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MODELLING REINFORCED CONCRETE STRUCTURES IN DYNA3D

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SUMMARY

A material model for reinforced concrete has been implemented in the transient structural dynamics code DYNA3D.

This paper outlines the constitutive material model, and presents comparisons of DYNA3D calculations and experiments on impulsively loaded panels, covering the full range of panel damage states from light cracking through to panel collapse or perforation.

The results are presented using the post-processor code TAURUS, which has also been modified to provide mesh diagrams with superimposed crack patterns from the DYNA3D predictions.

1. INTRODUCTION

Over the past decade the UKAEA has engaged in an expanding programme of work on the response of metal and reinforced concrete structures to impact loadings. A material model for reinforced concrete was developed and tested in the finite difference code DRASTIC [1], and this material model has recently been implemented in the DYNA3D code [2], under contract for AWRE Foulness who also supplied the experimental data for code validation of the blast loaded panels in Section 4.

The numerical output from DYNA3D is processed by the TAURUS code [3], to provide mesh diagrams and history plots. The TAURUS code has been modified to draw crack patterns superimposed on the finite element mesh.

This paper outlines the material model, and shows examples of the validation for panels subjected to aircraft impact loads and for blast loaded panels. The examples show that the model can be used to bound the failure loading of the panels.

2. THE MATERIAL MODEL FOR REINFORCED CONCRETE

The material model is described in detail in reference 1. The concrete is treated as a linear material within a failure surface fitted by Ottosen [4] to the available experimental test data. This failure surface is defined in terms of the invariants of the stress tensor, and in principal stress space has the form of a paraboloid oriented on the hydrostatic axis. Figure 1a shows a cross-section in the deviatoric plane, which changes from a smoothed triangle at low pressure to very nearly circular at high pressures. The fit to experimental results can be seen in the Rendulic section in Figure 1b, and the biaxial section in Figure 1c. The material flows plastically as a result of failure in compression, but up to three orthogonal cracks can be formed in response to tensile principal stresses.

After crack initiation, the crack-normal stress is allowed to decay as a linear function of crack-normal extension, see Figure 2a, and elastic unloading from, and reloading to the stress decay path is modelled. A physical stress decay length is input, being determined from experimental measurement of concrete fracture energy, see for example reference 5. Shear transfer due to aggregate interlock across opening cracks is modelled by reducing the calculated crack-parallel shear stress using the parabolic function based on aggregate size, shown in Figure 2b. Both of these stress decay functions employ a crack width, determined from the product of the crack-normal strain and a characteristic length based on the cube root of the element volume.

A single material subroutine updates the elastic concrete and rebar stresses separately, modifies the concrete stresses for existing cracks; checks for further concrete failures and flags new cracks; modifies the rebar stresses for yielding or failure, and finally combines the concrete and rebar stresses to form the total mesh stresses. The total stresses are then returned to the subroutine controlling the solution of the acceleration equations for the nodes.

Additional modifications have been made in the data input and initialisation sections to allow input of the material properties and reinforcement disposition and quantities.

The additional coding is fully vectorised, and calculation times of 60 μs (cpu) per zone-cycle on CRAY-XMP computer compare favourably with times of 20 μs per zone-cycle for the simplest elastic-plastic material models in the standard code.

3. IMPLEMENTATION OF CRACK PLOTTING IN TAURUS

In order to transfer crack information from DYNA3D to TAURUS, a separate 'crack' dump is written by DYNA3D. 16 variables are written for each cracked element: the element number, then for each of three possible cracks; the crack state (decay path), the three direction cosines, and the crack width.

A new TAURUS command 'cracks w' can be used to cause cracks of a minimum width, w, to be superimposed on the deformed mesh diagram. This can be used in conjunction with the simple 'draw' command, or with the full hidden line removal algorithm invoked by 'view'. Only cracks on surfaces can be drawn, as the considerable logical problems associated with 'slicing' through cracked elements have not yet been tackled.

4. CODE VERIFICATION CALCULATIONS FOR BLAST-LOADED PANELS

4.1 TEST 1: BARE PANEL SUBJECTED TO UNIFORM BLAST LOADING

A thin microconcrete slab, 391 mm square and 15.2 mm thick, was supported on the edges of a steel box so that the upper face of the slab was flush with the ground. The corners were held down with clamps attached to the box, and the unsupported span was 366 mm. The lower face of the slab was reinforced to a level of 0.75% each way with 1.63 mm wires at 22.1 mm centres.

Two nominally identical panels with concrete compressive strengths of approximately 28 MPa were subjected to peak blast pressure loadings of 96.3 kPa (14 psi) and 138 kPa (20 psi) respectively.

The calculations simulated one quarter of the panel, taking advantage of the planes of symmetry through the mid-sides of the panel. This assumed the blast to act simultaneously over the whole surface area of the panel, and was justified by the relatively long response time of the panel compared with the short transit time of the blast wave. The corner clamps were not modelled, since the degree of restraint was judged to be small.

The finite element mesh was generated using the I-DEAS package [6], and an interface to DYNA3D written at AEEW [7].

4.1.1 <u>14 psi LOAD CASE</u>

In the experiment the panel survived the blast loading and formed diagonal cracks as expected from the classic yield line pattern for a square slab. This cracking was reproduced in the DYNA3D calculation, which also showed splitting cracks in the central zone of each edge, where the main reaction load is generated.

4.1.2 <u>20 psi LOAD CASE</u>

The loading applied to the upper surface of the panel was represented by the data pairs:

time, ms	0	2	4	6	8	10
pressure, kPa	140	133	127	121	115	111

The calculation was taken to 3 ms at which time the central deflection was 14 mm and the downward velocity was a constant 7 ms^{-1}, suggesting that the panel had collapsed.

Figure 3a shows the crack patterns on the lower surface of the panel for the DYNA3D calculation. The predicted cracks bounding the rectangular central zone had widths of up to 0.5 mm, the plastic strain in the rebars in this region was about half the failure strain. The through-thickness cracks shown in Figure 3b are those having a width greater than 0.1 mm, but the printed output indicates that they do penetrate to the top surface with a width of about 70 μm. The central rectangular zone is clearly predicted to be separated from the remainder of the panel, and is bounded by cracks parallel to the rebar alignment.

The experimental result in Figure 3c confirms this prediction.

4.2 <u>TEST 2: A PANEL WITH SAND OVERBURDEN</u>

A square panel, nominally identical to those used in the previous tests, was supported on a similar steel box buried in the ground with compacted sand overburden to a depth of half the span of the slab. The material properties for a similar sand were obtained from tests carried out at the City University, which showed that its deviatoric behaviour could be described by the simple Mohr-Coulomb failure surface.

The material model used for the overburden in the DYNA3D analysis was the 'soil/crushable foam' model. This provides a generalised Drucker-Prager yield surface, which is cylindrical about the hydrostatic axis. The values of the constants were chosen to force the cylindrical yield surface to lie between the tensile and compressive meridia of the measured Mohr-Coulomb surface.

The blast pressure was applied to the upper surface of the overburden as a uniform pressure described by the following data pairs:

time, ms	0	5	10	15	20	25	30
pressure, kPa	517	400	310	248	193	145	103

Figure 4a shows the displacement histories of the nodes on the lower surface of the panel and upper surface of the overburden, on the centre line of the panel. A peak panel deflection of 21 mm is predicted, and the overburden exhibits compaction by a further 16 mm.

Figure 4b shows the lower surface crack pattern at peak deflection, and clearly illustrates the different mode of response compared with the bare panels. The predominant failures are in the form of shear cracks at the supported edges, and there are no diagonal hinge cracks. The buried panel is predicted to have survived the loading which is approximately four times the failure load of the bare panel.

This result is consistent with experimental findings, and the reason is clearly illustrated in figure 5, which shows the pressure distribution in the sand overburden. Reflection of the initially plane loading wave forms a low pressure region over the majority of the panel. By 2.25 ms a complete pressure arch has been formed over the panel, and this remains throughout the transient. Thus the load is transmitted to the edge of the panel, and a higher pressure loading can be sustained.

5. CODE VERIFICATION CALCULATIONS FOR MISSILE IMPACT TESTS

Three tests are described, representing the full range of damage states expected from soft missile impacts on thin reinforced concrete panels. The panels were all circular, with a diameter of 1800 mm, and their thicknesses were 82 mm, 56 mm, and 40 mm. The each way, each face (ewef) bending reinforcement quantities were 0.125%, 0.7%, and 0.25% respectively. All the panels had nominal shear rebars at 0.003% of the plan area. The panels were built into a massive reinforced concrete ring-beam supported on a steel frame.

Figure 6 shows the finite element structure of the model for the 82 mm panel; similar meshes were used for the other panels. Again, only one quarter of the panel was modelled. The "support spring" shown in the figure is a ring of elastic elements representing the measured stiffness of the support frame.

The loading in the experiments was generated from the impact of a simulated "Tornado" military aircraft, which was made up of a multi-sectioned thin walled alloy tube. It is not practical to model this explicitly in these calculations, and the loading was simulated by applying the known time-dependent pressure loading for the missile to the appropriate element faces in the centre front face of the panel.

The material properties for concrete and reinforcement were taken from test samples for the individual experiments. Concrete compressive strengths varied from 28 MPa to 40 MPa, and the reinforcement yield stresses varied from 328 MPa to 459 MPa.

5.1 TEST 3: 82 MM PANEL

In this test the measured peak deflection was 5 mm, and the post-shot observation of the panel recorded "light radial cracking on the rear face".

Figure 7a shows the deflection histories calculated by DYNA3D at three radial measuring positions, compared with the measured results. The shaded area on the graphs show the range of results from several nominally identical tests. The DYNA3D calculation result shows excellent agreement with experiment, on peak deflection and timing.

Figure 7b shows the deformed mesh at 8 ms, with all fully formed cracks superimposed; there are no cracks on the impact face. The rear face exhibits light radial cracking, and there are very few through-thickness cracks shown in the cross-section. None of the cracks exceeded 0.25 mm in width. These results are consistent with the post-shot observation of the panel.

5.2 TEST 4: 56 MM PANEL

In this test the peak measured deflection was 20 mm, and the post-shot observation of the panel recorded "a small indentation of 1 mm depth in the impact face, and a partially formed circular crack of radius 200 mm in the rear face".

Figure 8a shows the calculated and measured displacement histories at three radial measuring positions; there are two measurements at diametrically opposite locations at each radius, to indicate the symmetry of the test. The DYNA3D calculation gives excellent agreement at all positions.

Figure 8b shows the deformed mesh at 6 ms with all fully formed cracks superimposed. On the impact face there is a small indentation mark defined by a circular crack. The mean radius of the damage zone on the rear face is about 200 mm, although the cross-section shows that the through-thickness cracks do not penetrate the rear face at this radius. Given that there was only partial penetration of the cracks in the experiment, the calculation gives a good prediction of the extent of the damage zone.

5.3 TEST 5: 40 MM PANEL

In this test the panel was perforated by the missile, leaving an elliptical hole of 135 mm X 155 mm on the front face, and a scab of diameter 350 mm on the rear face. The exit velocity of the missile was 65 ms^{-1}, and the measured peak deflection was 9.5 mm at radius 200 mm.

Figure 9 shows the distorted mesh at 9 ms. The central plug is moving downwards at about 50 ms^{-1}, and the bending reinforcement has failed in the central element on the rear face. Clearly the model has predicted perforation of the panel by the missile. The rear face scab is of the correct size, but the region of circular cracks on the impact face is somewhat exaggerated due to excessive bending. Because the total mass of ejected material is a little too high, the predicted exit velocity is slightly underestimated.

6. CONCLUSIONS

A material model for reinforced concrete has been implemented in DYNA3D. The model has been tested for the response of thin reinforced concrete panels subjected to blast loading and soft missile impacts.

The range of test problems covered, for both types of loading, indicates that the model gives excellent agreement with experiments for cases where the damage level is relatively low, and very good agreement at higher damage states. Full panel collapse due to blast pressure loading, and perforation by missiles are also correctly predicted.

The graphical post-processing code TAURUS has been modified to superimpose crack patterns on the deformed mesh diagrams from the DYNA3D output.

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[1] BROADHOUSE, B J. DRASTIC A Computer Code for Dynamic Analysis of Stress Transients in Reinforced Concrete. AEEW - R 2124. 1986.

[2] HALLQUIST, J O. Theoretical Manual for DYNA3D. UCID - 19401. June 1982

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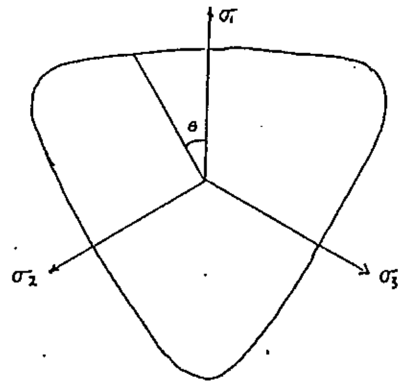
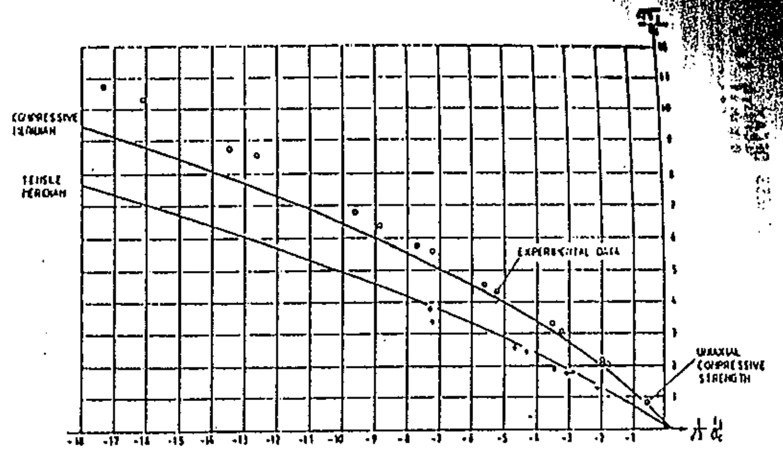
[5] PETERSSON, P E. Crack Growth and Development of Fracture Zones in Plain Concrete and Similar Materials. LUTVDG/TVBM-1006. Division of Building Materials, Lund Institute of Technology, Sweden. 1981.

[6] I-DEAS User Manuals. CAE International, Hitchen, England.

[7] ANDRESS, J C. An Interface between I-DEAS and DYNA3D. AEEW - M 2273. January 1986.



1a. DEVIATORIC SECTION



1b. RENDULIC SECTION

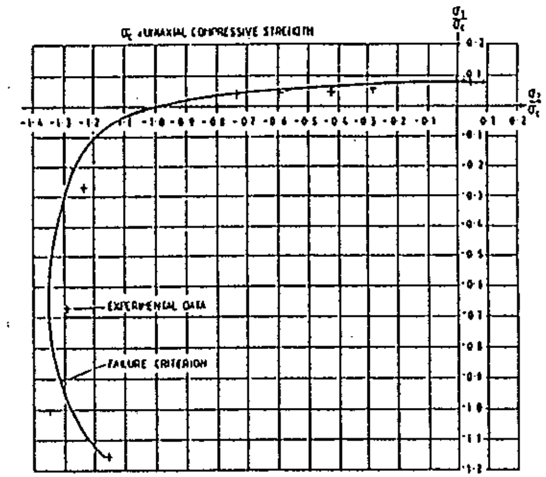
$$A \frac{S_2}{\sigma_c^2} + \lambda \frac{\sqrt{S_2}}{\sigma_c} + B \frac{J_1}{\sigma_c} - 1 = 0$$

where $\lambda = K_1 \cos\left[\frac{1}{3} \cos^{-1}(K_2 \cos 3\theta)\right]$ for $\cos 3\theta \geq 0$

$\lambda = K_1 \cos\left[\frac{\pi}{3} - \frac{1}{3} \cos^{-1}(-K_2 \cos 3\theta)\right]$ for $\cos 3\theta \leq 0$

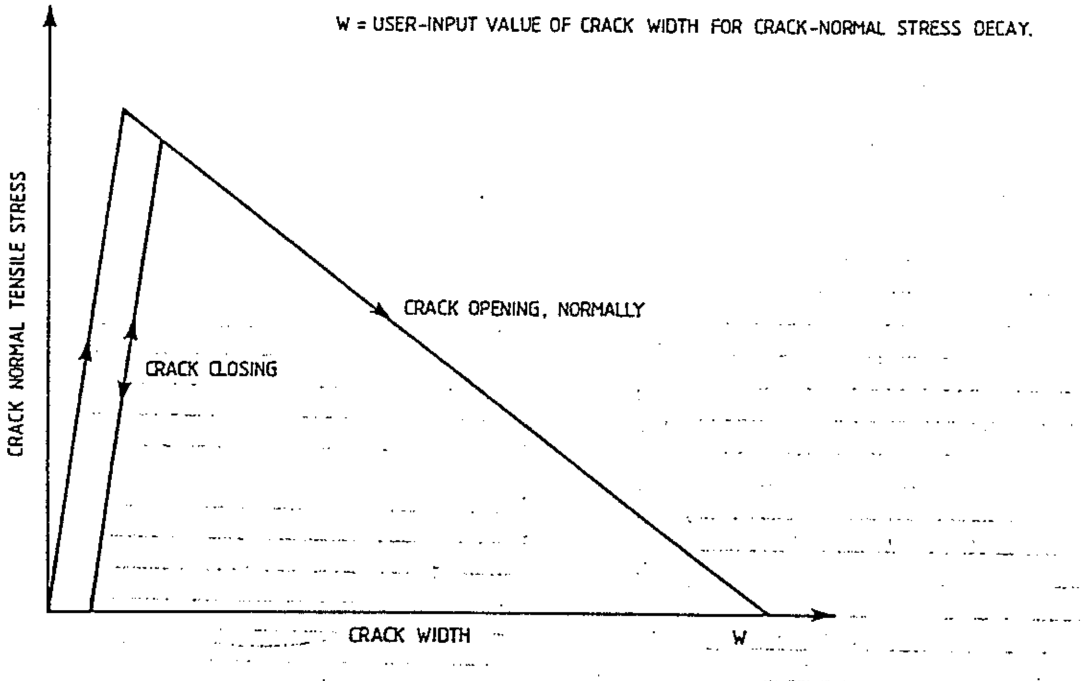
$\cos 3\theta = \frac{3\sqrt{3}}{2} \frac{S_3}{S_1^{1.5}}$

and A, B, K_1, K_2 are functions of $\frac{\sigma_t}{\sigma_c}$

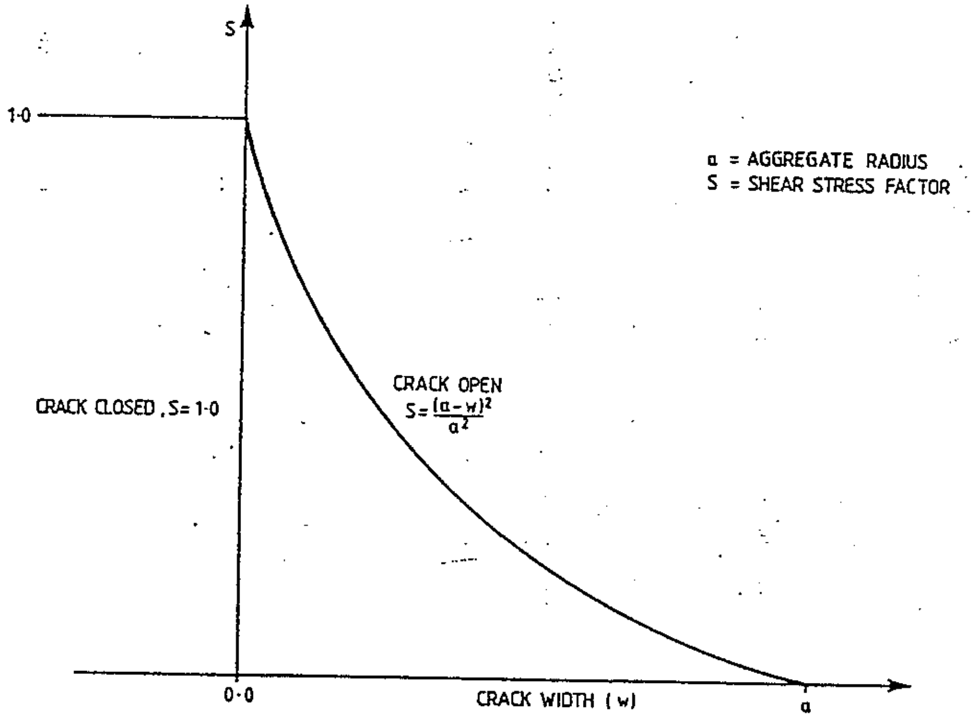


1c. BI-AXIAL SECTION

FIGURE 1. OTTOSEN FAILURE CRITERION FOR CONCRETE



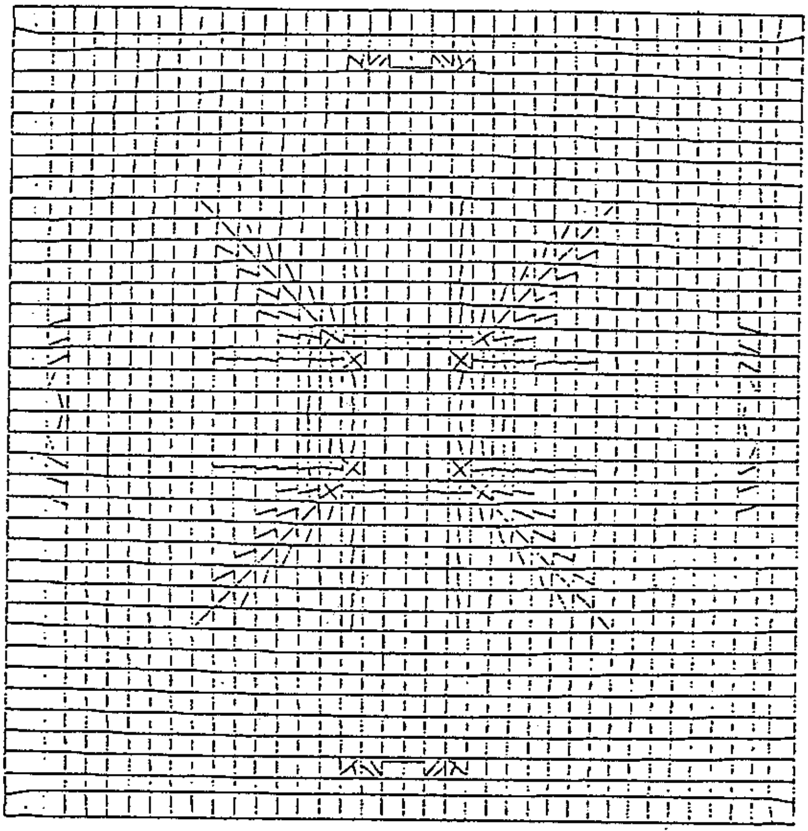
2a. CRACK-NORMAL TENSILE STRESS DECAY ROUTES



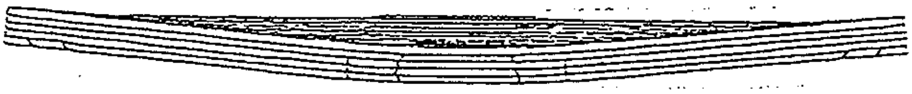
2b. CRACK-PARALLEL SHEAR STRESS DECAY FACTOR

FIGURE 2. POST-CRACKING BEHAVIOUR OF CONCRETE MATERIAL

a) DYNA3D.
(LOWER SURFACE)



b) DYNA3D
(CROSS-SECTION)



c) EXPERIMENT
(LOWER SURFACE)

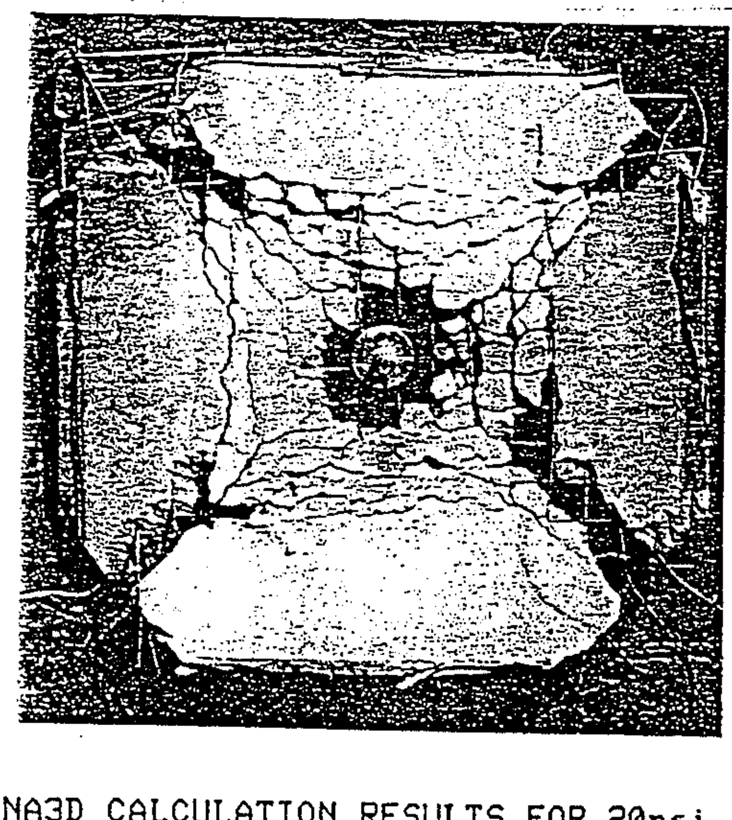
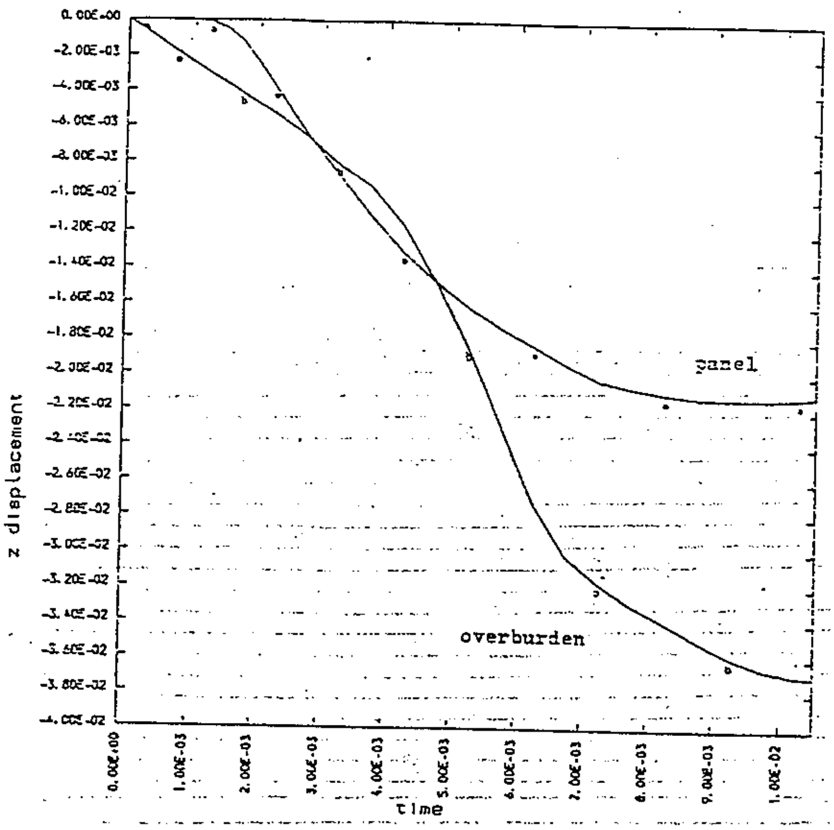
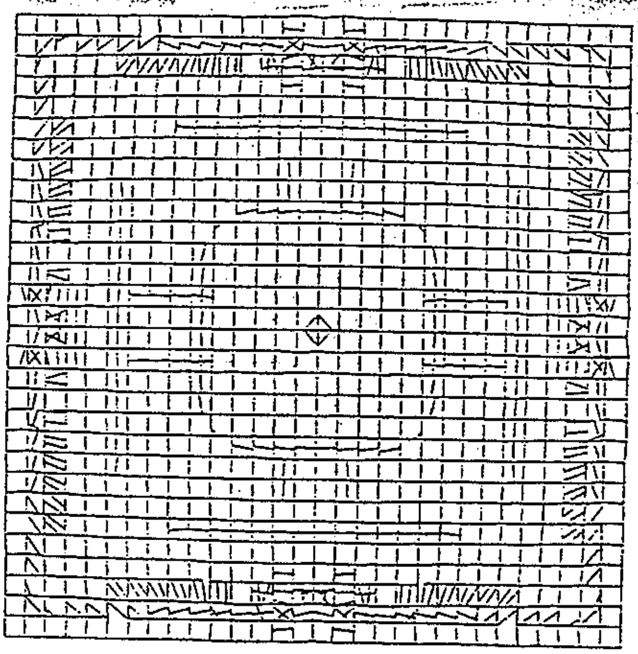


FIGURE 3. DYNA3D CALCULATION RESULTS FOR 20psi BLAST LOADED PANEL, COMPARED WITH EXPERIMENTAL RESULT



4a. CENTRAL DEFLECTION OF PANEL AND OVERBURDEN



4b. CRACK PATTERN ON REAR FACE OF PANEL

FIGURE 4. DYNA3D CALCULATION RESULTS FOR BURIED PANEL

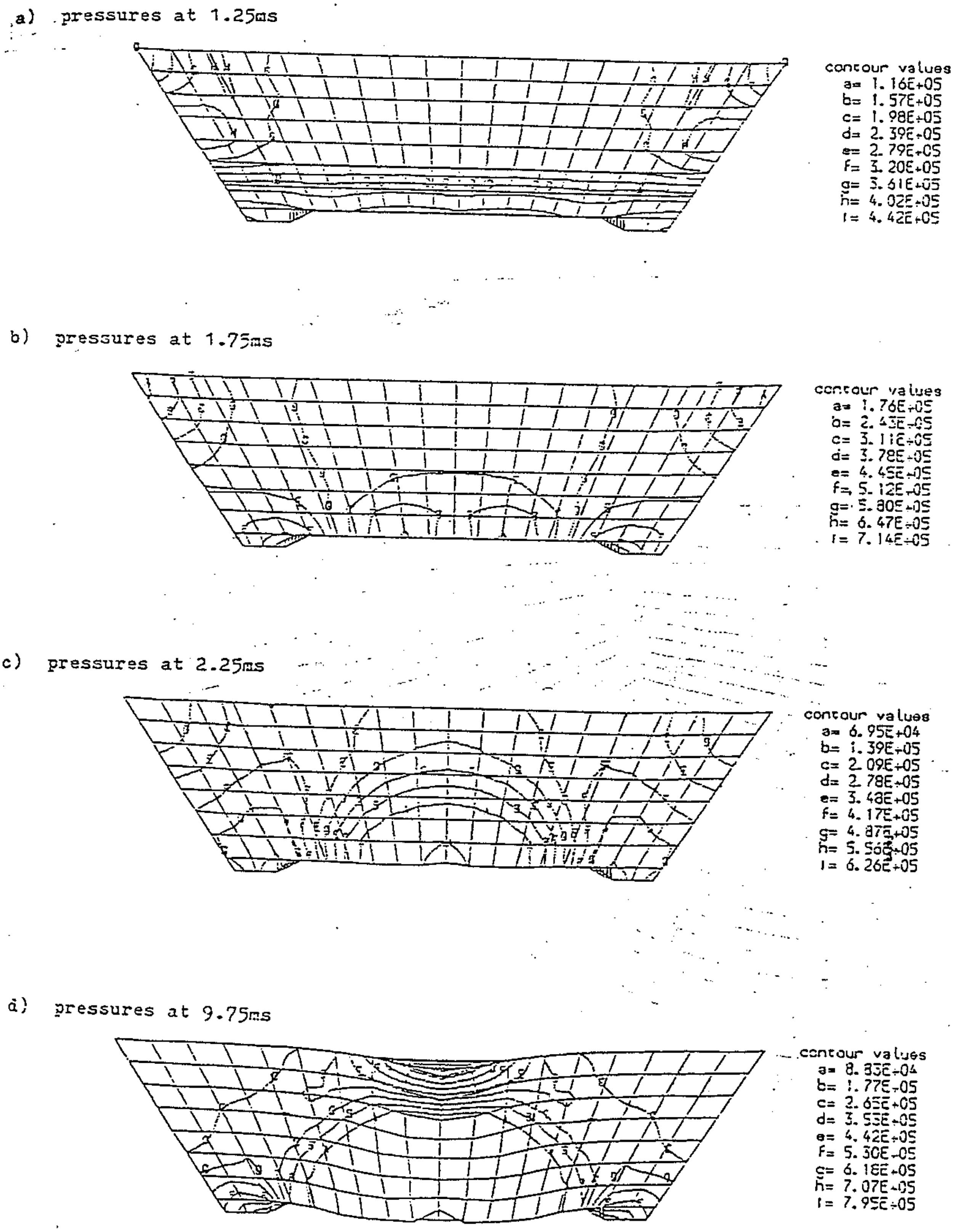


FIGURE 5. DYNA3D CALCULATION RESULTS FOR BURIED PANEL: PRESSURE DISTRIBUTION IN SAND OVERBURDEN

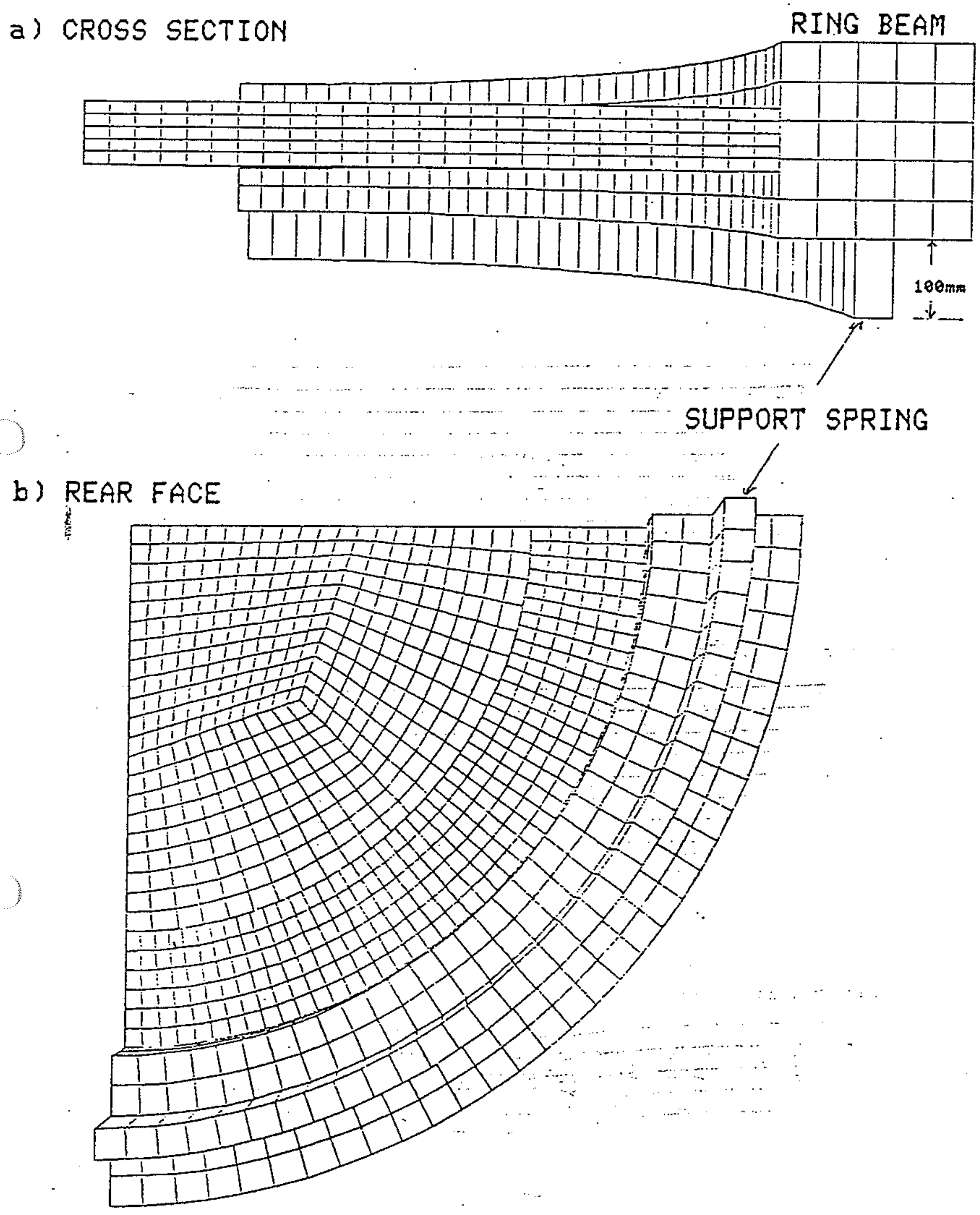
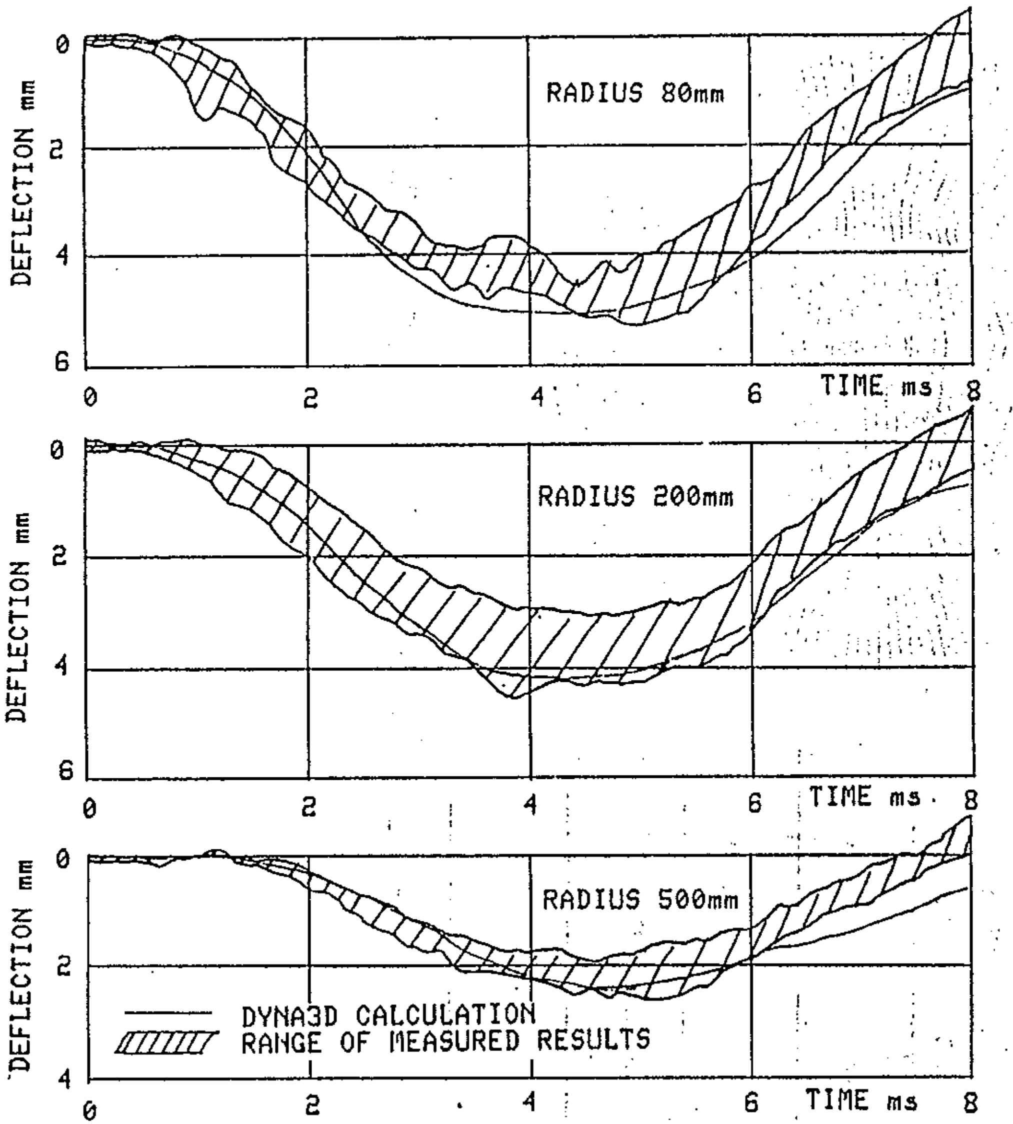
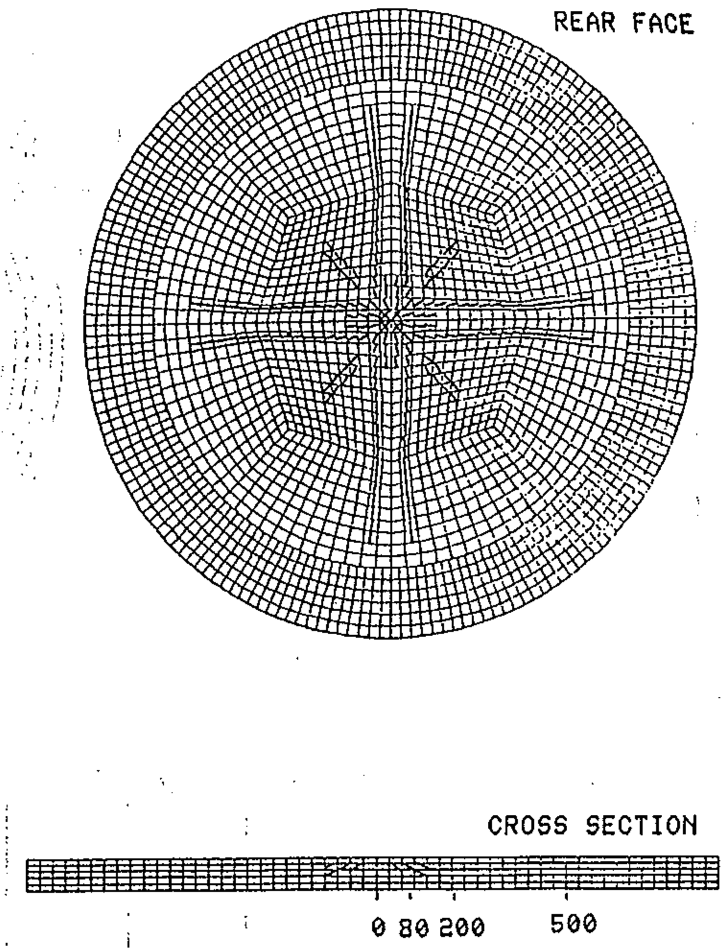


FIGURE 6. FINITE ELEMENT MODEL FOR 82mm PANEL

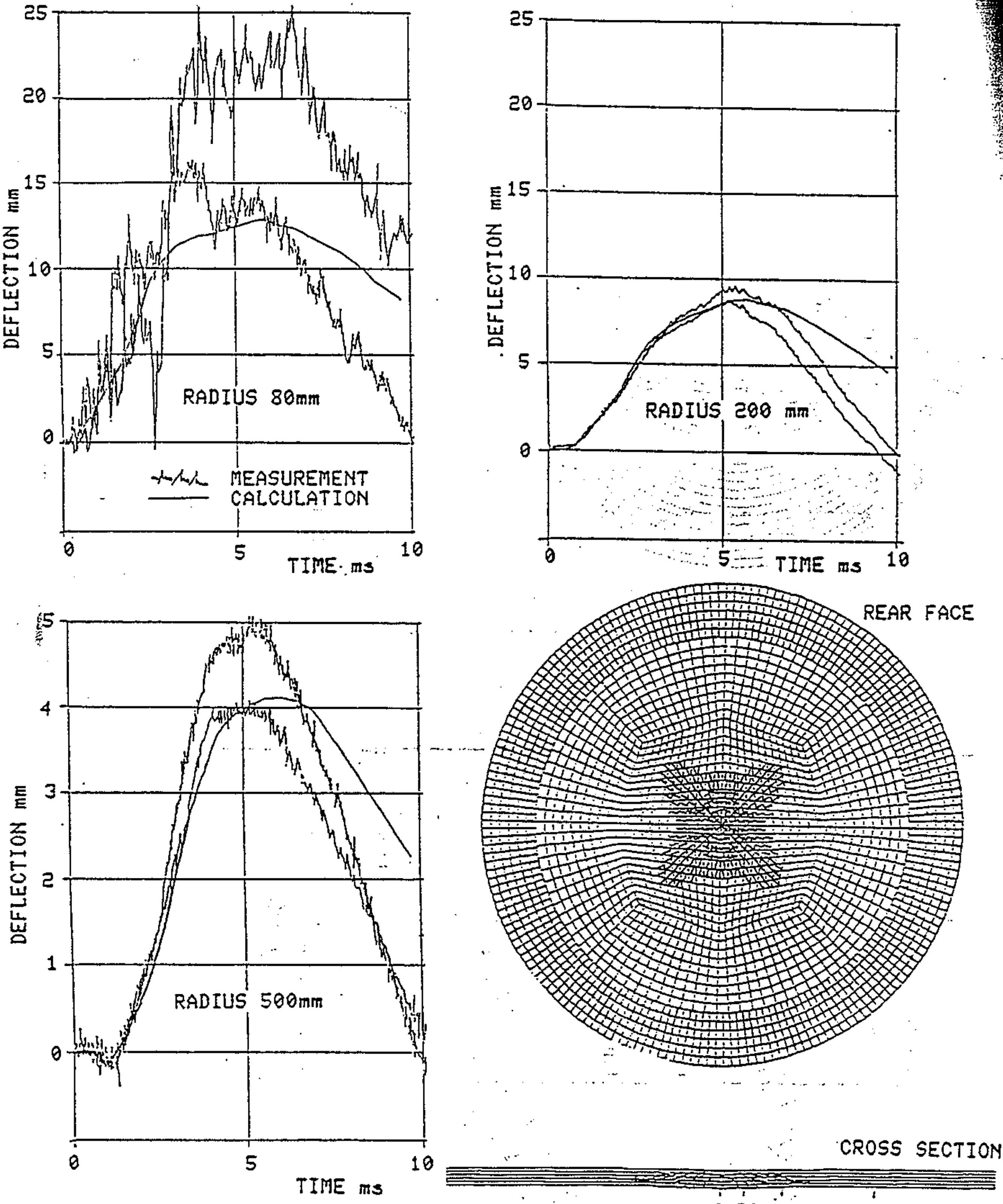


7a. DEFLECTION HISTORIES



7b. CRACK PATTERNS

FIGURE 7. DYNA3D CALCULATION RESULTS FOR 82mm PANEL



8a. DEFLECTION HISTORIES

8b. CRACK PATTERNS

FIGURE 8. DYNA3D CALCULATION RESULTS FOR 56mm PANEL

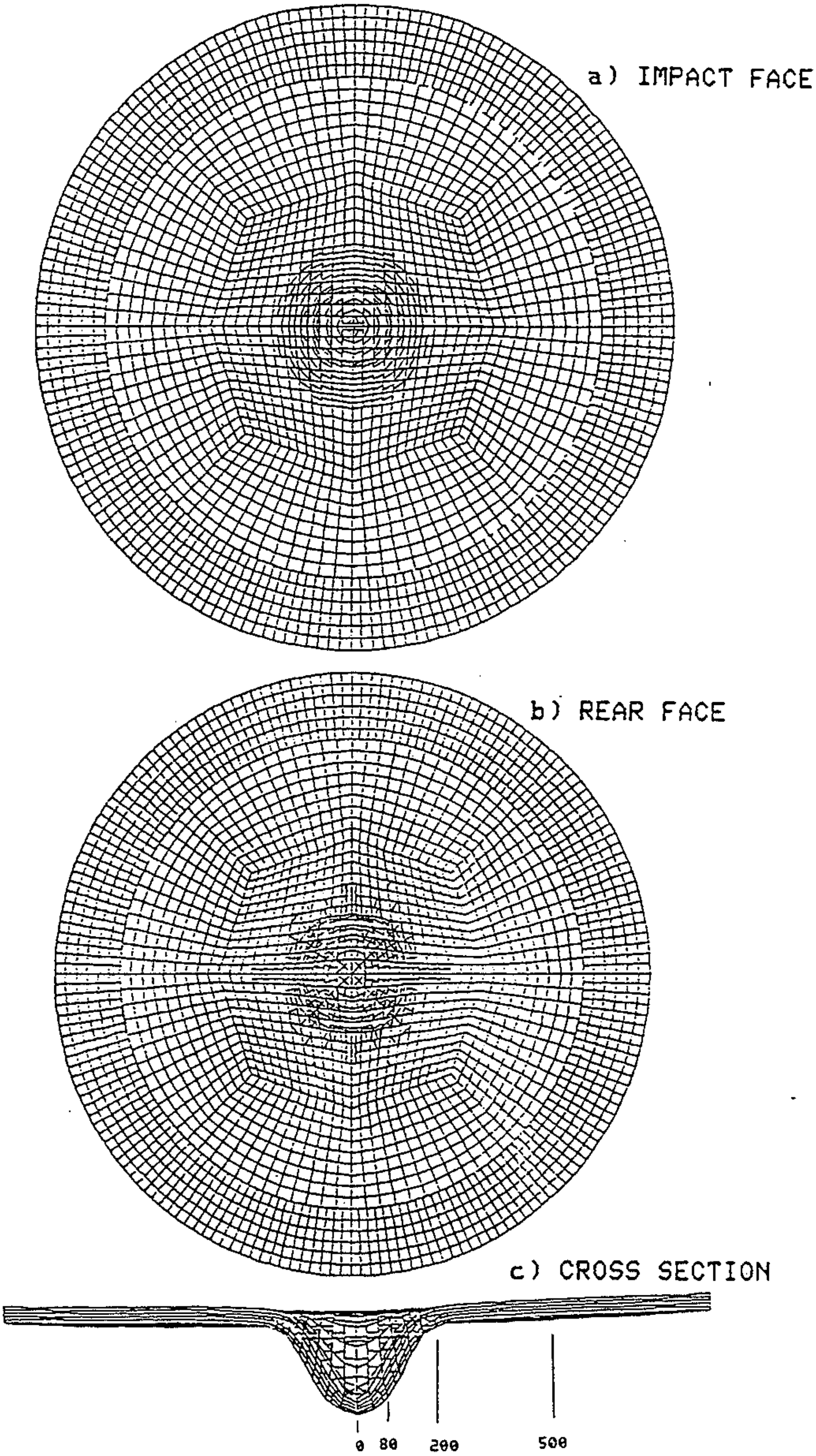


FIGURE 9. DYNA3D CALCULATION RESULTS FOR 40mm PANEL