Three dimensional finite difference analysis of a corner drop of Magnox nuclear fuel transport flask

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1 INTRODUCTION

Nuclear fuel transport flask designs have to be tested under various impact conditions in order to demonstrate their capability of surviving similar severe accidents without releasing radioactivity to the environment. Full scale and scale model tests may be performed but these are expensive and time consuming. Instrumentation during the impact event is necessarily limited by the number of channels which can be accommodated and it can only provide information at a discrete number of sites. An alternative is to conduct a numerical analysis of the event and thereby gain greater insight into the various mechanisms that operate during the impact.

The International Atomic Energy Agency Transport Regulations (1985), form the basis of most radioactive material transport legislation. They specify that Type B packages, such as the Magnox flask, must withstand a free drop from a height of nine metres. In this paper a numerical simulation of a drop of a Magnox fuel transport flask from twice this height is reported. The IAEA Regulations require flasks to withstand impacts from any attitude. The attitude selected for this investigation is such that one lid corner first contacts the target, with the centre of gravity of the flask and lid assembly being vertically above the impact point. The target was modelled as a thick steel plate in order to mirror the test conditions.

After describing the problem and the numerical methodology the paper goes on to compare results obtained from the analysis with measured values from an extensive test programme using scale models. In spite of the complexity of the problem close agreement was obtained between the numerical predictions and the measured values, thus validating the numerical procedure as a viable tool for such investigations.

2 PROBLEM DESCRIPTION

The Magnox nuclear fuel transport flask is basically a thick walled steel box and lid with overall dimensions 2.2m x 2.6m x 2.2m. The wall thickness is approximately 0.37m. Cooling fins extend from the front walls. The lid, attached to the body by 16 high strength steel bolts, has shock absorbing features machined into the four corners. The weight of body, lid and bolts is 44 tonnes which is increased during normal transport to 48 tonnes by a skip, fuel and water.

The chosen impact attitude is particularly severe for numerical analysis since there are no planes of symmetry. It should also be noted that the experimental results were not made available to the analysts prior to completion of the computation.

3 ANALYSIS METHODOLOGY

Impact problems are commonly of a short duration and involve very large material and geometric non-linearities. The material non-linearities arise from the high stress levels produced during impact, and the geometric ones from the large deformations produced by these stresses. It is generally accepted that of the solution techniques available explicit time-marching methods are best-suited for the accurate numerical treatment of such problems.

The analysis reported here was performed using PR3D (PML), which is a well-tested commercially available computer program. PR3D is an explicit, finite-difference Lagrange code, based on a central difference scheme in both time and space. The solution procedure treats two basic sets of equations. These are the constitutive equations and the momentum equations. The constitutive equations are formulated incrementally and applied explicitly, i.e. stress tensor increments are computed as a function of stresses, strains, strain-rates, etc. The three-dimensional momentum equations are similarly integrated explicitly on a time-marching basis. The Courant condition for stability imposes a small time-step of integration but this limitation is of little concern in short duration problems. In order to avoid artificial stiffening of the mesh during plastic deformation, as well as hour-glassing problems, a mixed discretisation scheme (Marti and Cundall 1980) has been implemented within PR3D. In this scheme the deviatoric and isotropic parts of the stress and strain tensors are referred to different space discretisations. As a result plastic flow can be modelled accurately whilst inhibiting unrestrained hour glassing modes in the solution.

4 CONTINUUM MODELLING

Once space is discretised, each node represents a small volume of material,and the mass of that volume is lumped at the node. Thereafter the analysis progresses in cycles, each of which corresponds to the duration of one integration timestep.

The element stresses are integrated around all grid points to yield the resultant force acting on the grid point. Other forces, such as body forces or those arising from interactions with other bodies, are also added to that resultant force. The current grid point acceleration is then obtained by dividing the force by the grid point mass. Explicit integration of the acceleration generates the new velocity and position of the grid point. Incremental strains and rotations are obtained from the incremental formulation of the constitutive laws to yield the new stresses. These then lead back to the beginning of the computational cycle.

It should be noted that due to the incremental character of the calculations a linear strain formulation is sufficient to generate the large strain tensors. This is so because the strain increments are individually small, the geometry is continually updated and Jaumann derivatives are implemented.

5 MODELLING OF BOLTS

Bolts are modelled within PR3D with simple structural elements. The threaded part is able to sustain both tension and compression, whilst the unthreaded portion can support tensile forces only. The resistance to shear failure of the bolts is also taken into account by the program. The available constitutive behaviour of the bolts is fairly general and includes elasticity, yield, hardening, failure, as well as different compressive and tensile behaviour.

6 CONTACT LOGIC

Potential contact areas are 'seeded' by providing PR3D with one pair of contacts per mating region of contact area. The program then checks every timestep whether any external nodes surrounding one involved in a contact are themselves involved in contacts. Hence the program will automatically expand the contact interface until it is bounded by nodes with negative penetrations. Contacts can be of the node-to-node, node-to-edge, or node-to-face kind. Once relative velocities across the contact interface have been computed mechanical contact laws can then be applied to generate the local forces of interaction. Whilst the contact laws can be quite general in this application they are elastic in the normal and tangential direction. In the tangential direction, beyond slip they are governed by a friction coefficient

7 NUMERICAL IDEALISATION

The flask body, lid and target plate have been modelled using solid tetrahedral elements. The bolts which hold the flask and lid together were modelled as one dimensional structural elements. Figure 1 shows an exploded view of the flask body and lid as well as the locations of the sixteen bolts. As can be seen the area of contact between the lid and the flask has been modelled with a fairly fine mesh in order to accurately model the interactions here. Further, the mesh has been specially refined in the region of impact in order to adequately represent any shock absorbing capabilities of the lid corner, and this geometry is shown in detail in figure 2. Care has been taken in representing the (flask) wall-lid interface in order to ensure that the maximum design clearance, figure 3, is included in the idealisation. The fins surrounding the flask have not been idealised, but their mass, as well as that of the internal skip and the fuel has been taken into account by lumping masses onto the flask walls and the underside of the lid. Thus the total mass of the flask has been correctly represented as 47.9 tonnes. The mathematical model used in the analysis consisted of 10,701 tetrahedrons and 2759 nodes. 48 structural elements were used to represent the sixteen bolts.

The flask body, lid and target plate are of steel construction, and their material behaviour has been modelled by a strain-rate dependent, non-ideal, elastoplastic law based on a Von Mises yield criterion.

The bolts that hold the lid tight against the flask have been modelled with an elastic, linear-hardening law. The unthreaded section of the bolts was modelled so as to exhibit identical behaviour in both tension and compression, whilst the threaded part of the bolts had the same value in tension, but was unable to take any compression.

The friction coefficient at the contact surfaces between the lid and the flask, and between these and the target plate was taken as 0.15.

Prior to performing the impact analysis, the bolts were loaded to a pre-stress of 200 MPa. These computations were performed using PR3D with appropriate damping added until a static solution corresponding to this loading had been achieved. The attitude of the flask at impact is shown in figure 4. The impact was designed to occur at one corner of the lid, with the centre of gravity of the flask being vertically above this corner. The specified drop-height was 18m, leading to an impact velocity of 18.8m/s.

The initial critical timestep was approximately 3 microseconds, but decreased with increasing deformations at the impacted corner, to a low of about 0.75 microseconds. At late stages of the analysis corresponding to rebound of the flask there was some elastic recovery in the impacted region and this increased the timestep to around 1 microsecond.

8 COMPARISION OF EXPERIMENTAL AND ANALYTICAL RESULTS

A highly instrumented 1/4 scale model of the same type of flask was dropped from 18m. in the lid corner attitude as part of a scalability exercise. The results of this test have been reported (Donelan and Dowling 1985) elsewhere. Several very different parameters have been selected to compare the experimental and analytical results.

Figure 5 compares an accelerometer trace from the model, normalised to full scale magnitudes, with the acceleration from the numerical model at a corresponding position on the flask body. The agreement is good in both the magnitude and transient pattern. The small relative time shift is irrelevant since the time-zero datum is arbitrary. This global behaviour is governed primarily by the local deformation at the impact point which has clearly been well modelled by the finite difference program. The experimental acceleration trace was filtered electronically and the analysis output was filtered numerically to a similar degree. In this way the high frequency oscillations caused by stress wave reflections within individual elements were removed from the raw output of the analysis.

More localised behaviour is illustrated by the relative motion between the flask body and lid during the impact transient. In the model drop test the relative displacement in the plane of the lid and parallel to the flask walls was monitored by displacement transducers fitted in the corner of the body on two adjacent walls. By comparing nodal displacements in the finite difference model at similar positions on the lid and body it was possible to gauge how well the analysis had followed this parameter. Figures 6 and 7 compare the analysis and experimental displacements in two orthognal directions. It should be noted that the magnitude of the displacment is dependent on the distribution of the initial lid-to-body clearance around the lid circumference. This could not accurately be preset in the bolted down condition of the model flask but can be set up accurately in the numerical model. Nevertheless the qualitative behaviour of the lid-to-body motion during the transient can be seen to have been modelled extremely well.

Having investigated global and local quantities during the transient, the final comparisons are with quantities which are measured on the models after the transient has terminated. These are permanent bolt extensions and lid-to-body gap measurements normal to the plane of the lid. Gaps are compared in Figure 8 and bolt extensions in Figure 9. Again the qualitative agreement is very good and it was noted that the highest stressed bolts were still undergoing strain at the time the analysis was terminated, 20ms after impact.

9 CONCLUSIONS

The finite difference program PR3D has successfully analysed the impact of a nuclear fuel transport flask into a thick steel anvil. Excellent agreement between analysis and experiment has been achieved for global and local transient parameters. Good qualitative agreement was observed between typical post-test measurements and the corresponding quantities at the termination of the analysis.

ACKNOWLEDGEMENTS

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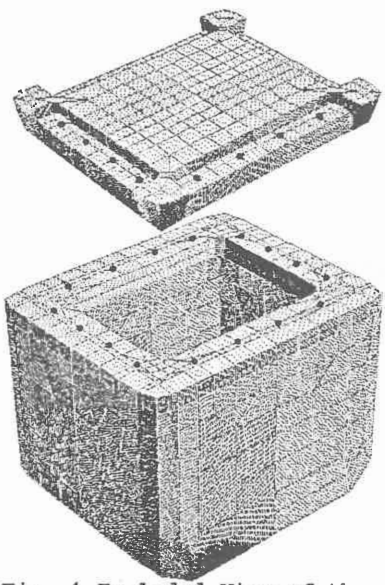

Fig. 1 Exploded View of the Flask Idealisation showing Bolt Locations

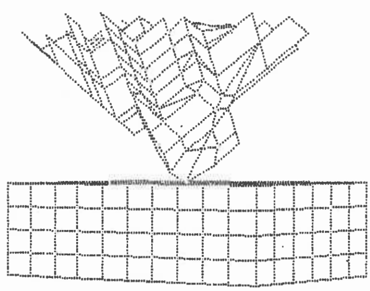

Fig.2 Detailed Discretisation of Impacting Lid Corner

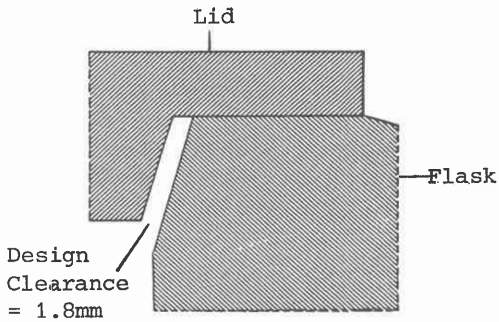

Fig.3 Wall-Lid Interface showing the Design Clearance

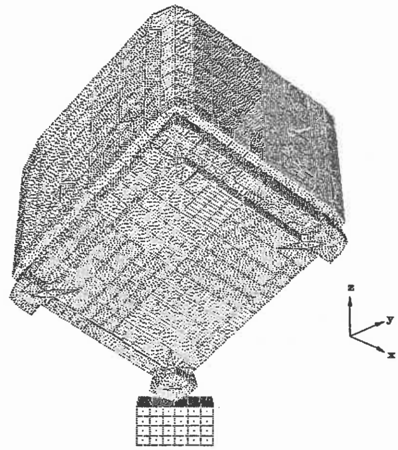

Fig.4 A View of the Flask at Initial Impact

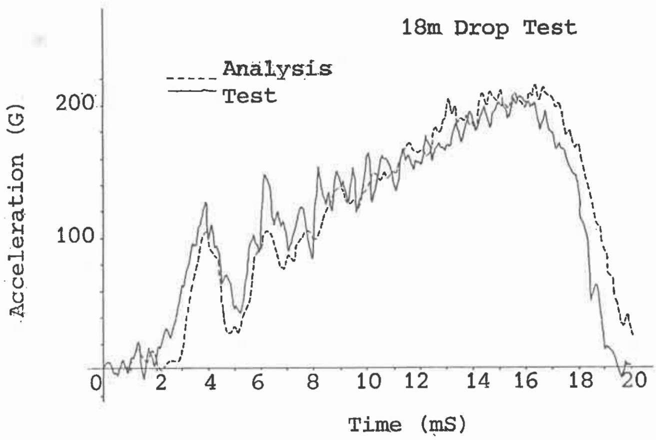

Fig.5 Acceleration Time Histories

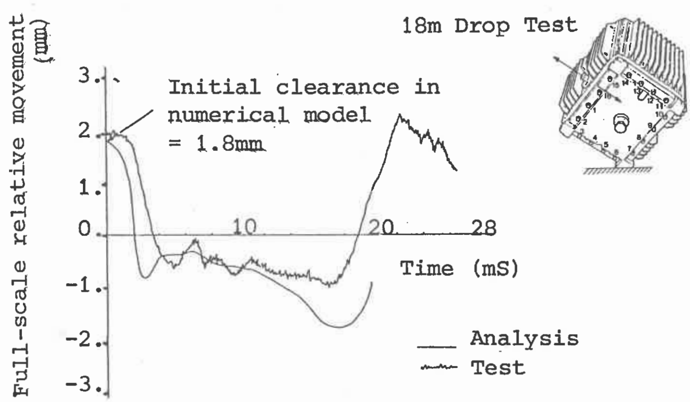

Fig.6 Relative Displacement in the Short Side Direction

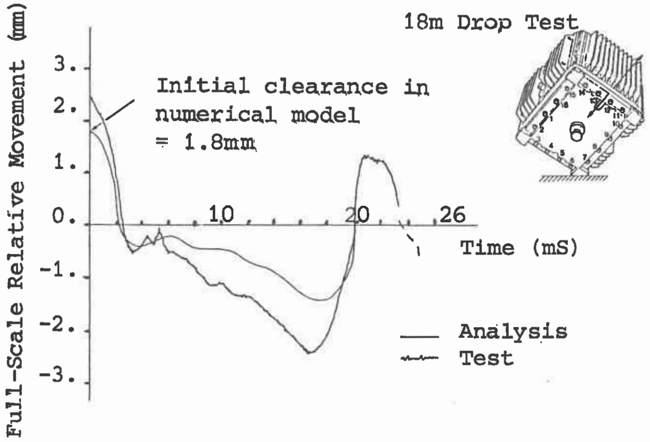

Fig.7 Relative Displacement in the Long-Side Direction

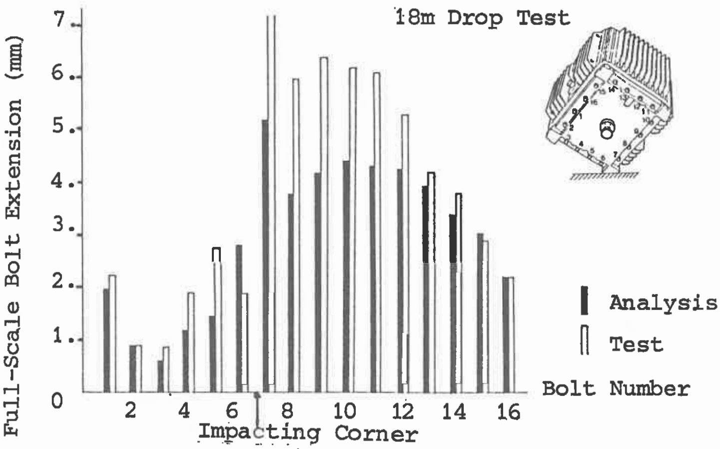

Fig.8 Bolt Extensions

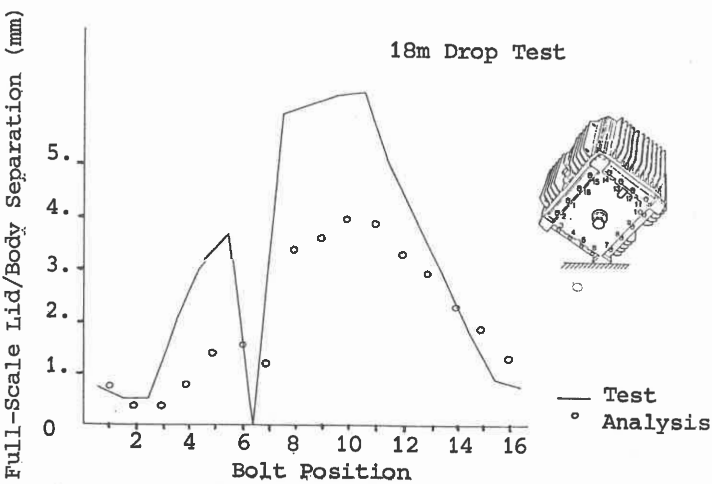

Fig.9 Lid-to-Body Separation