Use of PLEXUS as a LMFBR Primary Containment Code for the CONT Benchmark Problem

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INTRODUCTION

The response of the primary containment of a LMFBR to a postulated CDA is often analysed using specialised computer codes. A few years ago, the performance of such codes was compared on a reference benchmark case proposed by the Containment Loading and Response Group (CONT) of the Safety Working Group -- Fast Reactor Coordination Committee of the Commission of the European Communities. The results were summarized by Benuzzi (1987). Recently, the same test problem has been tackled with the computer code PLEXUS, part of the CASTEM system, which is currently being developed by the Commissariat à l'Energie Atomique (CEA) at Saclay (F). PLEXUS is a general-purpose, nonlinear finite-element code which treats fast dynamic problems in structures also in the presence of fluids. The objective was to check its possible utilisation as an easy-to-use and flexible tool for the analysis of this class of problems.

Being a general computer code, PLEXUS contains various models that could in principle be suitable for representing the behaviour of reactor primary containment following a postulated CDA, each one having its own advantages and drawbacks in terms of precision and efficiency. Moreover, it should be pointed out that the code is still under development, and new models are continuously being added and validated. Of particular importance for the subject discussed in this paper are : a) the validation activity performed at ENEA since a few years, which allowed to point out which aspects of the models needed to be improved or further developed and b) the collaboration between the CEA and the Commission of European Communities (CEC), Joint Research Centre, Ispra Establishment. The latter has led to the development of PLEXIS-3C, a joint product compatible with PLEXUS, in which new models for the treatment of compressible fluids and fluid-structure interactions particularly effective for problems such as the CONT exercise were first introduced. These models are now shared by the two codes and therefore are fully available in PLEXUS also.

In the following sections, different approaches to the CONT problem, using various models, will be presented. The calculations were performed over a relatively long period, whenever new models became available in PLEXUS. First, an approach based on the Lagrangian formulation will be presented and discussed, then the improvements realised by an Arbitrary Lagrangian-Eulerian (ALE) model will be shown. Finally, the more sophisticated models included due to the PLEXIS-3C collaboration, still based on ALE techniques, will be considered. It should be pointed out, however, that these are by no means the only approaches to the CONT problem that are possible with PLEXUS. For example, a solution based on an Eulerian model has been obtained recently (Lepareux et al., 1989) and is being published elsewhere.

THE PLEXUS CODE

PLEXUS is, as already mentioned, a general finite-element computer code for the analysis of transient dynamic structural problems also in the presence of interactions with compressible fluids. It can treat problems in one, two and three dimensions and it accounts for various sources of nonlinearity, such as material (plasticity, viscoplasticity, etc.) and geometry (large displacements, large strains). The time integration algorithm is explicit. Three different formulations can be adopted in PLEXUS : Lagrangian (L), Eulerian (E) or Arbitrary Lagrangian-Eulerian (ALE). In the L-formulation the finite element mesh follows the motion of material particles, while in the E-formulation the mesh is fixed and material flows through the elements, thus requiring the introduction of transport terms in the equations. The L-formulation is more generally adopted to describe solids and structures, while the E-formulation is more natural for fluids. In coupled problems, where both structures and fluids are present, such as the one of interest here, both the L- and the E-formulation present difficulties : the L-formulation often leads to very large distortions of the finite element mesh in the fluid domain, if important motions take place. The E-formulation, on the other hand, introduces some difficulties in tracking fluid-fluid interfaces (e.g., free surfaces) and in describing the interaction between fluids and thin structures, that can undergo important displacements.

One possible way to overcome these difficulties is to adopt the ALE formulation for the bulk of the fluid domain. In this case, the mesh is free to move independently from material particles, since transport terms take into account the transfer of material (and energy, and momentum) from one element to the other. The motion of the mesh is actually prescribed by the program via 're-zoning' directives specified by the user and/or by a suitable automatic re-zoning algorithm. Thus, mesh distortion in the fluid can be kept within acceptable bounds. On the other hand, structures and fluid-fluid interfaces can still be treated locally as Lagrangian, which greatly facilitates the tracking of free surfaces for example. This freedom is obtained at the expense of transport terms calculation (as in the E-formulation) and of mesh re-zoning management. For the description of fluid interaction with thin structures, such as the primary containment in the test case, appropriate sliding algorithms can be devised. The reader interested in more details of the formulations and the models available in the PLEXUS (or in the PLEXIS-3C) code should refer to the companion papers (Bung et al., 1989; Casadei and Halleux, 1989).

THE CONT BENCHMARK PROBLEM

The original specifications of the CONT benchmark problem as described by Benuzzi (1987) have been assumed. Fig. 1a shows the model geometry : it is a very simplified model, in real scale, of a pool fast reactor of the SPX-1 type. The reactor roof is assumed to be rigid and fixed and the top part of the reactor tank is clamped to it. The effects of internal structures are schematically taken into account by the internal stainless-steel shield, hinged at its low end. Three fluids, sodium as coolant, argon as cover gas and expanding fuel vapour as a core bubble are contained in the reactor vessel. Their equations of state (see Benuzzi, 1987) are given in Fig. 1b for completeness of problem definition. A bilinear law (Fig. 1b) is assumed for the stainless steel of the tank and of the internal shield. Seven codes participated in the exercise, namely : ASTARTE-4B, CASSIOPEE, PISCES-2DELK, SEURBNUK (JRC), SEURBNUK (UK), SEURBNUK/EURDYN and SIRIUS.

SIMULATIONS, RESULTS AND COMPARISONS

Lagrangian simulation

An early attempt to model the CONT benchmark problem using PLEXUS was performed at ENEA-Bologna (Daneri and Toselli, 1986) by using the Lagrangian formulation. The mesh, based on triangular elements (type TRIA) in the fluid and shell elements (COQU) in the structures is shown in Fig. 2 at the initial (a) and final (b) times. The mesh distortion was, as expected, very large especially close to the inner shield, due to sodium flow around the shield itself, and at the explosive bubble/sodium interface. Nevertheless, the calculation could be carried out until the final time. The overall results were only qualitatively correct : some of them deviated significantly from the average ones reported by Benuzzi (1987) for the seven codes which participated in the original CONT exercise (see Table 1). It should be mentioned, however, that the CPU time needed by PLEXUS in this run was only about 40 minutes compared to, for example, over 4 hours used by ASTARTE-4B on the same machine (an IBM 370/168).

The sodium roof impact time was considerably underestimated, whereas the final tank and shield strains were more accurate (both underestimated of about 10 %). Moreover, the deformed tank presented a cuspid near the axis of revolution, which was not predicted by the other codes (see Fig. 5).

First ALE simulation

Because of the large distortions in the fluid mesh obtained with the L-formulation, it was decided to repeat the calculation by using the ALE formulation. This calculation was again performed at ENEA with an early version of PLEXUS including only limited modelling capabilities as far as mesh re-zoning is concerned. All re-zoning directives had to be 'manually' specified by the user, since an automatic re-zoning algorithm was not available at that time.

A mesh of quadrilateral elements (CAR1) was used this time (Fig. 3a). The final shape of the mesh (Fig. 3b) was more realistic than that obtained with the L-formulation. However, some large distortions were still present locally, due to the limited re-zoning possibilities offered by the manual techniques. There also seemed to be a problem on the axis of revolution, where the calculation appeared to be particularly inaccurate. The final shape of the tank (Fig. 5) was in better agreement than previously with that of the other codes, and the central cuspid was no longer present. The shield hoop strain was improved while the tank hoop strain was still underestimated (Table 1). The roof impact time was now overestimated. The CPU time needed for this calculation was 20 minutes on an IBM 3090/180.

Improved ALE simulation

As a result of the collaboration between CEA and CEC new, more sophisticated models have been introduced recently into PLEXUS for the treatment of fluid-structure interaction problems. The models include : a) a specialised quadrilateral/triangular element for the treatment of compressible fluids, b) an automatic mesh re-zoning algorithm for the ALE domain that can be used in conjunction with pre-existing manual re-zoning facilities and c) models for fluid sliding at the interface with structures. The models for fluid sliding are actually of two types : ALE sliding, for the permanently submerged parts of the model and Lagrangian sliding for the others. All these models result from JRC's experience in the treatment of safety problems similar to the example described here and were originally developed in the EURDYN series of codes (Donea et al., 1982; Giuliani, 1982). More about these models can be found in the companion paper (Casadei and Halleux, 1989).

The initial and deformed meshes are shown in Fig. 4 : it can be observed that the final mesh is more regular than before in the bulk of the fluid. There are still irregularities, however, at the bubble surface at late times. In fact, the interface between bubble and sodium is treated by the L-formulation and is not affected by the re-zoning algorithm. The final tank deformation is compared in Fig. 5 with the CONT range of solutions. It can be seen from Table 1 that the final deformations, especially those in the shield, are in better agreement than previously. The fact that slightly larger values than the mean from the CONT exercise are obtained is due to the use, in this last calculation, of an improved shell element which takes into account the change in shell thickness under (large) membrane deformation. The final figure (Fig. 6) compares the predicted pull-down loads at the upper support of the reactor tank; the improved ALE result best approximates the maximum value. The CPU time needed for this calculation was 30 minutes on an HP-9000 835s workstation at JRC Ispra.

CONCLUDING REMARKS

A satisfactory solution to problems of the CONT benchmark class can be obtained by a general code such as PLEXUS at comparatively low cost in terms of CPU usage with respect to more sophisticated specialised codes. Although not shown here, the effort for input data preparation is also very low. Further improvements of the results will require more sophisticated modelling of the phenomena, especially of the roof impact.

The only partial successes obtained with early versions show that the CONT problem, despite its apparent simplicity, contains various aspects (e.g., the interaction between the internal, deformable shield and the surrounding fluid, the presence of moving interfaces and of fluid-structure sliding, etc.) which require full understanding and appropriate modelling. The CONT case can therefore be considered a valid and challenging exercise that should be attempted by any code which tackles general fluid-structure problems in fast dynamics.

	CONT CODES			PLEXUS		
	MIN	MAX	MEAN	LAGR.	ALE(1)	ALE(2)
Roof impulse (MN.s) at 150 ms	22.2	26.0	23.5	—	—	12.3
Roof impulse (MN.s) at 250 ms	48.1	54.7	51.9	—	—	53.4
Sodium roof impact time (ms)	114.	122.	116.5	91.5	128.8	129.5
Sodium impact velocity (m/s)	11.3	17.4	13.8	20.7	—	11.5
Max. tank hoop strain (%)	2.9	4.3	3.44	3.0	2.97	3.67
Max. shield hoop strain (%)	2.1	2.8	2.40	2.2	2.5	2.75

Table 1 - Resumé of computed results

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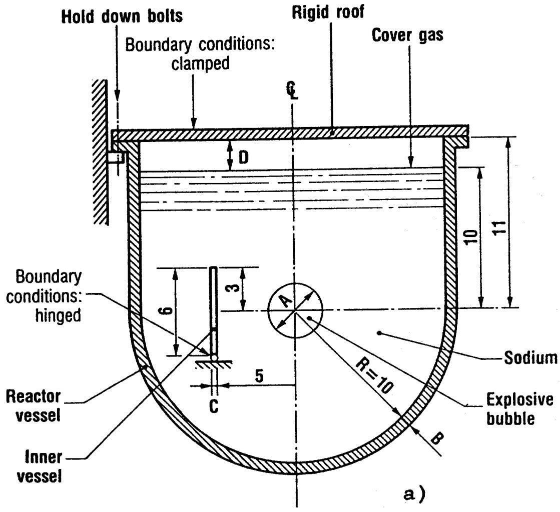

A	1.989	m
B	0.025	m
C	0.025	m
D	1.000	m
Temp.	723	K

Sodium equation of state :

$$\boxed{p = a_1\mu + a_2\mu|\mu| + E(b_0 + b_1\mu)} \qquad \boxed{\mu = \frac{\rho}{\rho_0} - 1}$$

ρ	current density
E	Internal energy per unit volume

ρ_0	832	kg/m^3
a_1	4440	Pa
a_2	4328	MPa
b_0	1.218	
b_1	1.218	

Bubble equation of state :

$$\boxed{p = p_0\left(\frac{\rho}{\rho_0}\right)^{\gamma}}$$

ρ	current density	
ρ_0	2427.8	kg/m^3
p_0	10	MPa
γ	0.75	

Argon equation of state :

$$\boxed{p = p_0\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma_c} - 1\right]}$$

ρ	current density	
ρ_0	0.242777	kg/m^3
p_0	0.1	MPa
γ_c	1.67	

Steel properties :

E	Young's modulus	160	GPa
ρ	Density	7800	kg/m^3
ν	Poisson's ratio	0.333	
σ_y	Yield stress	105	MPa
E_p	Plastic modulus	16	GPa

b)

Fig. 1 - The CONT benchmark problem : a) geometry, b) material properties.

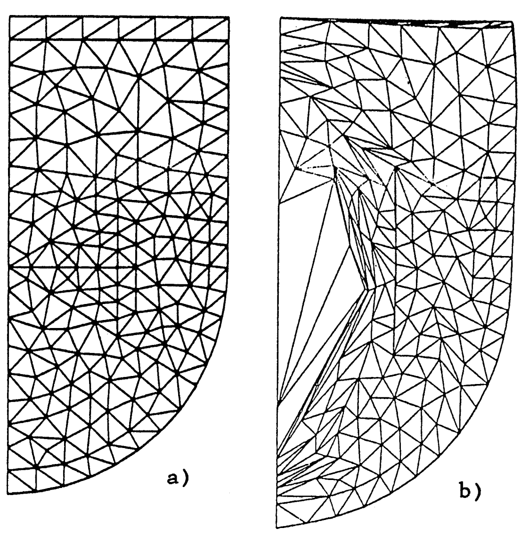

Fig. 2 - Lagrangian simulation : a) initial mesh, b) final mesh.

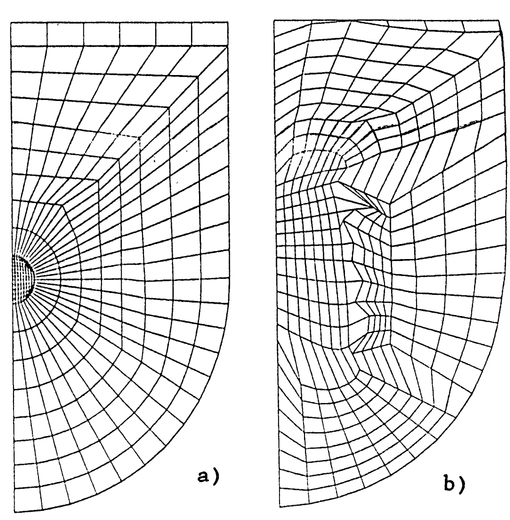

Fig. 3 - First ALE simulation : a) initial mesh, b) final mesh.

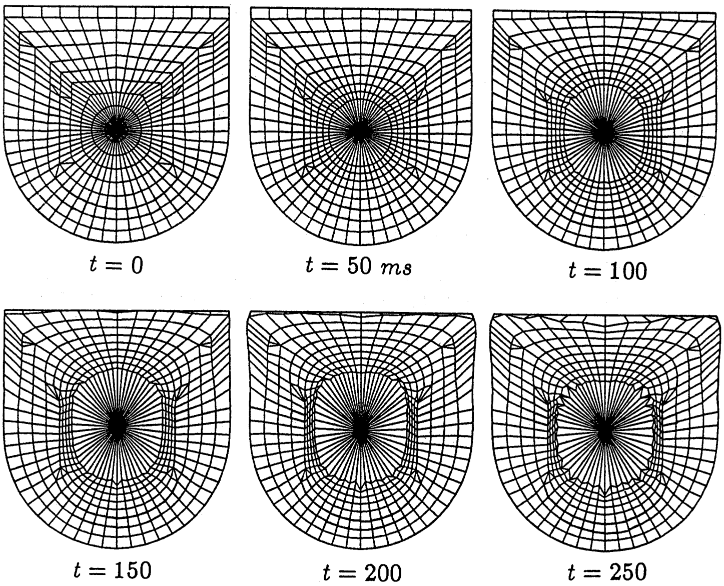

Fig. 4 - Improved ALE simulation : initial and deformed meshes.

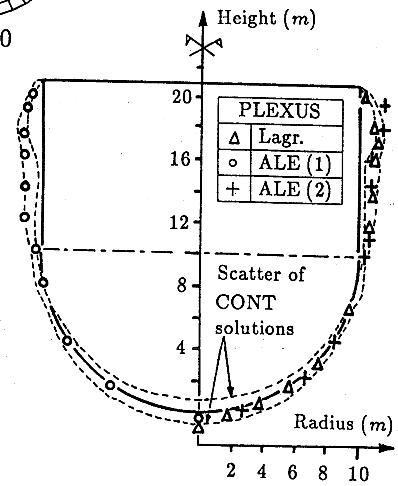

Fig. 5 - Comparison of final tank shapes (displacements magnified 5 times).

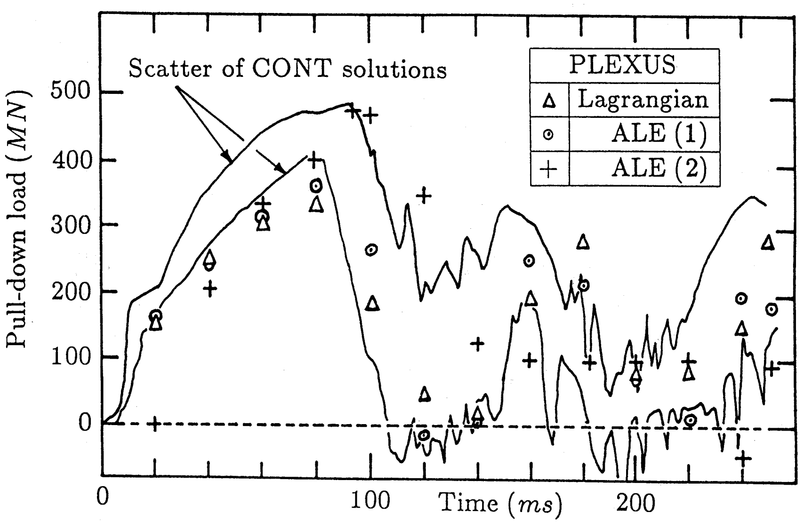

Fig. 6 - Pull-down load histories at the tank support.