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ENGINEERING SAFETY ANALYSIS VIA DESTRUCTIVE NUMERICAL EXPERIMENTS

E. HAUG (RUNGIS)

The paper is devoted to an overview of the numerical analysis of crash, impact, penetration, perforation and explosion problems which may arise in the safety consideration of automotive, naval, aerospace, nuclear and civil engineering industries. It first discusses methodologies as they have been applied to various fields of interest, stressing the success of mixed approaches where initial physical and numerical analyses for program validation are equally important. Modern numerical methods are briefly discussed and typical examples of problems solved in the mentioned categories are also given.

1. Introduction

The term "numerical experiment" encompasses the fundamental changes that problem solving activities in structural engineering and in many other areas have undergone.

It implies the existence of numerical tools, methods and apparatus to be applied directly to the solution of practical problems. The methods solve the mathematical descriptions of the underlying physical realities using the approximation theory and numerical mathematics; the tools are computer programs, and the apparatus are digital computers, harboring the programs and the problem data while performing automatically the necessary digital calculations. The numerical experiment, then, consists in setting up the input data to a program, running it on a computer, obtaining the results and in interpreting them.

The paper focusses on the numerical analysis of crash, impact, penetration/perforation and explosion problems which may arise in the safety considerations of automotive, naval, aerospace, nuclear and civil engineering industries.

It first discusses methodologies as they have been applied to various fields of interest, stressing the success of mixed approaches where initial physical testing and numerical analysis for program validation are equally important when the phenomena are yet unexplored and of great complexity. The paper discusses briefly modern numerical methods and gives typical examples of solved problems in the mentioned categories.

References [2] and [3] contain descriptions of two typical computer codes for the analysis of high speed and low speed phenomena. The first code (HEMP/ESI) uses an explicit finite difference scheme (FD) for the analysis of rapid phenomena and the second code (PAM-NL) uses the implicit finite element method (FE) for low frequency dynamic and static analyses.

2. General overview

Historically, the safety analysis of various categories of structures, buildings, armour, etc. due to a variety of severe loading conditions such as impacting missiles and explosions has been of interest primarily in the military domain.

More and more, however, such problems become preponderant in the civil domain where ever more stringent legal safety requirements, imposed by authorities, call for a detailed knowledge of the performance of a structure beyond its normal functioning into the range of accidental loading conditions, resulting in partial or total destruction. Examples are crashworthiness considerations of airplanes and helicopters in the aeronautical industry; of automobiles, buses, trucks in the automotive industry; the ultimate safety considerations of nuclear power plant piping and containment vessels under the hypothetical and accidental impact of military aircraft, or due to high speed rotation machine fragments, dropping weights, earthquakes or nearby explosions; the crash performance of seagoing vessels and railway trains.

3. Different methodologies

Before elaborate numerical calculations were possible, answers to these problems could be obtained mainly through physical destructive testing.

While this method seems possible in many cases, it seems to pose serious difficulties, for example in the assessment of the potential damage caused by the accidental impact of an airplane at high speed into a nuclear power plant. In order to break loose from the testing-only option, intensive research programs have been conducted in parallel by the military, where testing and numerical methods could be compared to the physical reality and thus be validated.

Once validated, the numerical methods not only allowed through their inherent transparency a much better insight into the high speed physical phenomena, but they also could be applied beneficially to a large number of parameter variations of the same problem and to similar cases, where actual testing might be too expensive.

This mixed approach seems indispensable in view of the great complexity of many high or low speed destructive phenomena, where physical testing can now sensibly be restricted to the exploration of typical accident conditions on idealized structures with benchmark characteristics and where validated numerical methods can take over to make the necessary extrapolation to the ever changing practical constellations of structure, material and loads.

4. Numerical methods

Also historically, the numerical method first applied to high speed dynamic destructive phenomena in military applications was the explicit finite difference method. This method prevails today in high speed impact (penetration) perforation and explosion problems where the physical phenomena are governed mainly by short duration wave propagation and reflection effects inside solids, fluids and gases, and where the structure may become highly distorted.

On the other hand, long duration slow motion dynamic or quasi-static phenomena have been treated using the implicit finite element method invented by structural engineers. This method seems more suited to the ruin analysis of complex structures with low frequency content, where the responses to be studied extend over periods of times way beyond typical material sound wave travel times from one end of the structure to another.

Both methods are based on discretization in space (FE, FD) and time (implicit, explicit). While the FD-explicit methods (as in HEMP/ESI) follow the dynamic evolution of events in discrete time steps of the order of magnitude of the sound wave propagation times between two discrete points in space, the FE-implicit methods work often with time steps many orders of magnitude larger (as in PAM-NL), at the expense of the need for linearization of the governing nonlinear sets of equations of motion and the ensuing need for a repeated solution of perhaps large sets of algebraic equations, resulting also in more complicated software. Today, space and time discretization types are often mixed to obtain, for example, FE-explicit or FD+FE explicit (as in HEMP/ESI) solution schemes.

5. Material description

While workable nonlinear discretization schemes in space and time seem to be available by now, major research efforts still have to be made in the field of constitutive material description at large deformations, rupture, fracture, tearing, folding etc. at low and high deformation rates and at low and high temperatures.

The lack of adequate material description and modelling for high speed destruction processes can be the major obstacle for a successful numerical simulation. Many materials, such as reinforced concrete, exhibit a rather complex constitutive behaviour, and variations in post-peak destruction material modelling may, for example, cause an impacting missile to perforate, rather than to be stopped by a concrete wall slab.

Again, parallel testing and validation of the numerical modelling of the material behaviour seem indispensable before more complex situations can be dealt with numerically.

6. Applications

6.1. *Air plane impact on a nuclear power plant* (*program* HEMP/ESI)

In certain countries nuclear safety regulations require the analysis of this hypothetical accident. Figure 1 shows a military aircraft impacting at a speed of about 200 m/s into the twin reinforced concrete safety containment of a nuclear reactor, causing local stresses and destruction beyond the elastic limit and causing a potentially damaging high frequency response of the containment and the interior of the structure.

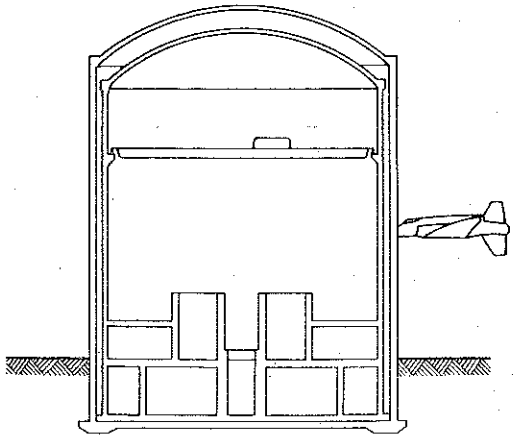

FIG. 1. Airplane impact on a reactor building (v=200 m/s).

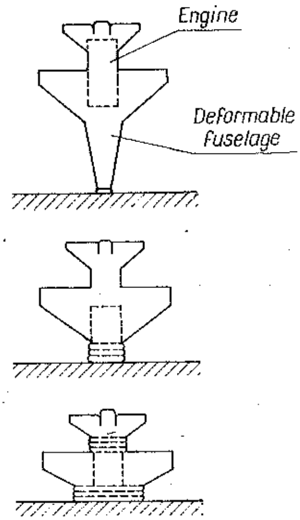

FIG. 2. Actual airplane crash sequences.

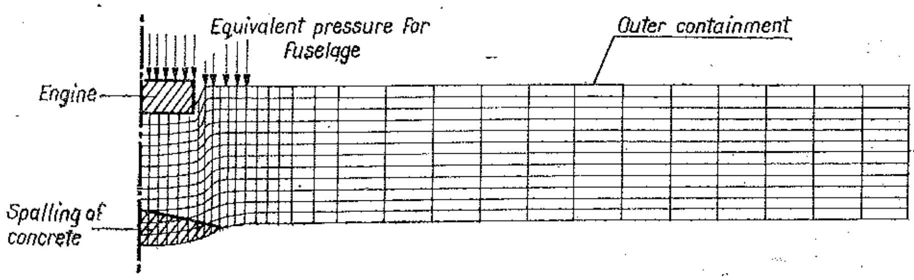

FIG. 3. Simulation of the airplane impact local penetration effects (program HEMP-ESI).

Figure 2 shows the impact of the deformable aircraft into a rigid support, which can be modelled in the computer by an assemblage of soft thin shell elements (fuselage) and more rigid elements (engine).

In Fig. 3 the local destruction of the outer concrete shell due to the engine impact is shown, inclusing high deformations and a spalling of the concrete on the side opposite to the impact point. The inner shell (not shown in Fig. 3) will be loaded through impact of ejected concrete and emerging engine with residual velocity after perforation of the outer shell.

Figure 4 depicts the overall dynamic response of the outer containment and the inner containment, which is loaded after perforation of the outer shell, using an axisymmetric finite element code which allows to consider non-axisymmetric loading via Fourier expansion. The outer and inner shell are loaded near the impact area with the forces found from the previous detailed analyses of the impact, and their response is coupled through the soil and the common base plate. The utilized concrete constitutive model has been calibrated after physical tests where large projectiles were shot onto typical concrete slabs.

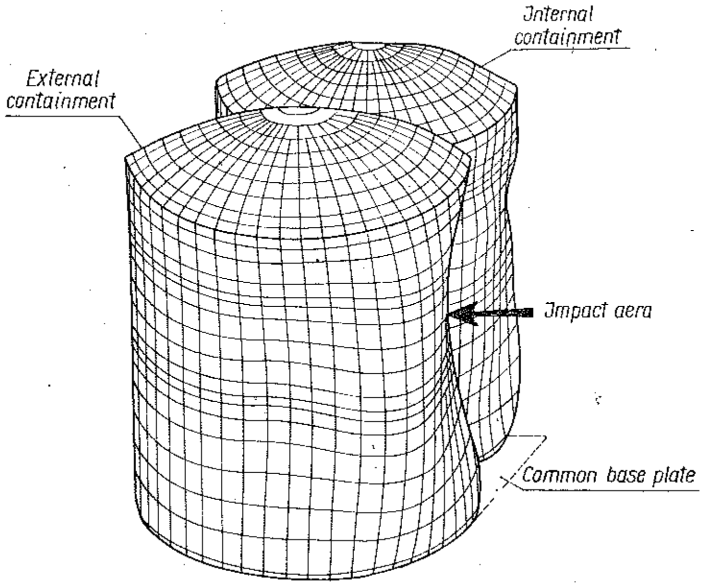

FIG. 4. Simulation of the airplane impact global structural effects on the nuclear power plant containments (program PAM-AX3D).

6.2. Expansion of an energetic gas bubble inside a fluid (program HEMP/ESI)

One of the extreme loading conditions to be considered in the dimensioning of fast breeder reactors is the rapid expansion (simulation time: 200 ms) of a sodium vapour bubble inside the liquid sodium filled reactor vessel. The consequences of this hypothetical accident can be the expulsion of the reactor lid and the disruption of the thin-walled steel containment.

Figure 5 shows the FD-solid zone (for the liquid part) plus the FE-thin shell model (for the containment shell and compartment walls) for the computer simulation which includes the bubble formation simulation and the interaction of the liquid and the deformable thin shell parts. Figure 6 shows the progressive elasto-plastic damage to the structure on a reduced model.

The rheological models and the law of the bubble expansion have been calibrated by applying the program to analyze simple physical tests with known results.

6.3. Numerical simulation of a helicopter crash (program PAM-NL)

The slow impact (10 m/sec) of a helicopter in autorotation on a hard surface can be simulated numerically in two stages. Stage 2 considers a global FE-model of the overall helicopter structure using nonlinear beam/frame type elements, see

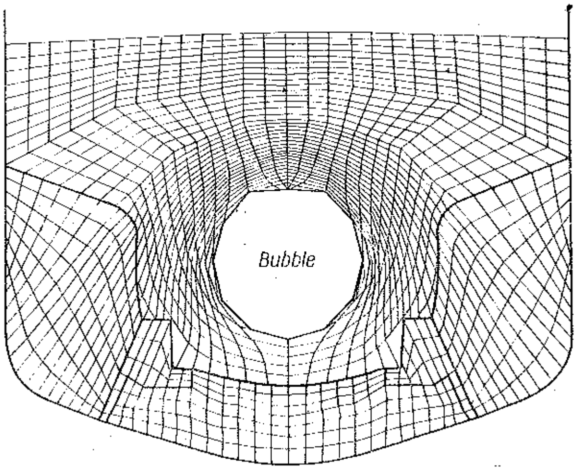

FIG. 5. Rapid bubble expansion in a hypothetical core accident of a fast breeder reactor. Program HEMP-ESI.

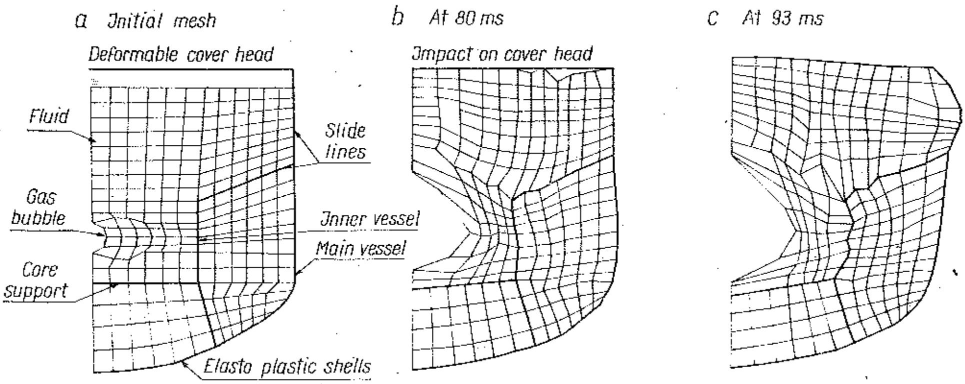

FIG. 6. Sequence of events in bubble expansion analysis (Program HEMP-ESI) of a fast breeder reactor.

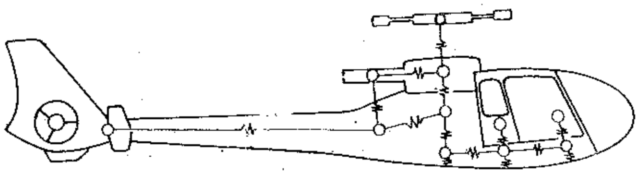

FIG. 7. Overall beam/frame type FE model to simulate a vertical helicopter crash ($v=10$ m/s).

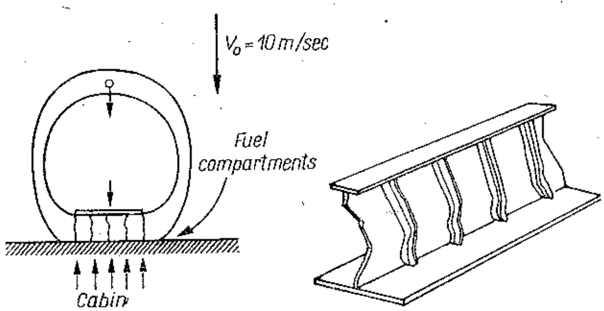

FIG. 8. Energy absorbing aluminum stiffened wall panel fuel compartment cell boxes under the helicopter pilot seat.

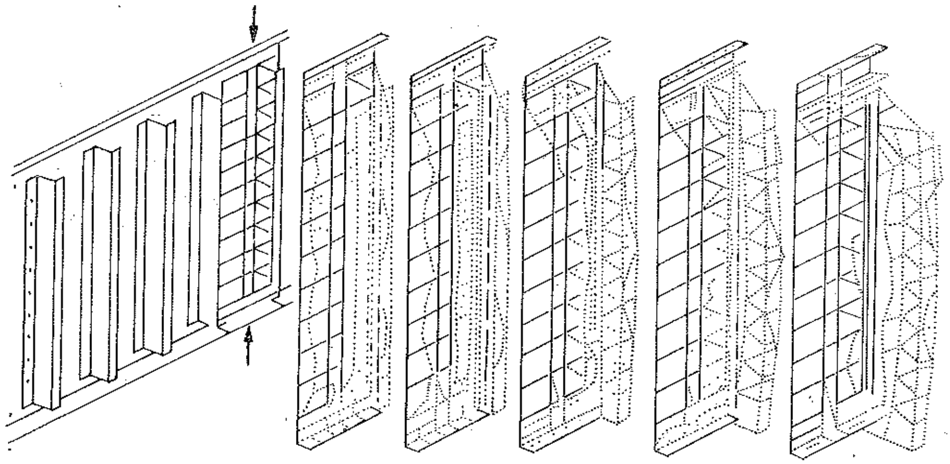

FIG. 9. Detailed nonlinear thin shell FE-model of helicopter.

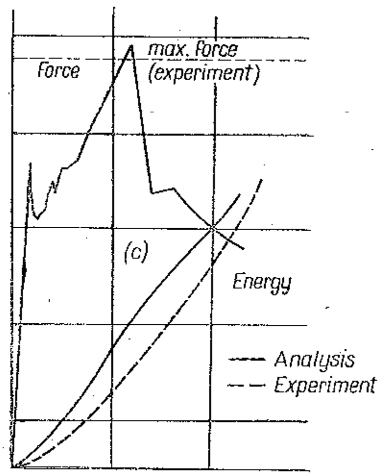

FIG. 10. Predicted energy absorption and peak force of fuel cells for the helicopter crash.

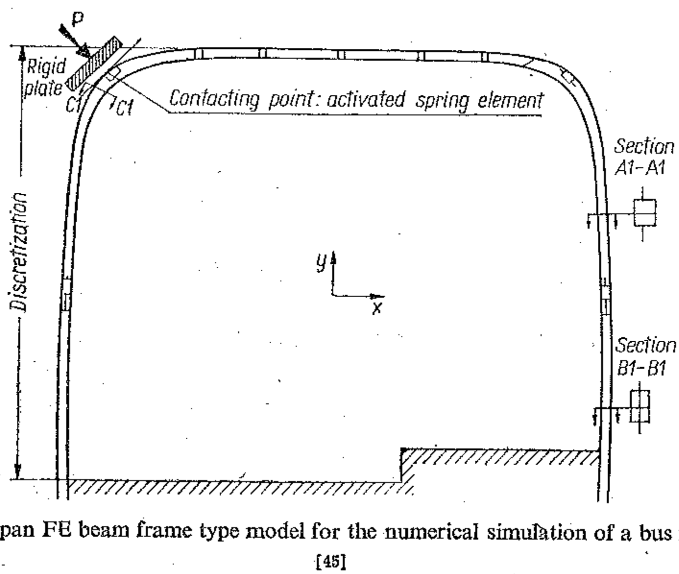

FIG. 11. Bus span FE beam frame type model for the numerical simulation of a bus roll-over test.

Fig. 7. The complex crushing behaviour of the individual elements can either be found experimentally, or, in stage 1 of an analysis, numerically, by establishing detailed numerical models of each component. One set of components vital to the absorption of energy during the crash are the aluminium stiffened fuel compartment cells under the pilot seat, as shown in the sketches of Fig. 8.

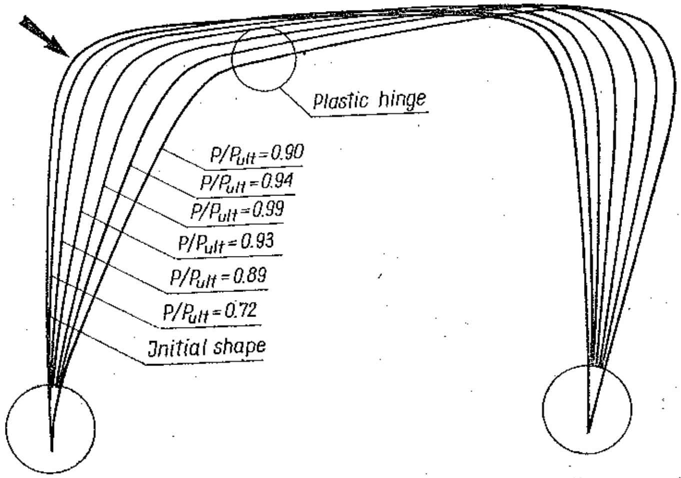

FIG. 12. Actual deformed shapes (magnification=1) of bus roll-over analysis.

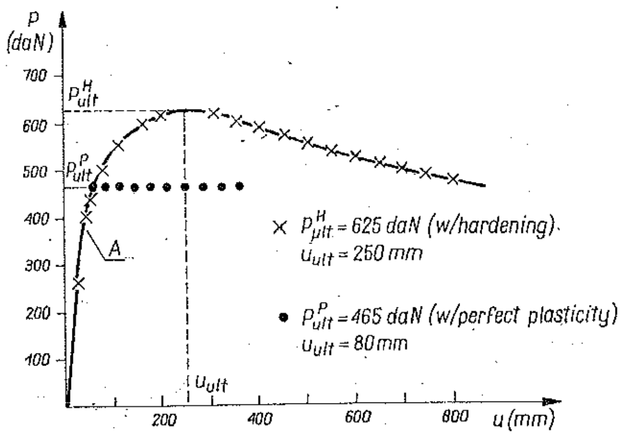

FIG. 13. Load vs deformation curve of bus roll-over analysis.

The quasi-static slow benchmark crushing test of the stiffened walls of those compartements was simulated using nonlinear elasto-plastic thin shell assemblies, as shown in Fig. 9. Figure 10 shows the satisfactory prediction of energy absorption and peak force capacity obtained by the analysis, as compared to experimental curves obtained for the same structure, thereby permitting the replacement of tests by analyses with due confidence.

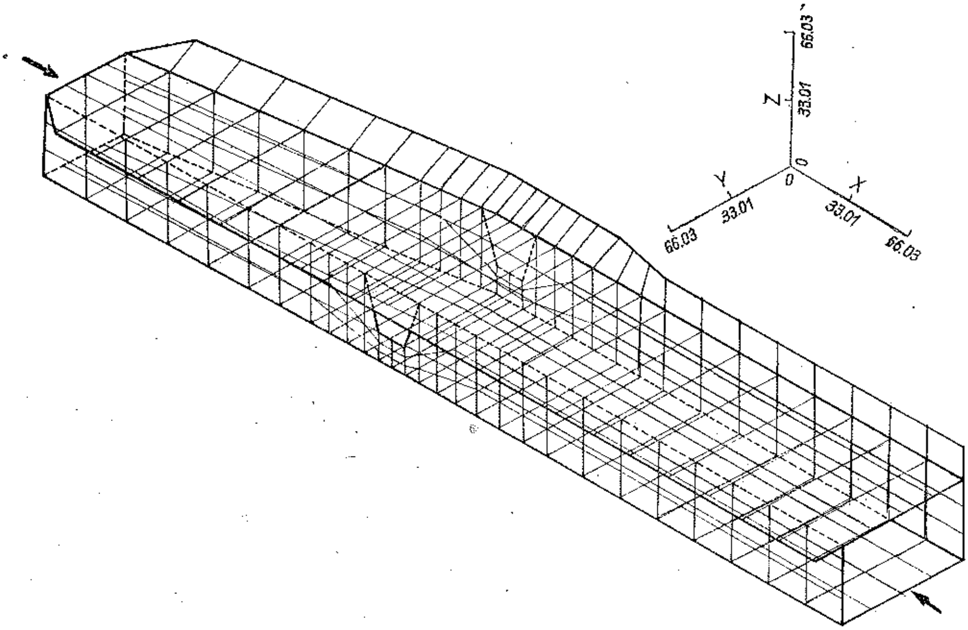

FIG. 14. Detailed thin shell FE-model of an energy absorbing element in the front structure of a passenger car.

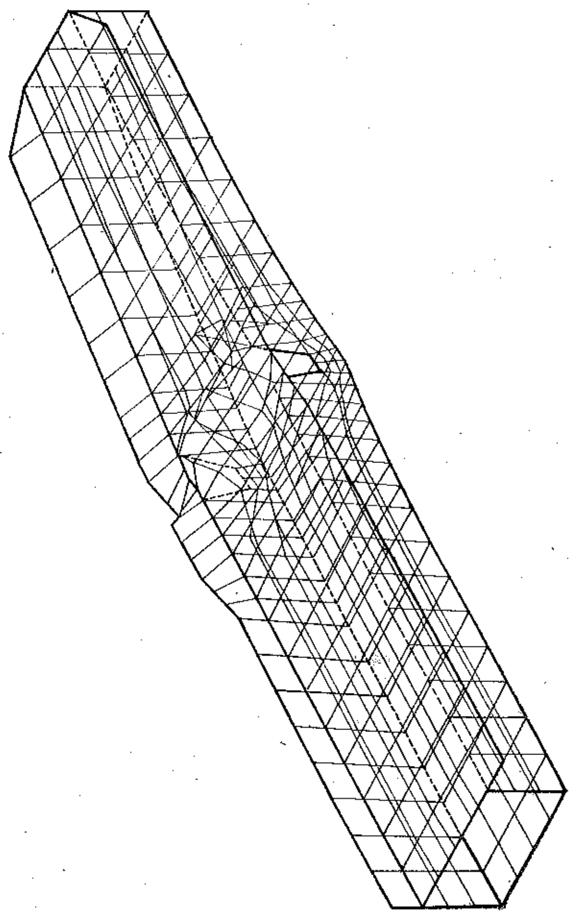

FIG. 15. Deformed element of maximum load carrying capacity, showing local elasto-plastic buckling and subsequent plastic-plastic hinge formation.

6.4. *Numerical simulation of automobile crashes (program* PAM-NL)

Again, two phases are possible in a numerical study of such events, namely phase 1, the numerical evaluation of nonlinear generalized force — generalized displacement (e.g. moment-curvature) relationships in which individual car members are modelled in detail and subjected to crushing loads, and phase 2, the global analysis of an accidental crash event, involving large parts of the overall vehicle structure using, for example, beam/frame type elements, the nonlinear force-displacement (moment-curvature), relationships of which are known from phase 1.

Figure 11 shows a phase 2 analysis of a bus roll-over accident using nonlinear beam/frame finite elements to model a typical bus frame where in the numerical simulation of a test (for validation purposes) a rigid plate is pushed under an inclination of 45° into the corner of the frame. Figure 12 contains the deformed shapes of the frame with the clearly visible plastic hinge formation, while Fig. 13 shows the obtained load-displacement curve.

Figure 14 shows a phase 1 analysis where an energy absorbing beam in the front part of a passenger car has been modelled in detail by nonlinear thin shell finite elements. The model has been loaded via imposed displacements in the axial direction to obtain a maximum predicted axial force resistance within a few percent of the physical tests. The displaced shape of the beam of axial load capacity is shown in Fig. 15, demonstrating local elasto-plastic buckling near midspan and the beginning of the formation of plastic hinges.

7. Conclusion

The successfully analyzed examples and benchmark events demonstrate the feasibility to replace in an increasing manner destructive physical experimenting by destructive "numerical experiments" using modern nonlinear, hydrodynamic and structural analysis programs in combination with high speed computers.

Physical testing remains indispensable for the study of new and complex phenomena, the simultaneous numerical analysis of which permits the calibration of numerical models and the validation of the programs used and gives a better understanding of the tests.

Judicious combinations of testing and analysis is believed to lead to the most powerful and economic engineering safety analyses approach in a wide range of practical problems.

The discussed examples have been elaborated by ESI staff under the participation and leadership of J. C. Bianchini, J. F. Chedmail, J. Dubois, E. Haug, J. F. Levy, J. M. Locci, A. de Rouvray, G. Winkelmuller. The numerical tools used are mostly developed by ESI. The HEMP code originates with Dr Wilkins at the Lawrence Livermore Laboratory, USA.

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3. E. Haug, J. M. Locci, F. A. Arneaudeau, *PAM-NL, A general finite element program for the nonlinear thermomechanical analysis of structures*, 5th Int. Conf. on Structural Mechanics in Reactor Technology (SMIRT-V). Berlin, August 1979.

Streszczenie

INŻYNIERSKA ANALIZA BEZPIECZEŃSTWA ZA POMOCĄ DESTRUKTYWNYCH NUMERYCZNYCH EKSPERYMENTÓW

Praca jest poświęcona przeglądowi metod analizy numerycznej problemów rozbicia, uderzenia, penetracji, perforacji i wybuchu, mogących wystąpić w zagadnieniach bezpieczeństwa pojazdów, statków, samolotów oraz elementów konstrukcji reaktorów. Omówiona jest przyjęta metodologia i podkreślone są zalety podejścia mieszanego wykorzystującego łącznie wyniki obliczeń numerycznych oraz pomiary i obserwacje doświadczalne. Przedstawione są w skrócie nowoczesne metody komputerowe i podane są rozwiązania dla typowych konstrukcji w rozważanej klasie problemów.

Резюме

ИНЖЕНЕРСКИЙ АНАЛИЗ БЕЗОПАСНОСТИ ПРИ ПОМОЩИ ДЕСТРУКТИВНЫХ ЧИСЛЕННЫХ ЭКСПЕРИМЕНТОВ

Работа посвящена обозрению методов численного анализа проблем разрушения, удара, пенетрации, перфорации и взрыва, могущих выступить в проблемах безопасности автомобилей, кораблей, самолетов, а также элементов конструкций реакторов. Обсуждена принятая методология и подчеркнуты достоинства смешанного подхода, использующего совместно результаты численных расчетов, а также измерения и экспериментальные набюдения. Представлены в сокращении современные компьютерные методы и приведены решения для типичных конструкций в рассматриваемом классе проблем.

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