EXPERIMENTAL VALIDATION OF THE EURDYN AND CADROS FINITE ELEMENT CODES FOR THE CALCULATION OF METAL TARGET RESPONSE TO LOW-VELOCITY MISSILES

A. J. NEILSON, P. G. CARTER
UKAEA, Atomic Energy Establishment, Reactor Development Division,
Winfrith, Dorchester, Dorset DT2 8DH, United Kingdom

The Safety and Reliability Directorate, Culcheth, and the Atomic Energy Establishment at Winfrith are undertaking a joint programme of experimental and theoretical work to provide the UKAEA with the expertise to analyse missile impacts on both metal and reinforced/prestressed concrete structures. The experiments and analyses of reinforced concrete structures in this programme of work form the basis of other papers at this conference presented by our colleagues at SRD, NPC and AWRE Foulness.

This paper presents the preliminary results of a series of experiments and supporting calculations at AEE Winfrith aimed at validating computer codes for the calculation of the response of metal targets to missile impacts. The experiments have concentrated on low-velocity impacts with velocities up to 20 m/s that can be achieved by simple drop tests. This regime is of interest in the assessment of a number of hazards arising from either accidental dropping of fuel subassemblies or fuel transport flasks during fuel transfers or from missile generation that might result from a power reactor core-disruptive accident.

In these tests the target thickness has been relatively thin in comparison with the missile diameter and as a result the principal mode of target response has been by bending with varying amounts of shear-punching or panel thinning leading ultimately to perforation of the targets. The experimental results include permanent deflection profiles and transient deflection measurements for the impact of rigid cylindrical missiles on square, circular and triangular target panels. The data obtained will indicate the effects of target support, panel material, missile nose shape and impacts off the centre of the panel. An analysis of the data is presented that provides a correlation between the damage and the stiffness of the target panel.

The computer codes used in this exercise are EURDYN/02 and CADROS/DPS. The EURDYN/02 code was written at JRC Ispra and calculates the dynamic elasto-plastic deformations of plane and axisymmetric structures using an 8-node isoparametric quadrilateral element. The CADROS/DPS code has been written for the UKAEA by staff at UC Swansea and calculates the dynamic elasto-plastic deformations of 3-d structures using a 20-node isoparametric solid element. For the non-circular targets, the standard results of linear elastic theory have been used to define the radii of 'equivalent circular plates' for comparison of EURDYN/02 predictions with experimental results and CADROS/DPS predictions.

Results are presented to illustrate that the EURDYN/02 and CADROS/DPS codes can be used to obtain adequate estimates of the target panel deflections. The expected and observed weaknesses of the codes in their current versions, viz restricted choice of element, no facility for sliding elements relative to each other and no explicit treatment of strain rate effects on material properties, have not detracted significantly from the utility of the codes in this application.

1 INTRODUCTION

Estimates of impact damage can be obtained from either empirical relationships for perforation velocity or from calculations using simplified physical models or numerical integration of the equations of motion for an elasto-plastic missile and target panel. The correlation formulae for perforation velocity can only be applied with confidence to the particular geometry and materials for which they were derived - extrapolation outside the range can lead to substantial errors (see for example the discussion given by White and Botsford (1)). In recent years, there has been an increase in the use of structural dynamics computer codes for estimating the deflections of structures subjected to projectile impact. Some of these codes such as HEMP (2) have been able to calculate complete perforation of the target by the missile. A review of impact calculations at ordnance velocities together with results from two finite element codes is given in reference 3. At the 4th SMiRT conference, Witmer and his co-workers (4, 5) presented comparisons of calculation and experiment for the impact of steel spheres on narrow plates and on circular containment rings. Both papers employed the finite element method.

A small programme of work using metal targets has been started in the UKAEA to investigate the applicability of calculation methods for impact safety assessments in the nuclear and non-nuclear industries. Finite element computer codes are currently in use for other structural safety assessments and two have been selected for initial comparison with experiment. Neither of these codes contain the contact impact logic, or that necessary to allow elements to slide relative to each other, that are a feature of the codes mentioned above. The comparisons presented have demonstrated that for low velocity impact of solid missiles at normal incidence to the target these are not severe omissions.

2 EXPERIMENTAL STUDIES

The objectives of the experimental programme were to obtain a series of measurements of transient and permanent panel deflections for comparison with calculations using simple analytic models and structural dynamics computer codes and also to determine the applicability of perforation velocity correlations in the low velocity regime. The experiments gave some data on the effects of missile size and impact velocity, target thickness and shape, and panel material. The missile in each case was a mild steel cylinder and three shapes of impact face were used, viz flat, hemispherical and conical (half-angle 45°). The impact velocities have been in the region below 20 ms^{-1}. Two materials were selected for the panels EN2 steel and 99.9% aluminium. Both were obtained as rolled sheet in thicknesses varying from 1.2 to 10 mm. Three shapes of target panel were used, square panels having a side of 220 mm, circular panels having diameters of 220 and 127 mm, and equilateral triangular panels having a side of 220 mm. Missile diameters ranged from 25 to 60 mm diameter with masses up to typically 5 kg.

Transient displacement measurements were made by attaching a linear displacement transducer to the target panel at the position of the impact. To provide a firm mounting for the transducer a 6 mm hole was drilled in the centre of the panel. A stud in the transducer's armature passed through this hole and was screwed into an 8 mm thick steel plate on the impact face having the same diameter as the missile. Two types of displacement transducers were used, a simple linear potentiometer and a linear capacitor with maximum possible measurements of 50 mm. The varying voltages from the transducers were recorded on a digital transient recorder and displayed on an oscilloscope. Deflections were measured directly from photographs of the oscilloscope trace. The recording system was triggered externally by a simple contact switch on the impact face of the target.

Post test measurements of the panel profiles were taken by remotely moving a linear potentiometer over the surface of the panel and recording the signal output on a flat-bed x-y plotter.

2.1 Correlation of experimental data on permanent panel deflection

The majority of experiments have used 3 or 4 mm thick targets struck by a 60 mm diameter missile with a mass of 4.28 kg. These panels have shown a linear relationship between impact velocity and permanent panel deflection. From a least squares fit to the data for each panel a minimum of four points spaced over the range of velocities between perforation and elastic behaviour, a velocity V_0 below which there is no permanent deflection has been obtained. This velocity appears to be constant for a given thickness of panel irrespective of shape and size over the ranges chosen. This velocity is not the same for panels of the same thickness but made from different materials.

For elastic plates under central point loadings the maximum deflection is given by an equation of the form $\delta = \alpha a^2 P/D$, (see for example Timoshenko (6)) where 'P' is the load, 'a' is the plate dimension and 'D' is the flexural rigidity, $Eh^3/12\ (1-\nu^2)$, h being the plate thickness. For clamped circular plates diameter 'a' $\alpha = 0.00497$ and for square plates side 'a' $\alpha = 0.0056$. Since we have chosen to make the plate deflections dimensionless with respect to the plate thickness, the parameter $\alpha a^2/(Dh)$ has been used to correlate deflection data. The inverse of this parameter is equal to the product of the stiffness of the panel and the panel thickness and has the dimensions of force.

The relationship between the slope of the deflection-impact velocity curve and the parameter $\alpha a^2/Dh$ for the square and circular panels is shown in figure 1. When all the data are plotted on the same graph there is a marked similarity in the slope of the data for the 3 mm steel and 4 mm aluminium panels in the same range of stiffnesses. The results for the two thicknesses of aluminium panels show a very good correlation, the values of data points being slightly higher than the points for steel. To within ± 15% the deflections for both steel and aluminium panels show a correlation with stiffness varying as the 0.38 power over a stiffness range of 10:1. This error is somewhat greater than the errors (standard deviations) indicated on the data points in the figure suggesting that the correlation is a simplification of the true variations but nonetheless still applicable over this range.

The data for the 4 mm thick aluminium equilateral triangular panels correlated with the data for the square and circular panels of the same thickness if the value of 'α' was set to 0.003 and the value of 'a' was taken as the length of the side of the triangle. These data are not included in the figure.

2.2 Tests with perforated panels

In some of the tests with aluminium panels at these low impact velocities perforation of the panel has occurred. The perforation velocity for the 3 mm aluminium panels appeared to be a linear function of the panel stiffness over a stiffness range of approximately 4:1.

The correlation most commonly used for determining the perforation velocity for steel target panels at relatively low velocities is that derived at the Stanford Research Institute. In no instance did all the geometry parameter ratios in our tests fall within those cited for the SRI formula but in each case the actual perforation energy was lower than the value obtained by extrapolation from that correlation. The experimental conditions are summarised in table 1 and the results confirm the observation made in reference 1 that the formula can be non conservative by up to 50% if applied outside its original range. The greatest deviations from the conditions used to derive the SRI formula occur in the material strength of the panels and the l/d ratios of the missile. The SRI formula was derived for mild steel plates with a nominal ultimate tensile strength of 0.3 GPa (cf 0.11 GPa for aluminium) and perforation energy was assumed to vary linearly with material strength. Further tests in our programme may identify the principal parameter causing the discrepancy between the formula and the experimental results.

3 COMPUTER CALCULATIONS

Calculations for impact problems can be divided into two groups. In the first group only the target is modelled and the missile is represented as a loading function applied at the area of impact. Clearly this introduces the problem of deriving the correct load-time function which will take account of both the behaviour of the missile and the relative motions of the missile and target during the impact. In the second group of calculations, the missile and target are both modelled explicitly and the missile either contacts the panel during the calculation or is initially in contact. Thus the loading on the target takes account of the relative motion of the two bodies.

The computer codes selected for these calculations were EURDYN/02 and CADROS/DPS. Both of these codes use isoparametric quadratic elements which enable relatively large volumes of the structure to be represented by only a few elements without sacrificing too much accuracy. The EURDYN suite of codes was written at JRC Ispra for reactor safety analyses (7). There are three codes in the suite using, respectively, constant strain triangle, isoparametric quadrilateral elements and thin shell elements. Of these the code EURDYN/02 has been selected for missile calculations as the triangular and thin shell elements impose too many limitations on the types of problem that can be considered. The principal limitation incurred with EURDYN/02 is that the problem must be axisymmetric if the missile is to be explicitly represented as part of the mesh (thereby avoiding the problems of devising loading functions representing the impact). The CADROS/DPS code has been written for the UKAEA by staff at UC Swansea and can represent 3-d geometries typically found in power reactors.

3.1 EURDYN/02 calculations

To examine the effect of mesh size and calculation timestep on the plate deflections, initial calculations with EURDYN/02 were made with a load time function to obtain comparisons with the modal solution presented by Goldsmith et al (8) for the elastic response of a flat circular plate to a central point load with a triangular load time history. The calculations showed that

i the accuracy of the calculated deflections is not reduced if only one element is used in the thickness of the plate,

ii within the limits of the Courant stability requirements, a factor of 2 difference in the calculation timestep appears to have an insignificant effect on the results,

iii a mesh aspect ratio of 2.5:1 produced very good agreement with the modal solution for this elastic problem,

iv using a mesh aspect ratio of 10:1 reduces the calculated central deflection by approximately 10% compared to the results using a mesh aspect ratio of 2.5:1.

Following this initial survey, calculations were made for the impact of cylindrical steel missiles on a clamped circular target panel for comparison with the experiments outlined in section 2. Since the EURDYN codes contain no contact-impact logic, the missile was represented explicitly as an element in contact with the panel. The nodes in the missile and at the missile-target interface were given an initial velocity corresponding to that of the missile prior to impact.

Figure 2 presents a comparison of the central deflections for a 3 mm EN2 steel plate 220 mm diameter struck by a 60 mm diameter steel missile mass 4.28 kg at a velocity of 14.7 ms^{-1}. In the EURDYN calculations, 3 elements (aspect ratio ~ 10:1) were used to represent the plate, one element represented the impact washer and one element represented the missile. Two sets of stress strain data were used in the calculations. The 'static' data were derived from experimental data obtained at AEE Winfrith. This is a tri-linear curve joining the - points (0.0, 0.0), (0.196 GPa, 0.001), (0.284 GPa, 0.091), (0.308 GPa, 0.20). This data results in good agreement with the peak deflection of 13.7 mm but the permanent deflection of 10.0 mm is overestimated by 22%. In the second calculation the stress-strain data were adjusted to take account of the average strain rate ~ 4 s^{-1} experienced by the panel during the initial deflection. These data were based on results presented by Manjoine (9) whose 'static' measurements agreed with the Winfrith data. The σ-ϵ co-ordinates used in this calculation were (0.0, 0.0), (0.295 GPa, 0.0015), (0.405 GPa, 0.062), (0.558 GPa, 0.2). The peak deflection in this case was underestimated by some 12% and the permanent deflection by some 3%. Subsequent calculations confirmed that the agreement could not be improved by increasing the number of elements in the plate, in contradiction to the conclusions drawn from the initial parameter survey using the elastic calculation described above. Perhaps the explanation for this result is that once plasticity has been identified small adjustments to the strain values have a very small effect on the energy absorbed by the system. For an elastic calculation, however, small changes in the strain values might be expected to have a significant effect on the energy required to deform the structure.

A calculation for an aluminium plate 4 mm thick and 220 mm diameter struck by the same missile has shown slightly worse agreement with experimental measurement. The peak deflection was underestimated by some 22% (15.9 mm calculated, 20 mm measured) and the timing of the peak was incorrect (calculated maximum at 1.8 ms, measured maximum at 2.3 ms).

The significant point to emerge from these calculations is the comparatively good agreement (calculated deflections within 25% of the experimental measurements) that can be obtained using an extremely simple representation of the geometry and the impact situation. High speed cine photography has shown that the missile and target are in contact until the first minimum following the peak transient deflection. Thus, for the period encompassing the first maximum in the deflection curve, the simple modelling used in the EURDYN/02 calculations is unlikely to be significantly in error.

3.2 Comparison of CADROS and EURDYN calculations for a square target

Using the results of linear elastic theory outlined in section 2, an equivalent circular panel can be devised having the same stiffness and thickness as a square panel. For a 220 mm square clamped panel, the radius of the equivalent circular panel is 116.7 mm. Using this relationship a comparison has been made between CADROS/DPS and EURDYN/02 for a 220 mm square clamped aluminium panel 4 mm thick struck centrally by a 60 mm diameter cylindrical steel missile having a mass of 4.28 kg. The impact velocity was 14.7 m/s.

In the CADROS/DPS calculation a quarter-plate segment using six 3-d elements and a further two elements represented a quarter segment of the missile and impact washer. The aluminium was modelled using a bilinear stress-strain curve joining the σ-ϵ points (0.0, 0.0) (0.1 GPa, 0.0014), (0.378 GPa, 0.2).

In the EURDYN/02 calculation, 4 axisymmetric elements represented the plate and a further two elements represented the washer and the missile. The aluminium was represented by a Ramberg Osgood curve of the form

$$\epsilon = \frac{\sigma}{70 \text{ GPa}} + \left(\frac{\sigma}{0.22 \text{ GPa}}\right)^{9.4}$$

The elastic yield stress was set at 70 MPa and of stress levels above 0.11 GPa the material was perfectly plastic. This was a very close fit to the experimentally measured stress-strain curve. The input data for CADROS/DPS was not able to accommodate such a formula, but the difference between the two sets of data used in the calculations is very small, at a strain of 5% the areas under the two curves differ only by 2%.

The two calculations are compared in figure 3 which shows the plate deflection profiles at 1 ms after impact. The agreement between the two sets of results is very good both directly and diagonally across the plate.

4 CONCLUSIONS

i A correlation between panel deflection and stiffness over a range of 10:1 has been shown for steel and aluminium panels of two thicknesses struck by the same missile. Further data are being obtained to extend the results to a wider range of thicknesses.

ii Data on panel perforation at low velocities have shown that extrapolation of the SRI formula outside the ranges of missile and target panel parameters for which it was derived can lead to results which are non-conservative by a factor up to x 2 in missile energy.

iii For low velocity normal impact of flat ended missiles on flat target panels an extremely simple representation of the geometry and the impact results in comparatively good agreement between finite element calculations and experimental measurements. Future tests will examine the applicability of this modelling at higher impact velocities.

iv The results of linear elastic theory can be used to derive the radii of equivalent circular plates corresponding to square panels. This allows impact calculations to be reduced from three dimensional to axisymmetric geometries when a missile strikes the centre of a panel.

REFERENCES

1 WHITE, R W, BOTSFORD, N B: "Containment of fragments from a runaway reactor", SRIA-113, September 1963

2 WILKINS, M L: "Computer simulation of high pressure systems", UCRL-79591, 1977

3 JONAS, G H, ZUKAS, J A: "Armour penetration: theory and experiment", Invited paper presented at 14th Annual Meeting of Society for Engineering Science, Lehigh University, Bethlehem, Pennsylvania, November 1977

4 SPILKER, R L, WITMER, E A: "Theoretical and experimental studies of the non-linear transient response of plates subjected to fragment impact", paper M7/3, 4th Intl Conference SMiRT, San Francisco, 1977

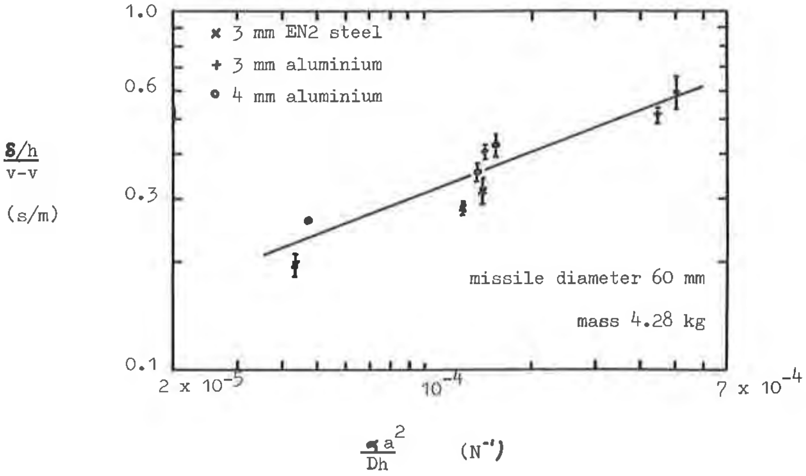
5 WITMER, E A, STAGLIANO, T R, RODAL, J J A: "Non-linear responses of beams and rings to impulse loading or fragment impact", paper M7/4 4th Intl Conference SMiRT, San Francisco, 1977

6 TIMOSHENKO, S WOINOWSKY-KRIEGER, S: "Theory of plates and shells", McGraw-Hill, New York, 1959

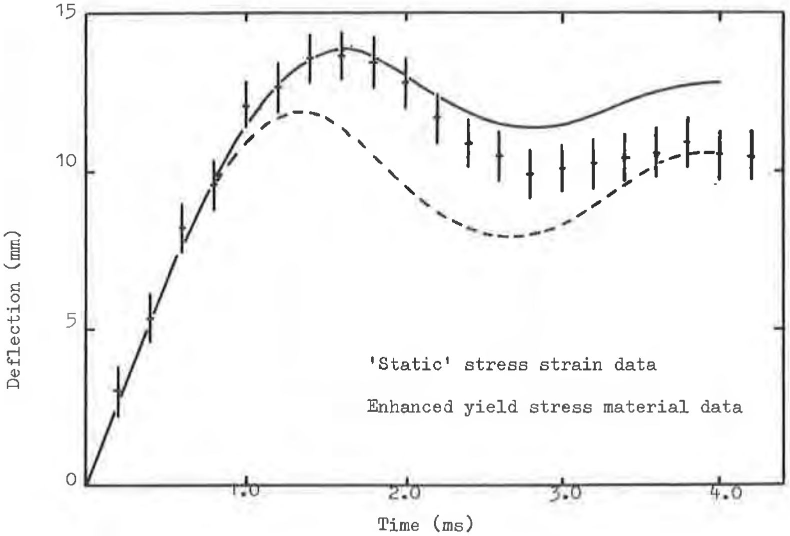
7 DONEA, J, GUILIANI, S, HALLEUX, J P: "Theoretical aspects of the EURDYN computer programs for non-linear transient dynamic analyses of structural components" EUR 5473 e, 1976

8 GOLDSMITH, W, LIN, T W, CHULAY, S: "Plate impact and perforation by projectiles", Exptl Mechanics, 5, 385, 1965

9 MANJOINE, M J: "Influence of rate of strain and temperature on yield stresses of mild steel", J Appl Mech, Trans ASME, 66, A-211, 1944



1 Correlation of permanent panel deflections in terms of panel stiffness



2 Transient central deflection of 3 mm steel plate 220 mm diameter struck by a cylindrical steel missile 60 mm diameter mass 4.28 kg at a velocity of 14.7 m/s

TABLE1: COMPARISON OF SRI AND DROP TEST CONDITIONS

Parameter	Range for SRI formula	Value in drop tests			
		1	2*	3	4
t/d	0.1 - 0.8	0.05	0.58	0.05	0.05
t/l	0.002 - 0.05	0.012		0.016	0.016
l/d	10 - 50	4.0		3.15	3.15
w/d	5 - 8	8.6	3.8	3.66	2.11
w/t	8 - 100		6.6	73	42
V_c,m/s	21 - 122	14.7	14.3	14.5	12.5
Perforation energy kJ/m	theoretical actual	2.5 1.2	38.7 26.1	8.2 5.5	6.0 4.1

* 5.9 kg missile with a cylindrical stub 17 mm dia on impact face

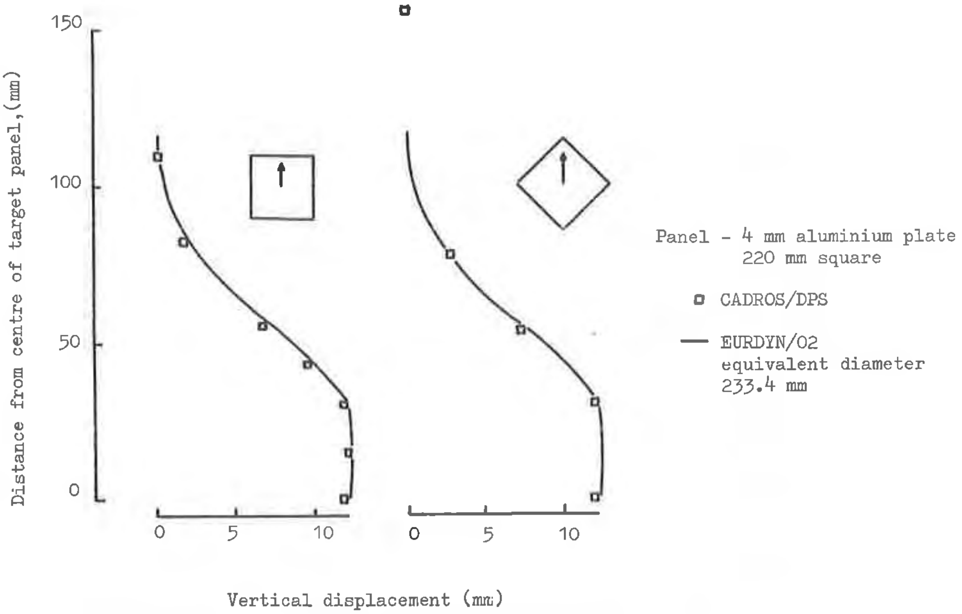
t = target panel thickness

d = missile diameter

l = missile length

w = target panel width

V_c= critical impact velocity



3 Comparison of axisymmetric and 3-d calculations for a square panel