetical accident situations in the necessary detail. Due to the uncertainties related to the time scales and peak pressures involved in such hypothetical accidents, there is a need for numerical methods of analyzing reactor components when subjected to a wide variety of large, transient loads. In this context a code validation program is presently being performed by the JRC-Ispra and UKAEA with the aim of developing and validating computer codes for the analysis of LMFBR primary containment structures. In addition, there is also a requirement for reliable and tested methods of predicting the response of fast-reactor core subassemblies for a wide range of pressure loadings and time scales. Using such numerical tools the analyst should be able to assess the consequences of postulated local accidents and their possible propagation to adjacent subassemblies.

The difficulties associated with the development of a computer code for transient subassembly deformation are due mainly to the coupling of hydrodynamic and structural effects and to the need of an adequate modeling of the various features present in a typical subassembly design. The validity of a computer code of this type is, of course, highly dependent on the extent of experimental verification. For this reason, a combined analytical-experimental program is being performed at the JRC-Ispra to develop and validate a subassembly accident code.

The computer code is a two-dimensional, dynamic transient code; it is based on a finite element procedure for both its structural and hydrodynamic parts. An explicit temporal integration is used in combination with a lumped-diagonal mass matrix and a direct evaluation of the internal resisting forces in terms of stresses. The structural elements are rectangular beams and the effects of large displacements and elasto-plastic behaviour are included. The hydrodynamic elements are triangles and/or quadrilaterals in which pressure, density and internal energy are assumed uniform. Purely Lagrangian, purely Eulerian and mixed formulations of the conservation statements of mass, momentum and energy are available.

To validate the subassembly accident code, experiments are planned in steps of increasing complexity so that each component of the computer code can be adequately tested. The experimental work starts with the development and calibration of an appropriate line source for plane strain studies of subassembly configurations. An adequate instrumentation must also be selected for measuring transient pressures, strains and displacements. A first series of experiments deals with single internally loaded hexagonal ducts. The programme continues by explosively loading a subassembly surrounded by one or two rows of water-filled subassemblies, which are held together by a rigid heavy ring. This configuration has well-defined boundary conditions, which are necessary for code validation purposes. Experiments are also planned in which the fuel element pins and their spacers will be modeled.

In section 2 of this paper we briefly discuss the method of analysis used in the subassembly accident code. More detailed developments of the finite element equations for hydrodynamics may be found in a companion paper presented at this conference [1].

Section 3 deals with a description of the experimental code validation programme and the associated instrumentation.

2. Method of Analysis

A key issue in the development of numerical techniques for the transient dynamic analysis of fast-reactor subassemblies is the efficiency of the formulation, so that large scale models including material and geometrical nonlinearities and fluid-solid interactions can be economically solved.

Herein, the finite element method has been chosen as a basic discretization technique for both fluid and solid parts. The discrete equations of motion are expressed in the form:

$$([M]\{\delta'\})' = \{F\} \quad (1)$$

where $[M]$ is the global mass matrix, $\{\delta'\}$ lists the nodal components of the velocity and $\{F\}$ represents the total nodal loads including internal resisting forces, eventual contributions due to transport of momentum and externally applied loads. The equations of motion are integrated in time by an explicit procedure combined with a diagonal form of the mass matrix. A central difference technique is employed in which the velocities are computed by

$$\{\delta'(t+\Delta t)\} = [M(t+\Delta t)]^{-1} \left\{ [M(t)]\{\delta'(t)\} + \frac{\Delta t}{2} (\{F(t)\} + \{F(t+\Delta t)\}) \right\} \quad (2)$$

When a purely Lagrangian description is used, the nodal masses are conserved and eq.(2) can be rewritten in the form

$$\{\delta'(t+\Delta t)\} = \{\delta'(t)\} + \frac{\Delta t}{2} (\{\delta''(t)\} + \{\delta''(t+\Delta t)\}) \quad (3)$$

where $\{\delta''\}$ lists the nodal components of acceleration.

The displacement components at moving nodes are then evaluated by

$$\{\delta(t+\Delta t)\} = \{\delta(t)\} + \Delta t \{\delta'(t)\} + \frac{1}{2} \Delta t^2 \{\delta''(t)\} \quad (4)$$

Note that the above integration scheme completely eliminates the usual limitations arising from bandwidth or problem size. Moreover, the efficacy of the combination of an explicit integration procedure with a lumped mass matrix has been amply demonstrated [2]. A major inconvenience of explicit integration schemes is that the time steps must be kept small enough to ensure computational stability. On the other hand, the use of small time increments makes it unnecessary to perform iterations within each time interval to deal with material nonlinearities.

The specific procedures used in structural and hydrodynamic elements are briefly discussed in the next two paragraphs.

2.1 Structural Elements

Because of the two-dimensionality of the code, the analyses are restricted to a horizontal cross section of a cluster of subassemblies. Rectilinear Euler-Bernoulli beam elements are employed to model the subassembly walls. In such beam elements the transverse displacement is assumed to have a cubic variation along the beam, while the axial displacement has a linear variation.

Geometrical nonlinearities caused by large rotations are treated by formulating the equations of motion in terms of convected coordinates, which are coordinates that rotate and translate with the elements. The detailed developments of equations for rectilinear beams may be found in reference [3]. In this procedure, the relationships between strains and deformation displacements in the convected coordinate system of each element are linear, provided the strains can be assumed small. The complexity of nodal force computations is thus greatly reduced with respect to other treatments of large displacement effects. Gaussian quadrature formulae are employed to evaluate the internal resisting forces in terms of convected stresses. Two points are used along the beam length and five points through its thickness.

Elastic-plastic relations of the incremental type are used for material description in connection with the Von Mises criterion of yielding. Use is made of the fact that small time steps are employed, so that the elasto-plastic matrix relating the stress increments to the total strain increments can be evaluated according to the stress state at the beginning of each time interval. Both isotropic and kinematic hardening models have been implemented in the computer code. Reference [4] gives the detailed developments of the incremental elasto-plastic constitutive laws.

2.2 Hydrodynamic Elements

The basic equations governing the flow of a compressible fluid are the conservation statements of mass, momentum and energy. Since the fluid distortions are relatively small in cross-sectional analyses of subassemblies, a Lagrangian description of the fluid motion could be adequate. Difficulties are nevertheless encountered if a purely Lagrangian approach is used for dealing with fluid-solid interfaces, where the tangential velocities can be different for the fluid and the subassembly walls. To avoid the introduction of slide lines, which would very much complicate the logic of the computer code, it has been preferred to link together fluid and solid nodes on the interfaces. As a consequence, transport of mass, momentum components and energy will occur across the boundaries of the interface hydrodynamic elements.

For the above mentioned reasons, the basic finite element equations expressing the conservation of mass, momentum and energy are formulated with reference to a volume, V , whose surface, S , may be moving with an arbitrarily prescribed velocity \vec{w} . The fluid is characterized by a density, ρ , a velocity, \vec{u} , an internal specific energy, i , and a pressure

$p = p(\rho, i)$. As shown in reference [1], the basic equations are obtained in the form

$$\frac{dm}{dt} = \frac{d}{dt} \int_V \rho dV = \int_S \rho(\vec{w} - \vec{u}) \cdot d\vec{S} \quad (\text{mass}) \quad (5)$$

$$\frac{dE}{dt} = \frac{d}{dt} \int_V \rho e dV = - \int_S p \vec{u} \cdot d\vec{S} + \int_S \rho e(\vec{w} - \vec{u}) \cdot d\vec{S} \quad (\text{total energy}) \quad (6)$$

$$\frac{d}{dt} ([m]^e \{u\}^e) = \{P\}^e + \{T\}^e + \{\bar{F}\}^e \quad (\text{momentum}) \quad (7)$$

If it is assumed that V represents the volume of a typical triangular or quadrilateral finite element, eqs. (5) and (6) can be used to update the density and the total specific energy $e = i + \frac{1}{2} \vec{u} \cdot \vec{u}$. We note that if $\vec{w} = \vec{u}$ the equations are Lagrangian, while if $\vec{w} = 0$ they are Eulerian.

The momentum equation (7) has been obtained using the Galerkin process [1]. In this equation, $[m]^e$ is the element diagonal mass matrix, $\{u\}^e$ lists the nodal components of fluid velocity, $\{P\}^e$ represents the internal resisting forces due to the hydrostatic pressure p , $\{T\}^e$ accounts for transport of momentum components across the element boundaries and $\{\bar{F}\}^e$ represents external loads eventually acting on the element boundaries.

The assembly of the element contributions to the global discrete momentum equations follows the usual finite element rules. The nodal components of fluid velocity are then advanced one step in time as indicated in eq. (2).

More details on the computational procedure and, in particular, on the evaluation of transport effects, are given in reference [1].

3. Experimental Programme

3.1 General Purpose

It has already been mentioned that the purpose of the experimental activities is not the modeling of a specific situation in a real reactor, but validating in a step-wise procedure a coupled hydrodynamic-structural code. It is assumed in the programme that explosive events may originate in an individual wrapper and eventually propagate to surrounding structures. It is also considered in the study that a superpromptcritical excursion occurred in the central part of the core and that a large pressure wave impacts on the reactor blanket zones, absorbing part of the mechanical energy released. The code developed excludes at the moment specific studies of heat transfer and of reactivity changes, but concentrates on the problem of structure loading and response.

In order to perform a consistent validation study, the experiments have to reproduce the phenomenological behaviour of the various features present in an LMFBR design. Boundary conditions have to be chosen such that they can clearly be reproduced in the calculations. The knowledge of properties of all components has to be assured. Good quality measurements are essential to reliably compare measured and calculated data.

3.2 Design of Experiments and Experimental Programme

A single hexagonal tube is the most simple and at the same time a representative structure in the reactor core. Due to the fact that the cross section is not axisymmetric, a 3-D approach would be needed to describe correctly the deformations in case of a central loading of the tube. To avoid these difficulties the experiment is designed to produce a 2-D deformation only. The length of the wrapper is reduced to 25 cm and the free ends are allowed to slide along a top and a bottom flange. The cross section of the tube is not reduced in size when compared to the reactor. The loading of the wrapper is supposed to be uniform over the whole length (see Fig. 1).

Once the ability of the code to describe single subassembly deformations has been checked, the study will proceed looking at the deformation of surrounding SAs. As shown in Fig. 2, the test section is mounted between two heavy undeformable flanges which are bolted together. A maximum of two rows of flexible or rigid hexcans can be mounted. The external radial constraint is made of rigid hexagonal beams which are clamped together by the flanges. These studies are, of course, much more complex than the single subassembly test. Pressure waves propagate through the whole system and have to be considered together with fluid flow between and in the tubes. It is expected that the latter problem will demand a separate study oriented towards solving the problem of pressure drop in transient fluid flow through complicated and continuously changing geometries.

3.3 Constitutive Relations for Materials

It should be noted that there is a lack of information on the effects of irradiation and temperature on subassembly material. This situation does not affect code validation in principle but it makes it difficult to define the range of plastic deformation up to which the code should be validated. This limit has been chosen to be about 10%. Beyond that value it is expected that subassemblies would rupture, creating a new geometrical situation which cannot be handled by present code capabilities.

Taking into account the above mentioned limitations, material constitutive laws are determined for a suitable strain rate range. Material samples are taken from hexcans in horizontal and vertical positions. Special care is given to study possible changes of material properties in the corners of the hexcan.

A more difficult question is related to the description of fuel element rods and their spacers. Modeling of each fuel element by finite elements would lead to an unacceptable amount of elements and it is therefore planned to define a constitutive law for spaced rods by performing static and dynamic tests.

3.4 Instrumentation and Data Acquisition System

MQ20 and other piezoelectric gauges are used to measure pressures at the upper and lower ends of the hexcans. Tourmaline gauges (a piezoelectric crystal attached to a wire) are immersed in water or cemented to flexible walls. Their reliability is less good

but they do not, or negligibly, influence the measurement by their mass. Both types of gauges are calibrated in a shock tube before and after each test.

An example of pressures measured with these gauges is given in Fig. 3. One may note that pressures measured on the hexcan wall of Fig. 1 are slightly higher than those recorded on the flanges.

Strain measurements are made with high elongation gauges which are applied to the walls using a special cementing procedure, which assures their resistance to dynamic loads. Inductive methods are used to measure displacements. The tasks for these methods could be defined as follows. Large displacements (10 to 20 mm) have to be measured when following the crushing of a wrapper by external loads. Small displacements (0 to ~ 6 mm) are caused by reducing the space between two adjacent hexcans. The inductive method has been chosen because of its insensitivity to a changing environment (water, gas) which excluded from the beginning the use of capacitive, ultrasound or light beam techniques. The above mentioned measurements of large displacements are easy to be performed. The moving surface changes its distance to a fixed coil which is mounted inside or outside the hexagonal tube. The coil has a diameter of ~ 25 mm and a height of 13 mm. A carrier frequency of 1 MHz assures a frequency response of the system of more than 100 kHz.

In order to perform the change of distance measurement between two wrapper walls, flat helical inductors were fabricated. They are obtained by photoetching a copper plated mylar ribbon. The inductors are cemented like a strain gauge to the surface and have an active diameter of 15 mm and a thickness of 0.125 mm. A frequency response of ~ 15 kHz was obtained. An example of displacement measurement is also given in Fig. 3.

Transient conditioning amplifiers, tape recorders and a computer for digitization are used as data acquisition system.

3.5 Choice and Development of an Energy Source

For code validation purposes the energy source has to be fully understood. One might therefore consider that Composition B (RDX/TNT 60/40) or a low density PETN charges as recently developed in the U.K., would give the best results. Unfortunately, both charges produce pressure time histories which cause stress and strain levels which are beyond those which are expected from UO_2 vapour expansion or FCI. A research programme is therefore underway in order to develop a gas producer which should provide a pre-established pressure time history. Fig. 1 shows the design of such a device. A thick-walled cylinder is filled with a deflagrating explosive. The explosive is fired by a detonator located at one end of the tube. Some ten holes are drilled in the wall of the tube through which the explosion products enter into the subassembly. By changing the thickness of a Pb liner, the pressure rise times can be changed and by varying the section of bolts which hold the tap on one end of the cylinder, the gas release and with it the pressure decay can be changed.

An undoubted advantage of this device is its high flexibility, the need to measure the $p(t)$ law instead of knowing a $p(v)$ law might be considered as less good for code validation purposes.

4. Conclusions

An experimental programme has been initiated to determine the response of fast-reactor core subassemblies to local accidents. Well-defined experiments will be performed in steps of increasing complexity and results from these experiments will be compared with computer-code predictions in order to check the accuracy of the analysis and the validity of the modeling used to represent the various features present in a subassembly design.

It is hoped that comparisons between experimental and analytical predictions for single internally loaded subassemblies and clusters of subassemblies will be available for presentation during the conference.

References

- [1] DONEA, J., FASOLI-STELLA, P. and GIULIANI, S., "Lagrangian and Eulerian Finite Element Techniques for Transient Fluid-Structure Interaction Problems", paper B 1/b presented at this Conference.
- [2] KRIEG, R.D. and KEY, S.W., "Transient Shell Response by Numerical Time Integration", Int. J. for Numerical Methods in Engineering, vol. 7, 273-286 (1973).
- [3] BELYTSCHKO, T. and HSIEH, B.J., "Nonlinear Transient Finite Element Analysis with Convected Coordinates", Int. J. for Numerical Methods in Engineering, vol. 7, 255-272 (1973).
- [4] DONEA, J., GIULIANI, S., HALLEUX, J.P., "Prediction of the Nonlinear Dynamic Response of Structural Components Using Finite Elements", Nuclear Engineering and Design, vol. 37, 95-114 (1976).

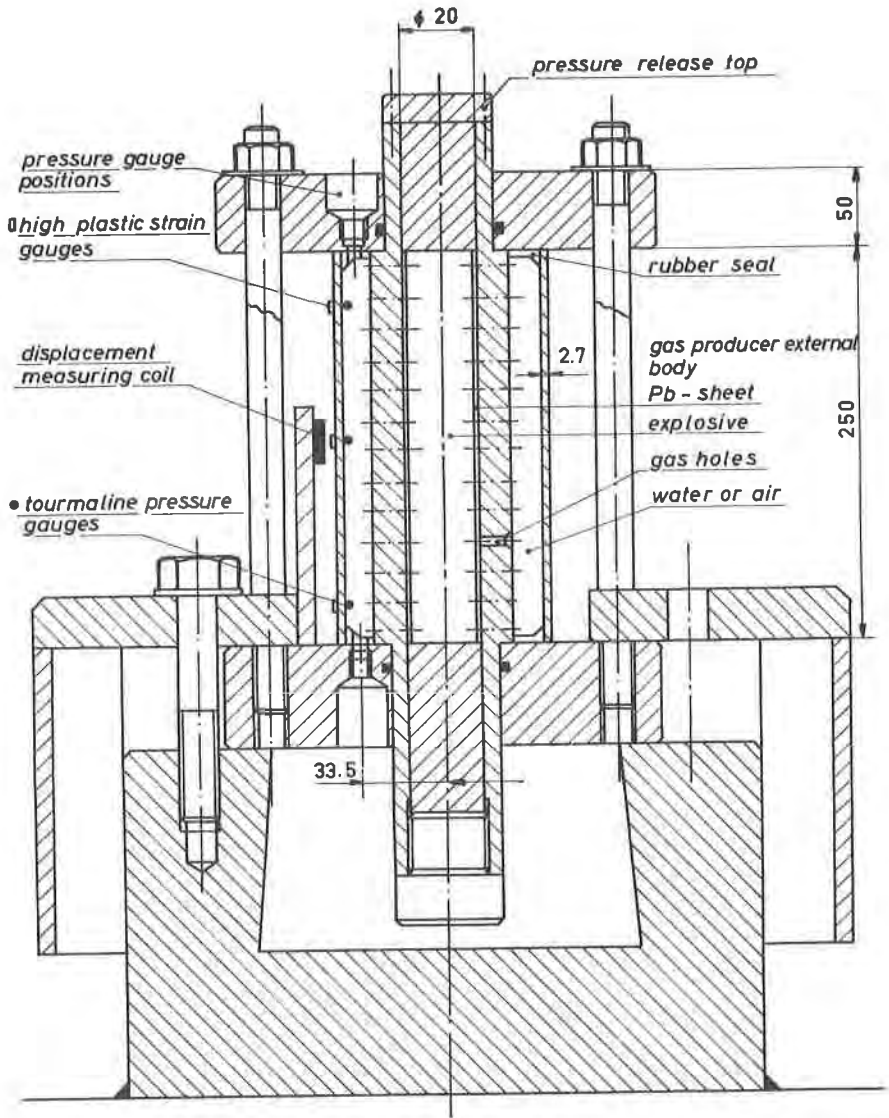


Fig. 1 - Single Subassembly test ring

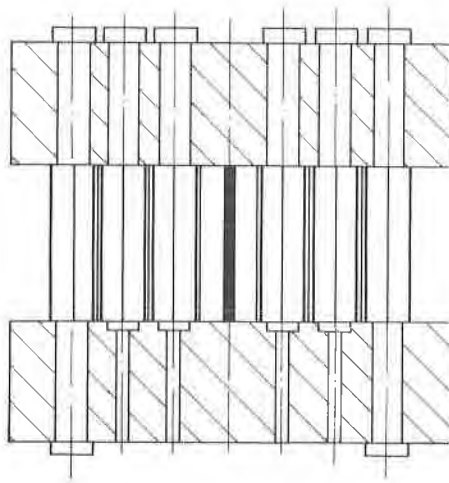
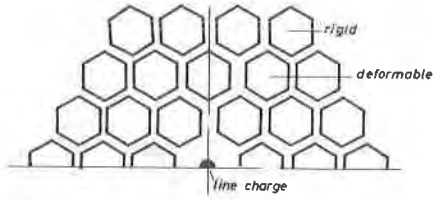


Fig. 2 - Test ring for a Cluster of Subassemblies

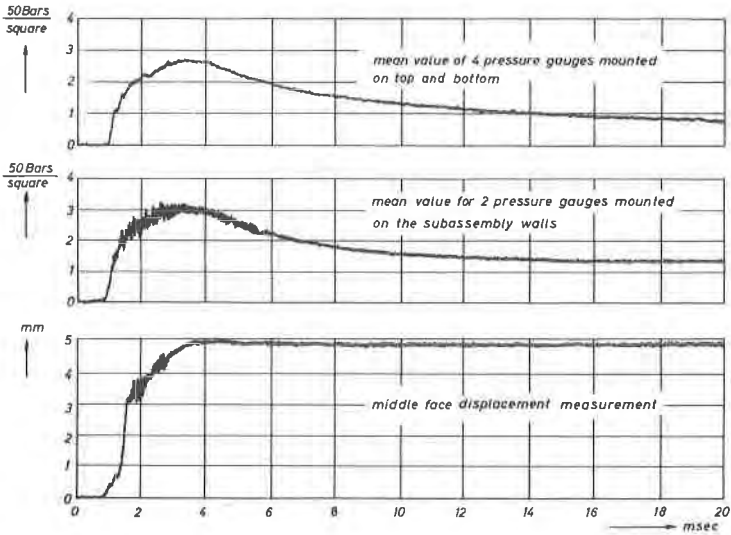


Fig. 3 - Typical Pressure-Time and Displacement-Time Records