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MEMORANDUM REPORT ARBRL-MR-03324

COMPUTER SIMULATION OF SCALED MARK84
BOMB IMPACT INTO CONCRETE

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November 1983



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents the results of three-dimensional finite element analyses of a scaled (1/15) MK84 bomb impacting thick concrete targets at large obliquities. Two bomb structures were modeled, one of solid steel and another with an 0.2cm steel wall, the cavity being filled with an inert simulant to represent the explosive tritonal. The analysis covers the latter one. The computations were performed with EPIC-3, a three-dimensional finite element program for the study of wave propagation and impact in homogeneous isotropic and anisotropic materials, as well as concrete. The critical impact angle for delineating		

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penetration and ricochet is determined as a function of bomb structure and obliquity. These prove to be in close agreement with experimental results. Some comments on computational approaches for rapid, cost-effective numerical studies of such situations conclude the paper.

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I. INTRODUCTION

Recently, there has been a renewed interest in bombs impacting concrete targets and their trajectory through the target. This is especially important when the bomb is equipped with a delay fuze. Experimental firings conducted by Roecker¹ of 1/15th scale MARK84 (MK84) bombs impacting thick concrete targets at various obliquity angles and striking velocities have shown the bomb to follow one of two trajectories:

(a) penetration - piercing of the target by the bomb. In some of the tests, partial penetration of the target was observed followed by ejection of the bomb from the crater and tumbling once clear of the target. This behavior is termed rebound.

(b) ricochet - deflection of the bomb from the target surface in which the nose of the bomb is never completely embedded in the target. A subset of ricochet is broaching wherein the bomb tunnels through the target along a trajectory parallel to the target surface, and after sometime it turns towards the target surface and exits.

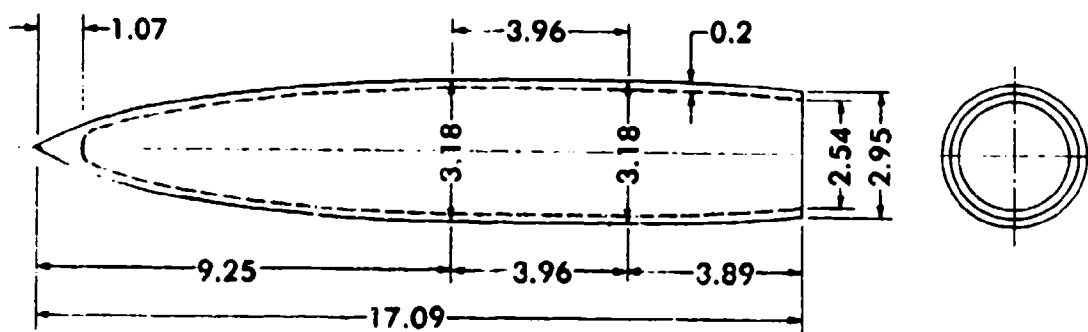
The experiments conducted by Roecker¹ established critical obliquity angles for delineating penetration and ricochet as a function of striking velocity for solid and thin-walled MK84 bombs. The bombs were inscribed by a polypropolux sabot and fired from a 57mm smooth-bore launcher at velocities from 150 m/s to 270 m/s. The concrete targets which were 15.24cm thick and approximately 1 meter square were placed at obliquities from 20° - 40°. The experimental evidence consists of post-impact measurements, flash radiographs, polaroid photographs, and some movies. Figure 1 shows a schematic of the thin-walled bomb. The solid bomb, which was fired to investigate the influence of wall thickness on the critical obliquity angle, has the same external dimensions.

Figure 2 is a photograph of typical pre- and post-impact conditions for a thin-wall bomb impacting the concrete target at 159 m/s at an obliquity of 31°. This happens to be a ricochet mode and the ogival nose essentially remains undeformed. What appears to be an indentation in photograph near the nose is a scar not a localized plastic deformation. The deformation near the rear of the bomb is the result of the tail of the bomb "slapping" the target in the late stages of the ricochet event.

To gain further insight into characterizing the mechanisms of the impact event which distinguish the different modes of penetration, numerical simulation of scaled MK84 bomb impacts have been performed using the EPIC-3² code. The results of these simulations are discussed and compared with experimental observations.

¹ E. T. Roecker, et. al., BRL Report in progress.

² G. R. Johnson, D. J. Vaurick, and D. D. Colby, "Further Development of EPIC-3 for Anisotropy, Sliding Surfaces, Plotting and Material Models," Ballistic Research Laboratory, ARBRL-CR-00429, May 1980 (AD B048305L).



NOTE: ALL DIMENSIONS IN cm.
CONSTANT WALL THICKNESS

Figure 1. Scaled MARK84 Thin-Wall Bomb



Figure 2. Pre- and Post-Impact Conditions for Thin-Wall Bomb
Impacting Concrete Target at 31° Obliquity at 159 m/s

II. NUMERICAL MODEL

The thin-walled bomb has been modelled with four rings of elements with the outer ring of elements representing the 2mm steel casing. The inner rings of elements represent the inert simulant to represent the explosive tritonal. The bomb contains 855 nodes and 3456 elements and the entire model is comprised of 8070 nodes and 39,744 constant strain tetrahedral elements.

A deep penetration "tunneling" model has been employed for treatment of the sliding surface. The bomb has been declared the master and the target has been declared the slave. This is the reverse of that employed by Johnson.³

The constitutive model in EPIC-3 employs an incremental elastic-plastic relationship using the von-Mises yield criterion to describe the deviatoric behavior of materials. Provision is made to account for strain rate, temperature, and strain hardening effects. Thermal softening and strain rate effects were not taken into account due to lack of data to support such models. The hydrostatic component of stress is obtained from the Mie-Gruneisen equation of state for the steel casing and explosive simulant.

A plain (unreinforced) concrete equation of state which is valid up to 30 GPa was used to model the concrete. The concrete model is discussed in References 2 and 4 and is presented briefly here for completeness. The concrete model is constructed from Hugoniot data by Gregson⁵ and static yield strength data from Chinn and Zimmerman.⁶ The aggregate used in Gregson's work had an average diameter of 3.2mm and an average initial density of 2.185 g/cm³. The concrete consisted of 18% voids, 25% granite, 20-25% quartz grains, and 25-30% cement paste by volume.

The pressure-volume relationship for the concrete model is shown in Figure 3. The estimated unloading path is one which permits the concrete to return to its solid density (2.6 g/cm³) when loaded past the point where all voids have collapsed, $\mu = 0.3$.

³ G. R. Johnson, Honeywell Inc., Defense Systems Division, Private communication.

⁴ J. J. Osborn and D. A. Matuska, "Dynamic Response of a Kinetic Energy Penetrator, Vol II. - Hydrocode Analysis," AFATL TR 78-24, March 1978.

⁵ V. G. Gregson, Jr., "A Shock Wave Study of Fondue-Frye WA-1 and a Concrete," DNA report 2797F, February 1972.

⁶ J. Chinn and R. M. Zimmerman, "Behavior of Plain Concrete Under Various High Triaxial Compression Loading Conditions," AFWL TR 64-163, August 1965.

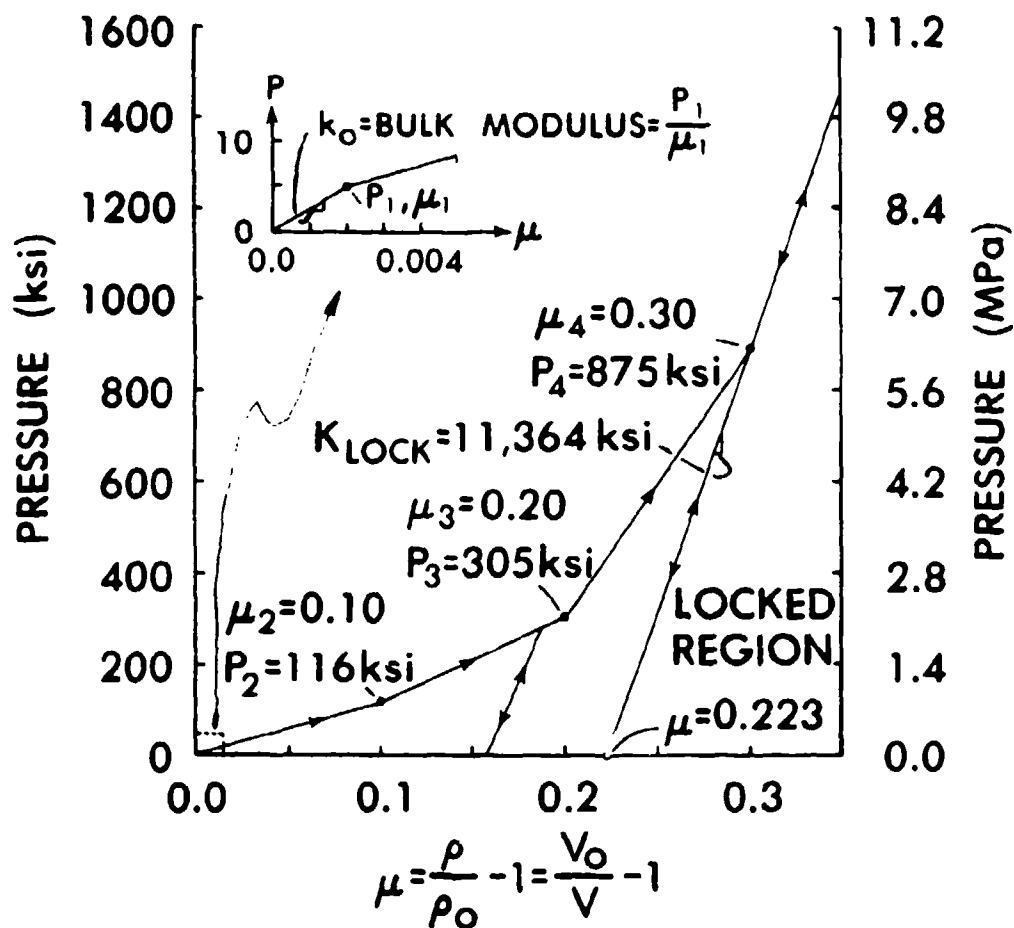


Figure 3. Pressure-Volume Relationship for Concrete Model

The unloading path is a straight line which connects with the load curve at the point where all the voids have collapsed and has a slope equal to that of the load curve at the point where total void collapse occurs. For values of excess compression below that where void collapse is initiated ($\mu = .002$), loading, unloading, and reloading occur along the same elastic path. For values of excess compression between these extremes, the bulk modulus is assumed to vary linearly between K_0 and K_{LOCK} .

The concrete model has been extensively and successfully employed by the Air Force Armament Laboratory for penetrations in the 60 to 300 m/s velocity range.⁴ A detailed description of the model can be found in References 2 and 4. Other pertinent literature is found in References 7 and 8. The use of the model should be limited to calculations with an impedance mismatch, such as steel and concrete in this case, because the model assumes no transmission of shock waves from the concrete into the penetrator.

In the calculations presented here the bomb elements were not permitted to fail. However, the concrete elements were completely failed, at which point the element no longer supports a pressure or tensile stress, when its equivalent plastic strain exceeded 30 percent. It should be noted that preliminary calculations which raised the equivalent plastic strain from 10-30 percent showed no distinct differences in target crater profile.

III. DISCUSSION OF RESULTS

Computations were performed for the thin-walled structure (Figure 1) at obliquity angles of 25.7° , 30° , and 33.8° with a striking velocity of 228 m/s. These obliquity angles and striking velocity were chosen due to the availability of experimental data. The experimental data indicated that with a striking velocity of 228 m/s the 25.7° impact has a 50% probability of ricochet and a 50% probability of rebound. The higher obliquity angles resulted in ricochet or broaching.

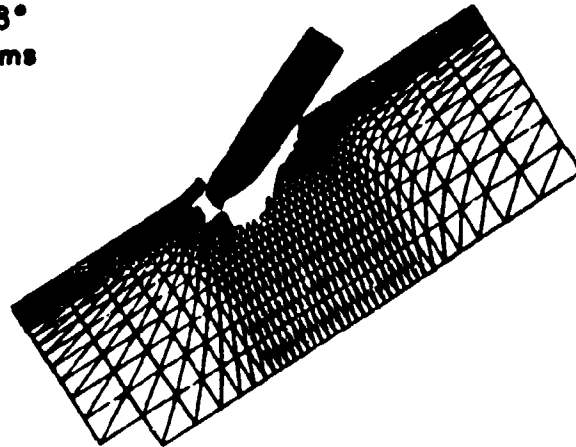
It should be noted that in light of the excessive amount of computer time required by these calculations the solid bomb has not been extensively pursued and the results herein pertain to the thin-walled structure only. The explicit integration scheme employed in EPIC-3 required approximately 85 μ seconds per microsecond of simulation on a CDC Cyber 76 for the results presented herein.

Figure 4 shows the deformation profiles for the three different obliquity angles at the time where maximum penetration is achieved. Appendix A contains a complete temporal sequence of deformation profiles for the different obliquities. In general, the deformation profiles in Figure 4 closely resemble those observed in the experiments. The discontinuity in the nose of the bomb is an artifact of the sliding surface technique. The target crater profiles, in the symmetry plane, are delineated by elements which have not exceeded an equivalent plastic strain of 30 percent.

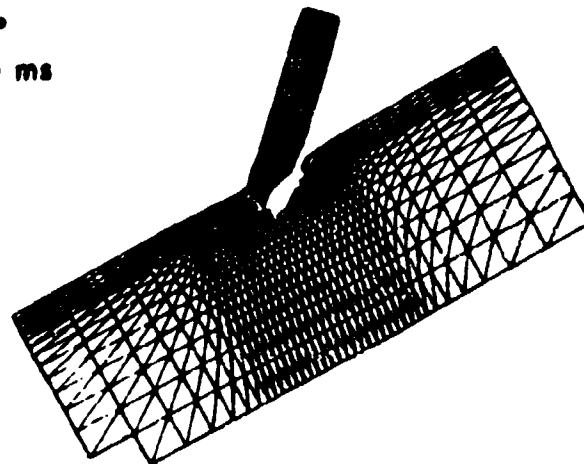
⁴ D. McHenry and J. Karmi, "Strength of Concrete Under Combined Tensile and Compressive Stress," American Concrete Institute, page 54, 10 April 1958.

⁸ K. E. Crawford, C. J. Higgins, and E. H. Bultmann, "The Air Force Manual for Design and Analysis of Hardened Structures," AFWL TR-74-102, October 1974.

33.8°
1.1 ms



30°
0.6 ms



25.7°
0.5 ms

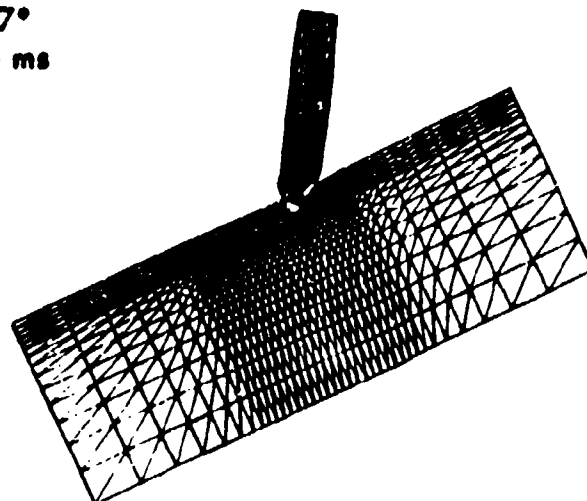


Figure 4. Deformation Profiles for Thin-Wall Bomb at Indicated Obliquities

The net velocity and angular velocity histories for the different obliquities are compared in Figures 5 and 6, respectively. As can be seen in Figure 5, at approximately 0.3ms the net velocity of the 25.7° impact starts to increase. Furthermore, the vertical component of velocity changes sign. This, in our opinion, is indicative of a rebound mode. One can also note the slower deceleration of the higher obliquity impacts.

The comparison of angular velocity, i.e. the rate at which the tail of the bomb is falling towards the target, histories for the different obliquities presented in Figure 6 show that the higher obliquity impacts result in a large angular acceleration being imparted to the bomb. In fact, the 33.8° impact has been carried out beyond one millisecond at which time there appears to be a steady state angular velocity of 500 rad/s and the net velocity has been reduced to approximately 10% of the striking velocity. This angular velocity history for the 33.8° impact coupled with the deformation profile at 1.1ms (see Figure 4 which indicates the initiation of tunneling) indicates a broaching mode, in our opinion. The intermediate obliquity is felt to be a ricochet mode in that no tunneling behavior has been observed out to 600 ms.

The response of the thin-walled bomb at the various obliquities is further compared in Figures 7-9 which show the time history of bending moment, shear stress, and axial load, respectively, for the indicated obliquities. These temporal histories are for the layer of elements in the cylindrical portion of the bomb just above the ogival nose. No distinct difference is noted for distinguishing penetration and ricochet based on the temporal histories for bending moment and shear stress. However, the reduction in axial load beyond 0.3ms for the 25.7° obliquity (Figure 9), in conjunction with the corresponding net velocity history (Figure 6), is indicative of "rebounding."

IV. SUMMARY

Shortly after impact, an angular acceleration is imparted to the bomb and the magnitude and duration of this angular acceleration is proportional to the incidence angle. Eventually, the angular acceleration imparted to the bomb reaches a steady state. A large steady state angular velocity appears to be characteristic of a broaching mode of penetration accompanied by slower deceleration of the bomb.

The computer simulations presented here predict the critical angle for ricocheting within 3-5°. They are quite expensive (80-90 CPU seconds/1 μ s of real time). This is due principally to the fact that explicit integration is used throughout. While accuracy considerations require a time step characteristic of explicit integration schemes during the early stages of impact (0-100 μ s), low impact velocity computations such as these could be conducted far more economically by switching to an implicit scheme once details of wave motion are no longer important. The principal advantage of codes such as EPIC-3 for these applications is their ability to supplement the meager information obtained from impact experiments. The judicious combination of computations and experiments can lead to effective designs with cost and efficiency factors below those from either technique alone.

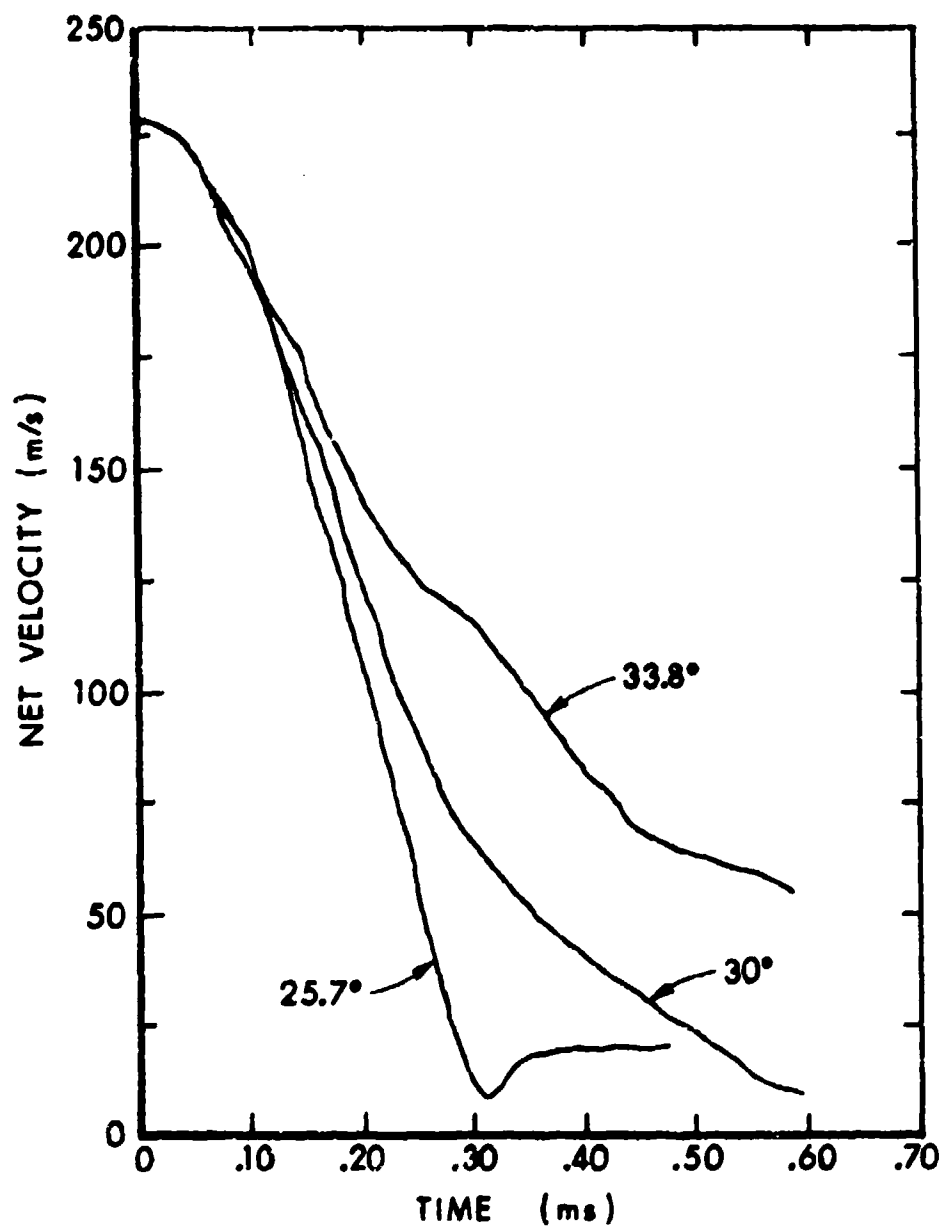


Figure 5. Net Velocity History for Thin-Wall Bomb

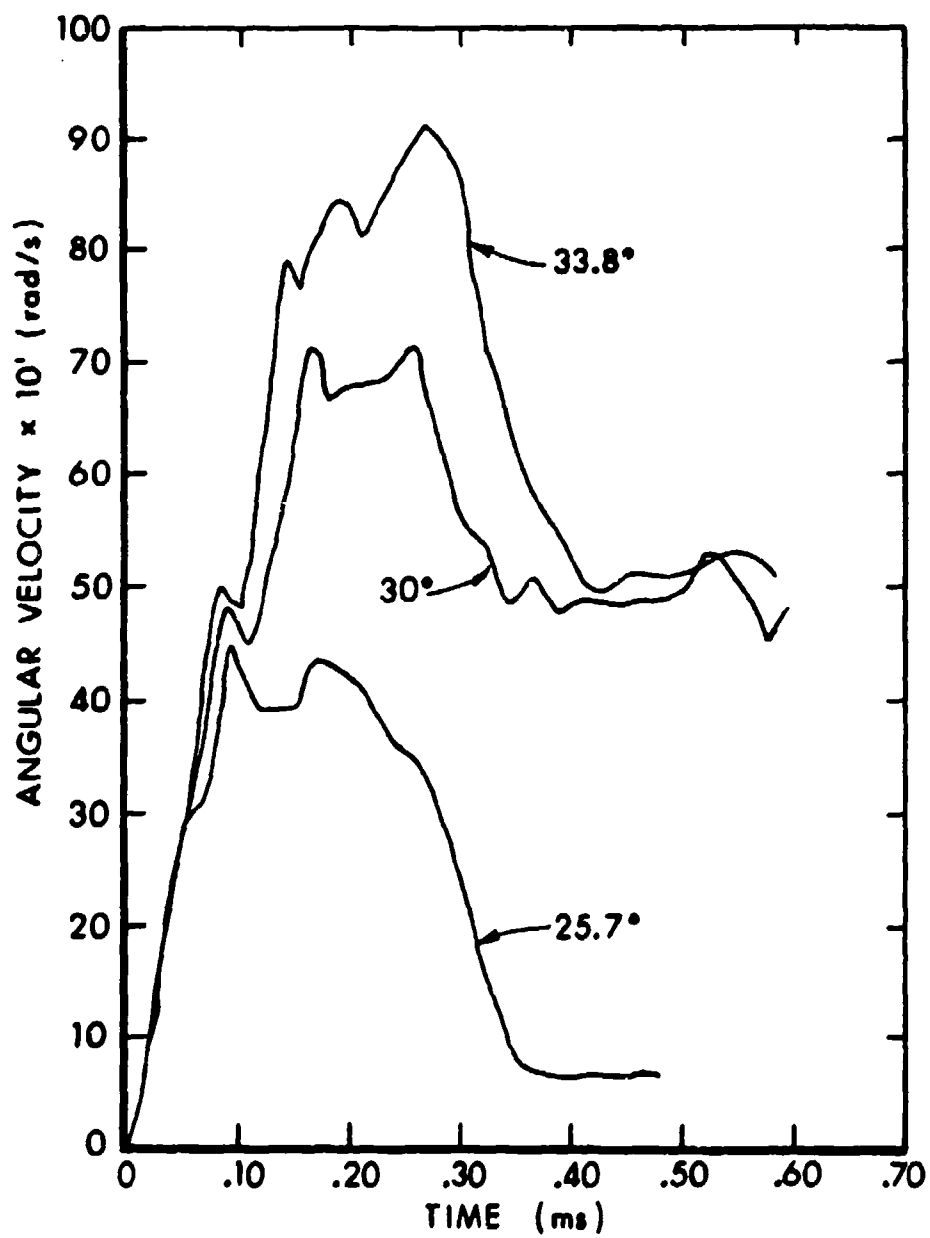


Figure 6. Angular Velocity History for Thin-Wall Bomb

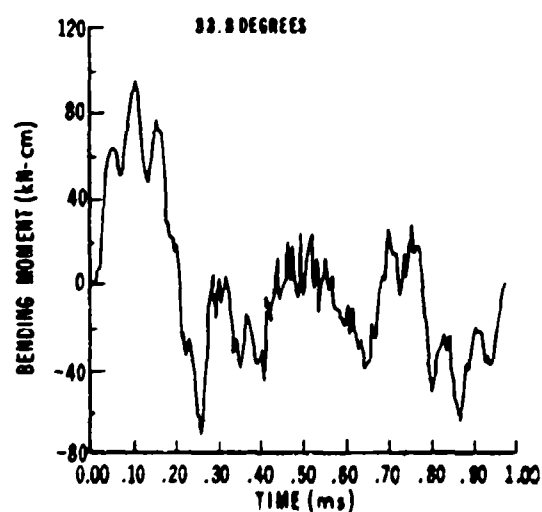
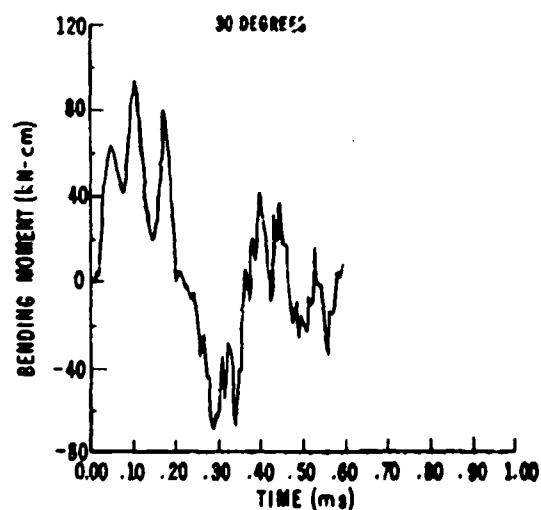
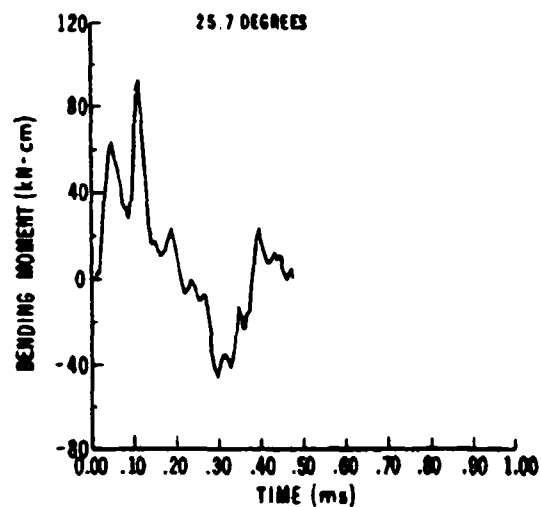


Figure 7. Bending Moment History for Thin-Wall Bomb at Indicated Obliquities

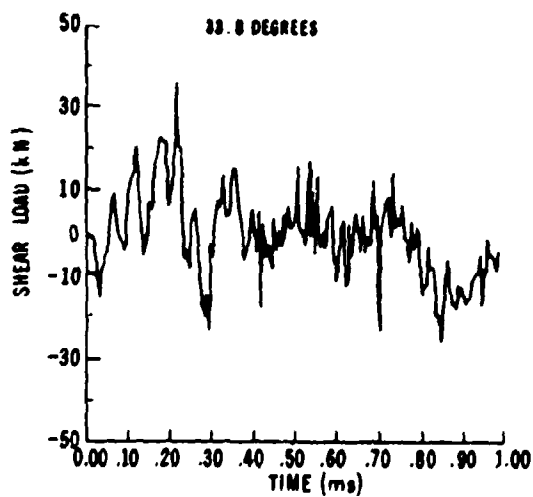
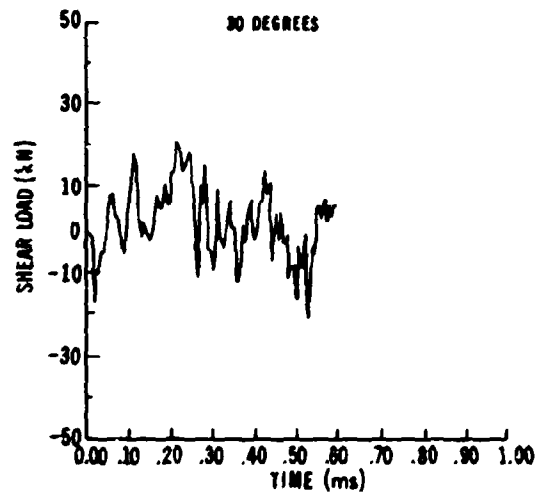
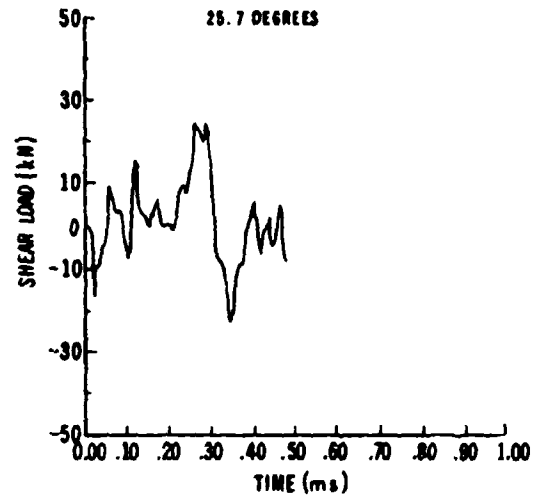


Figure 8. Shear Stress History for Thin-Wall Bomb at Indicated Obliquities

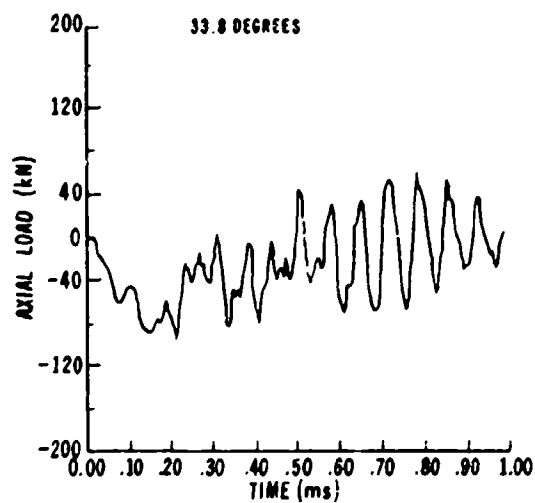
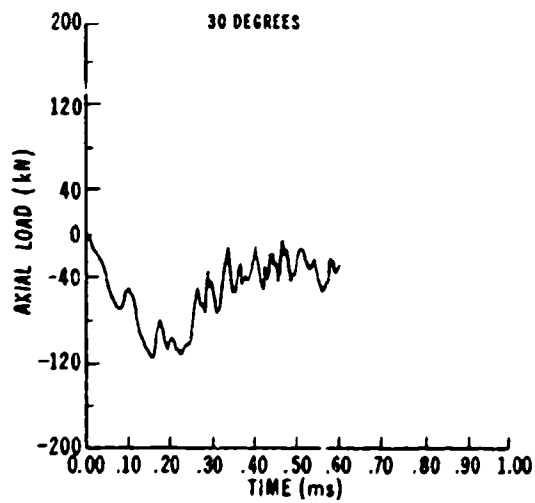
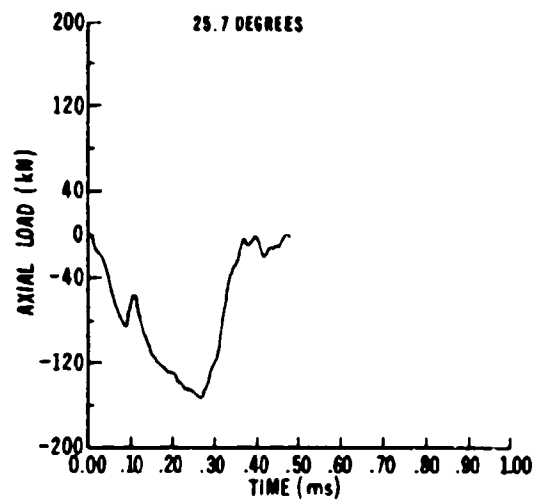


Figure 9. Axial Load History for Thin-Wall Bomb at Indicated Obliquities

APPENDIX A

Temporal Sequence of Deformation Profiles

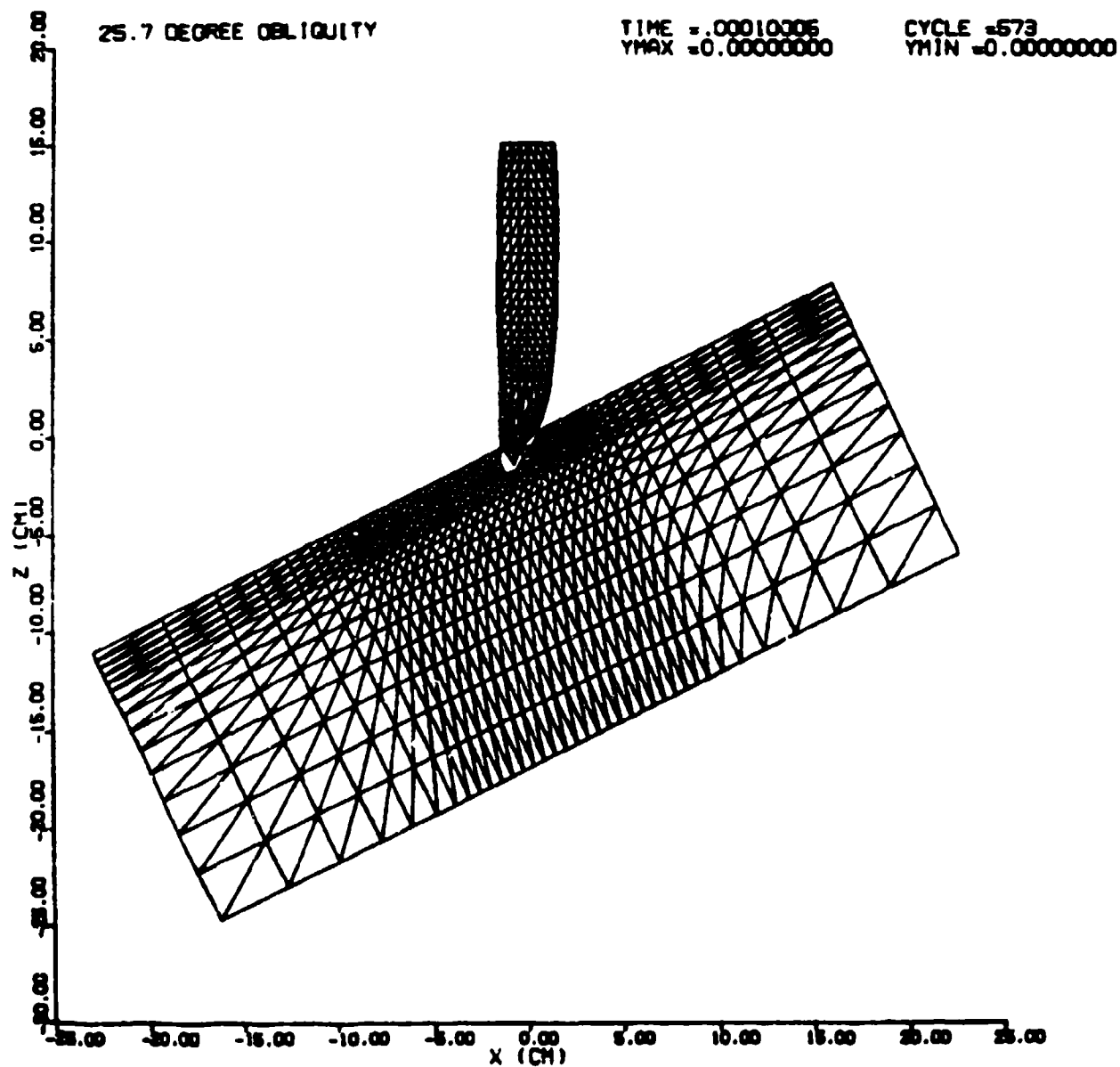


Figure A1. Deformation Profile for 25.7° Obliquity at $T = 10 \mu s$

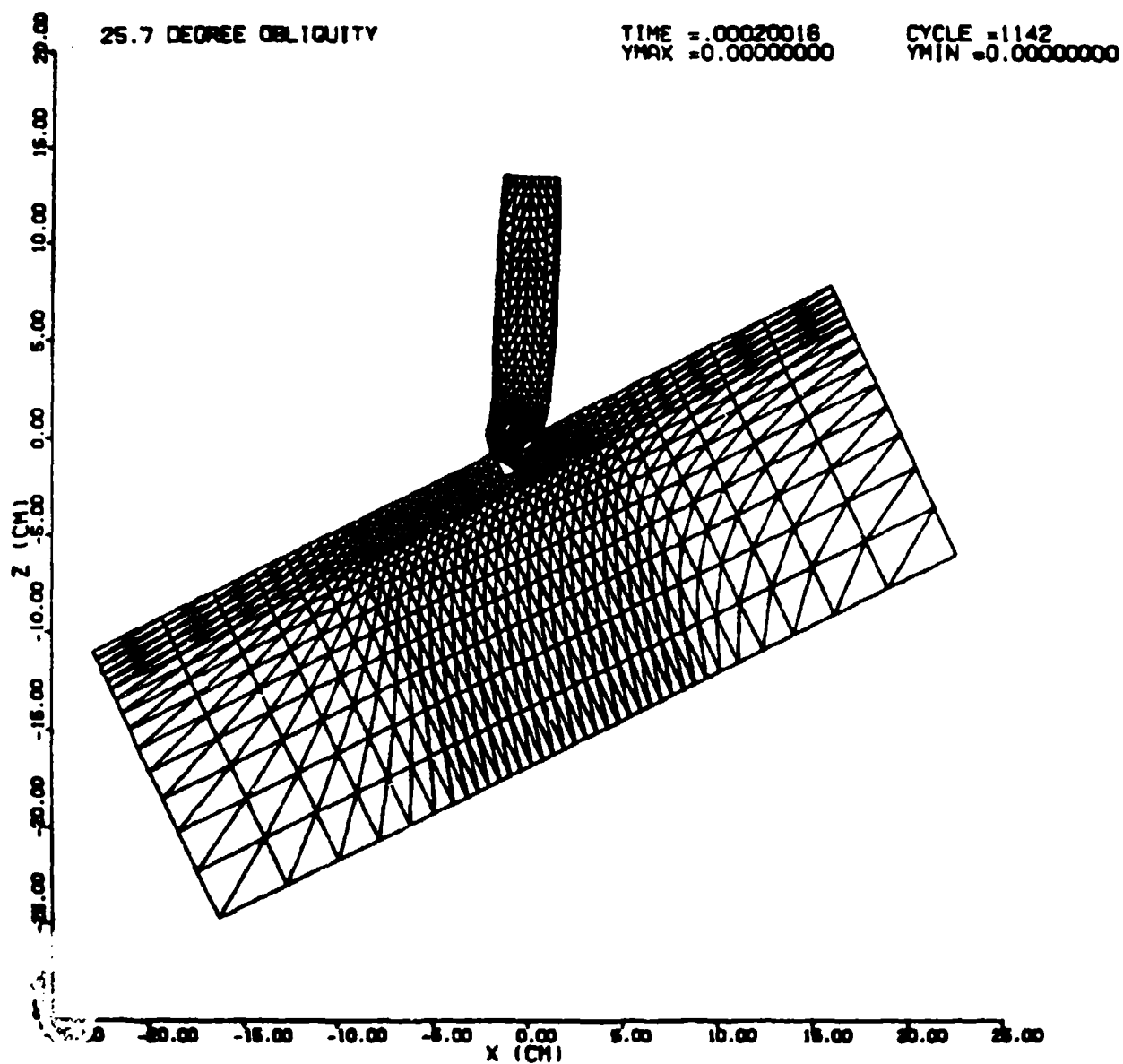


Figure A2. Deformation Profile for 25.7° Obliquity at $T = 20 \mu s$

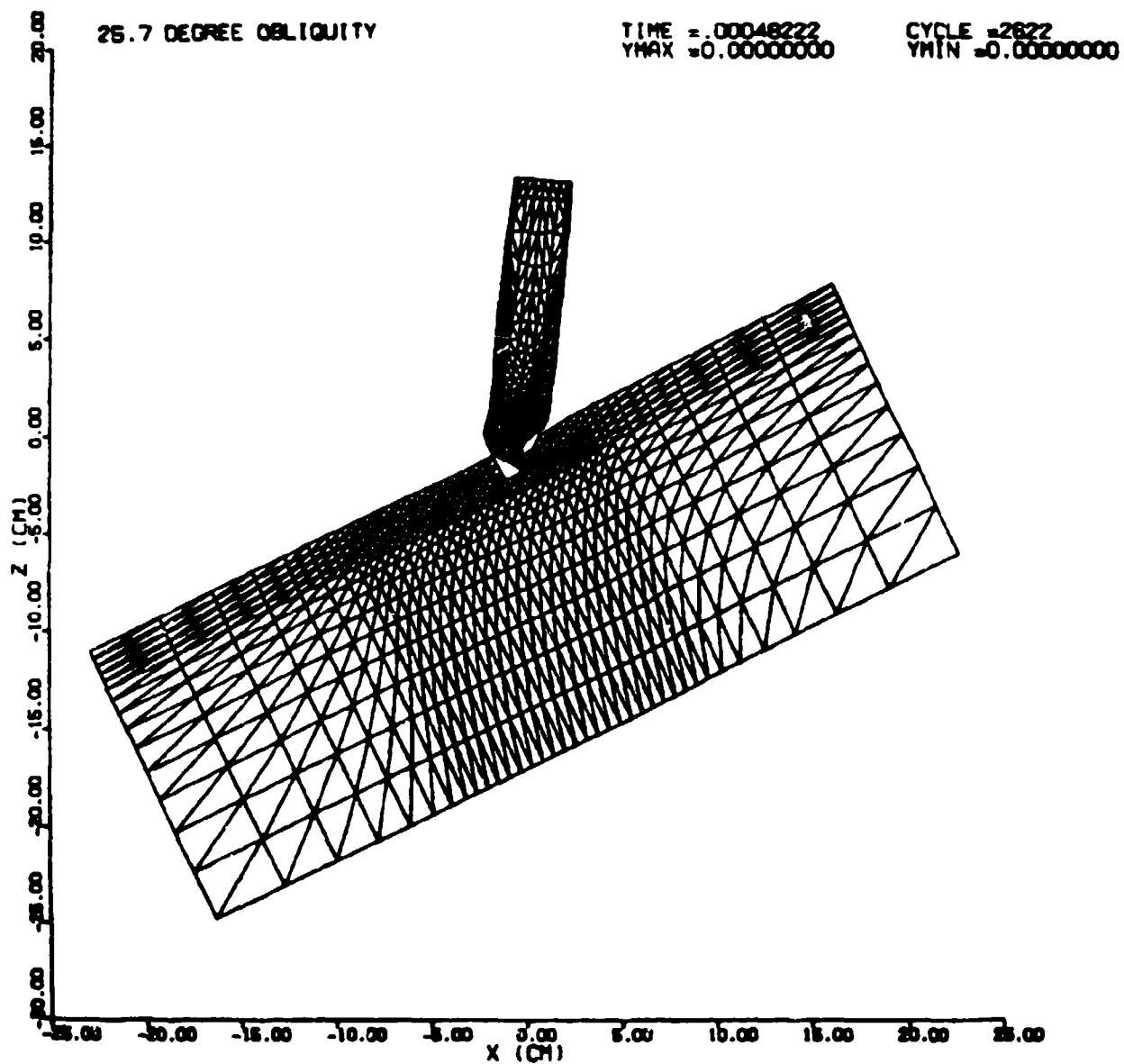


Figure A3. Deformation Profile for 25.7° Obliquity at $T = 48.2 \mu s$

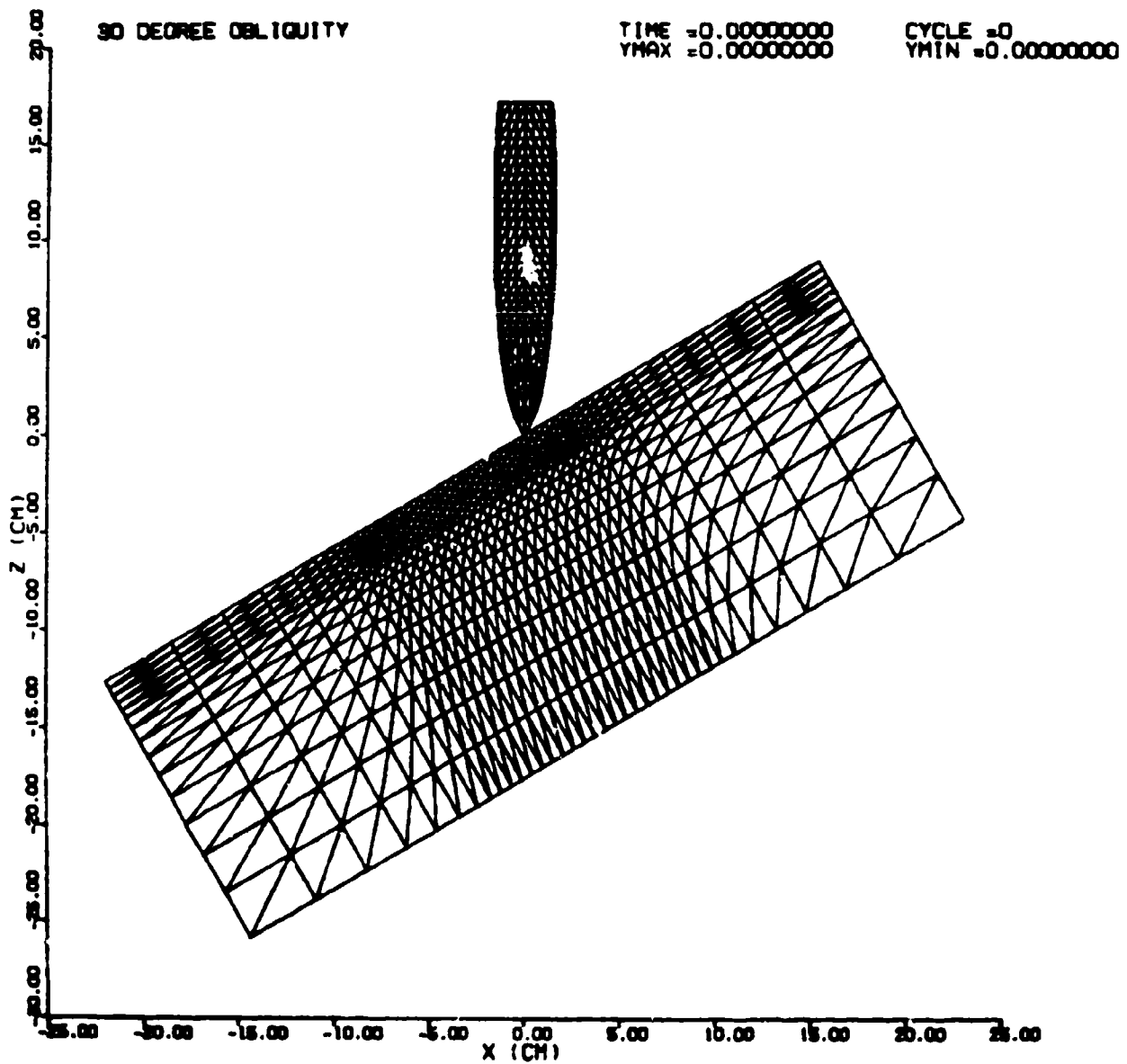


Figure A4. Deformation Profile for 30° Obliquity at $T = 0 \mu s$

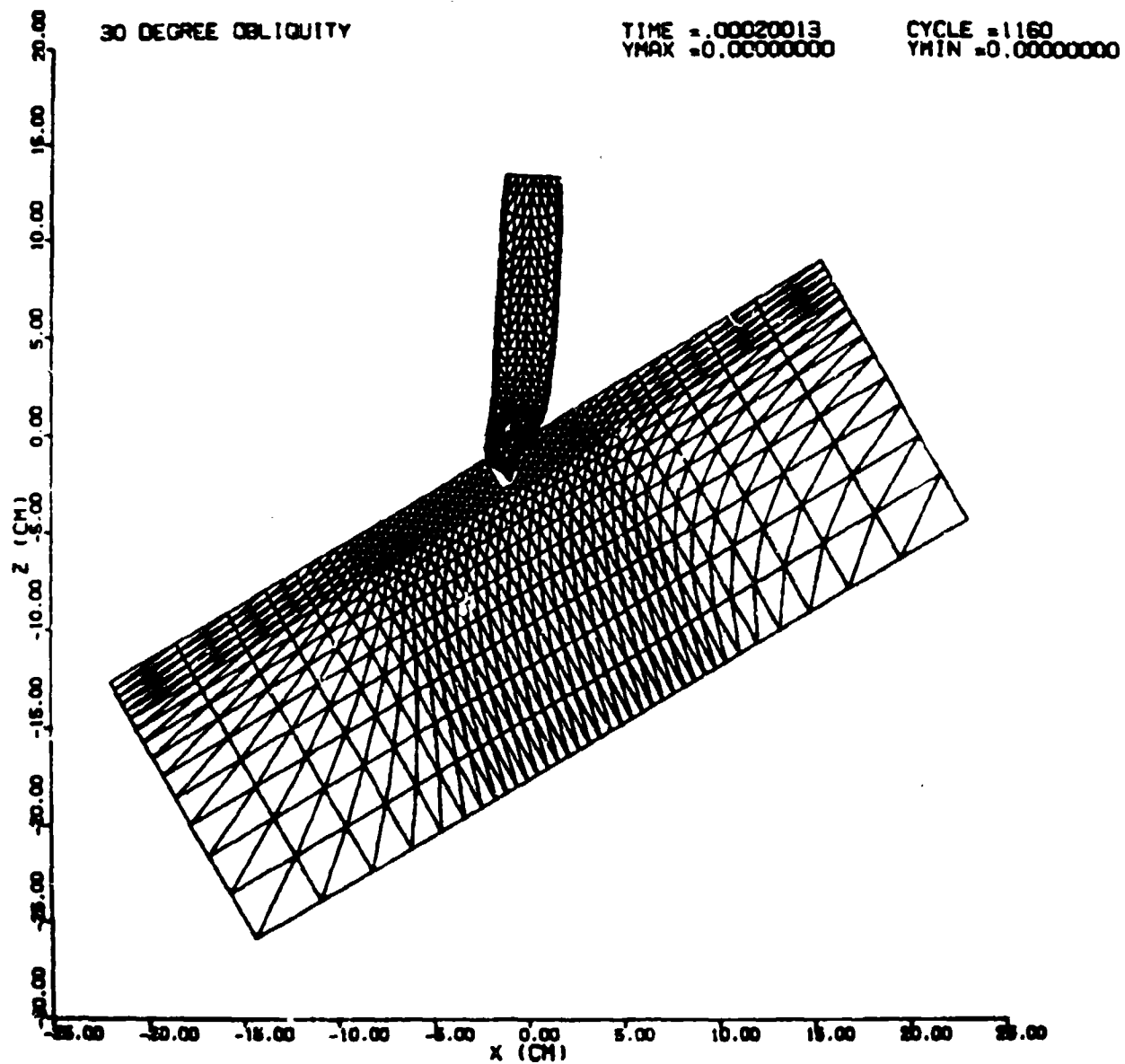


Figure A5. Deformation Profile for 30° Obliquity at $T = 20 \mu s$

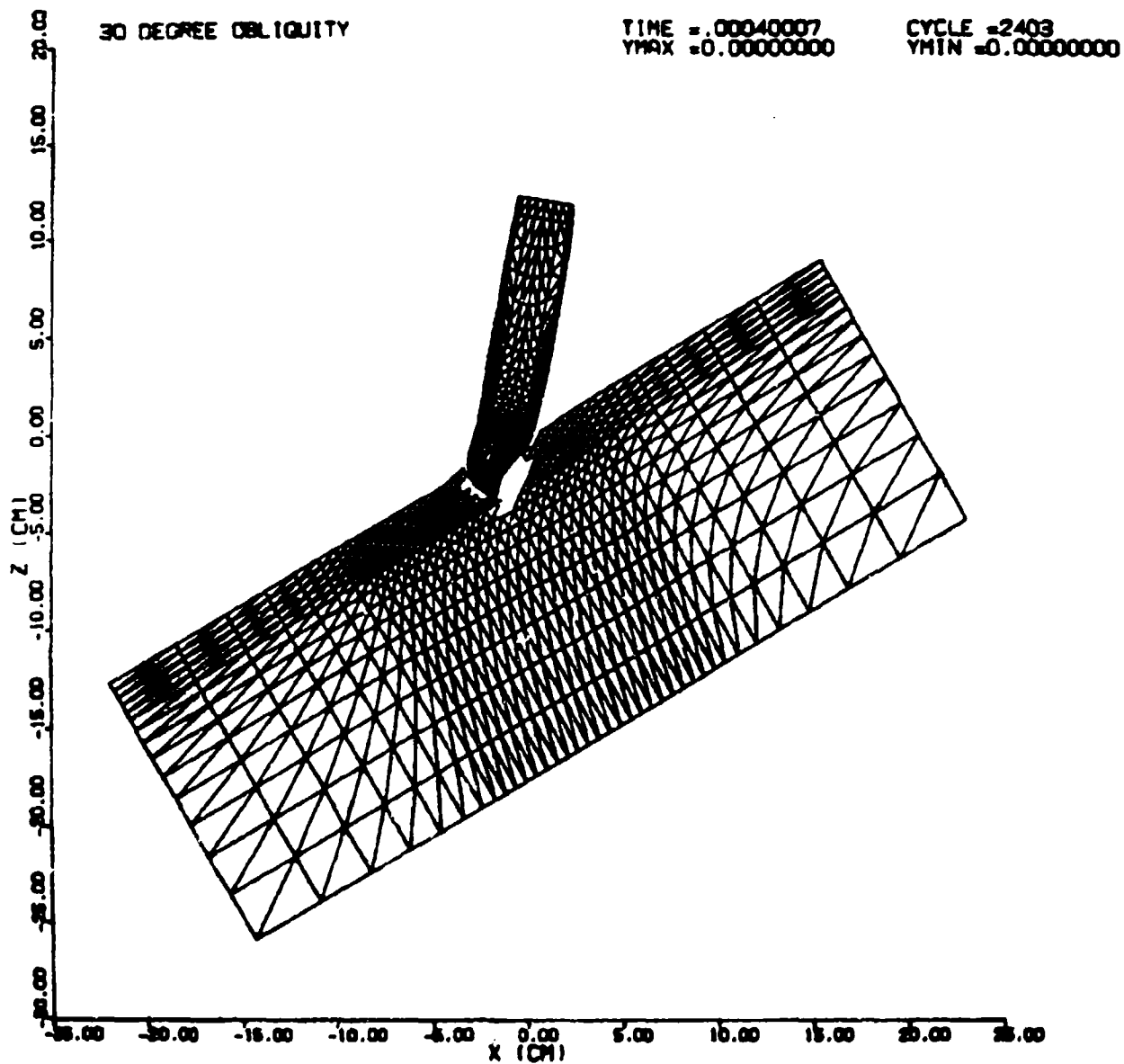


Figure A6. Deformation Profile for 30° Obliquity at $T = 40 \mu s$

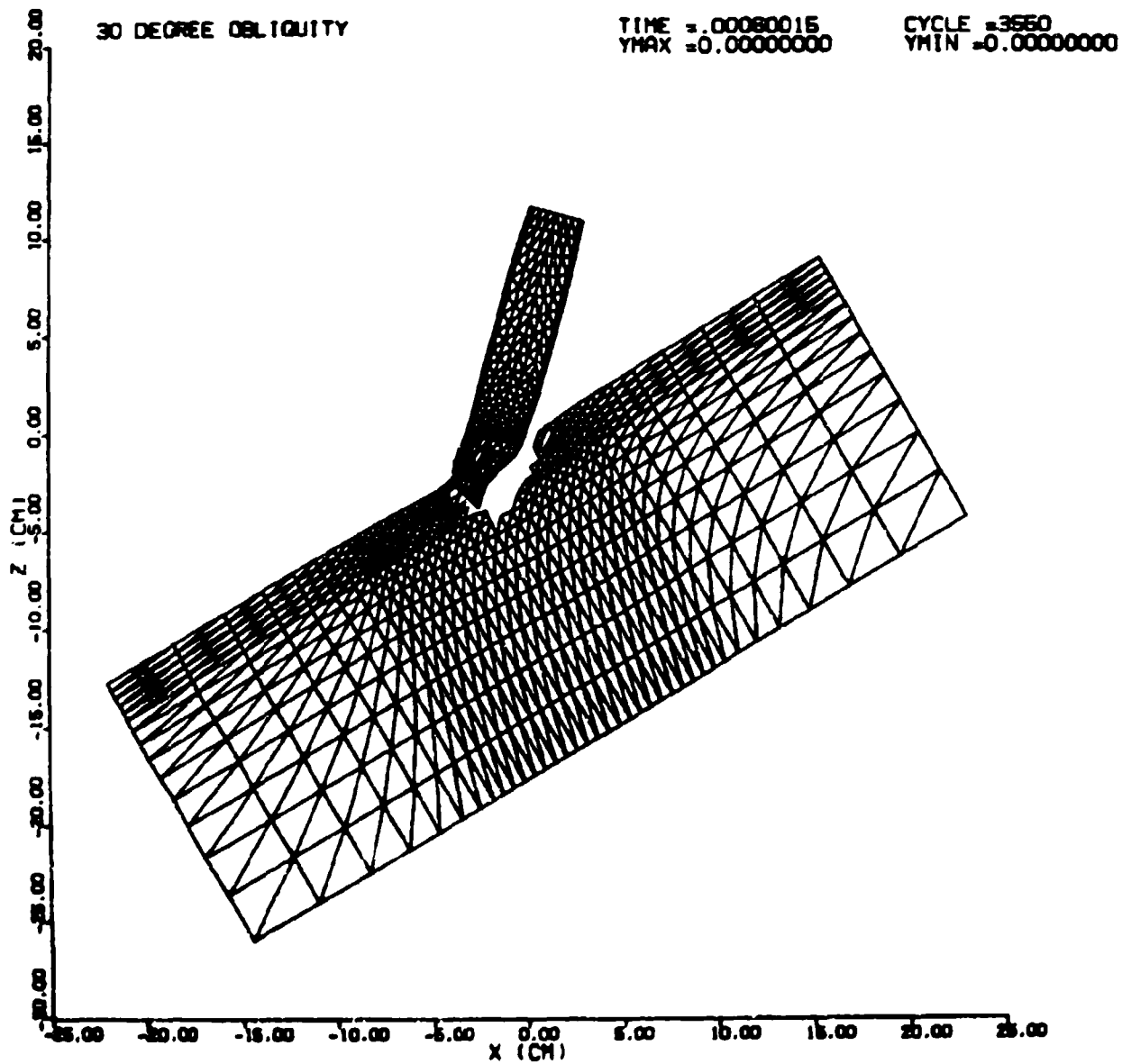


Figure A7. Deformation Profile for 30° Obliquity at $T = 60 \mu s$

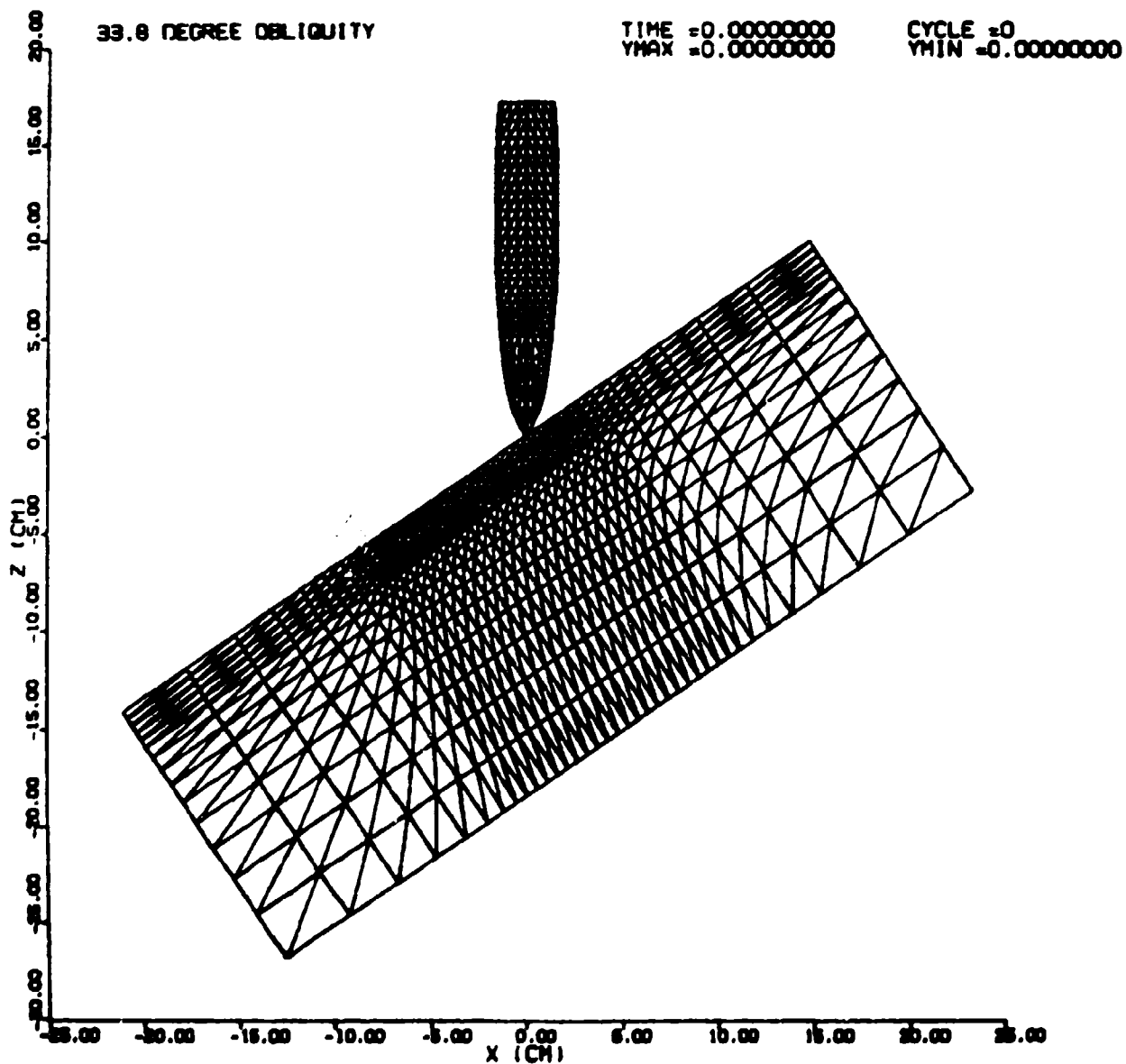


Figure A8. Deformation Profile for 33.8° Obliquity at $T = 0 \mu s$

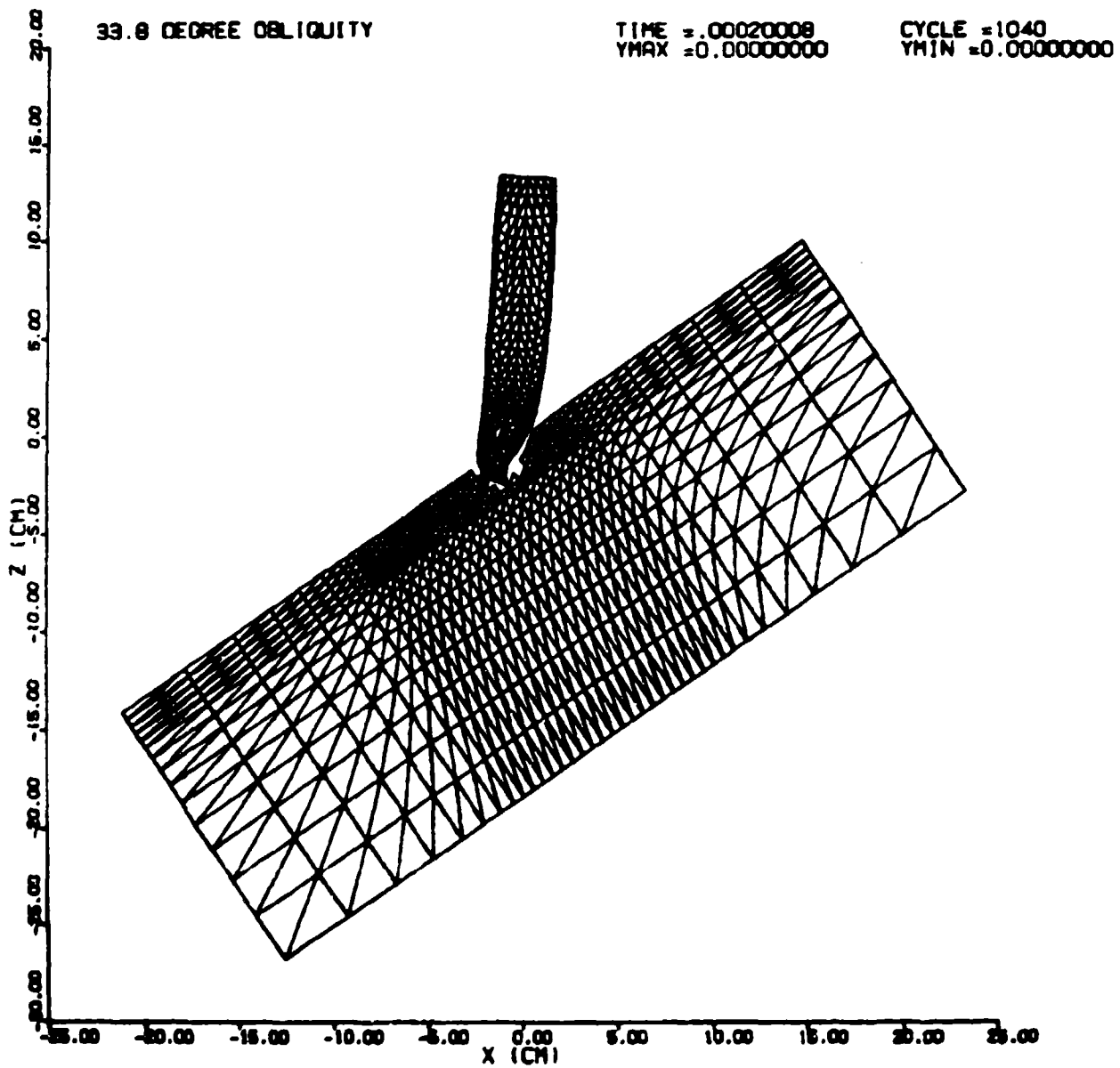


Figure A9. Deformation Profile for 33.8° Obliquity at $T = 20 \mu s$

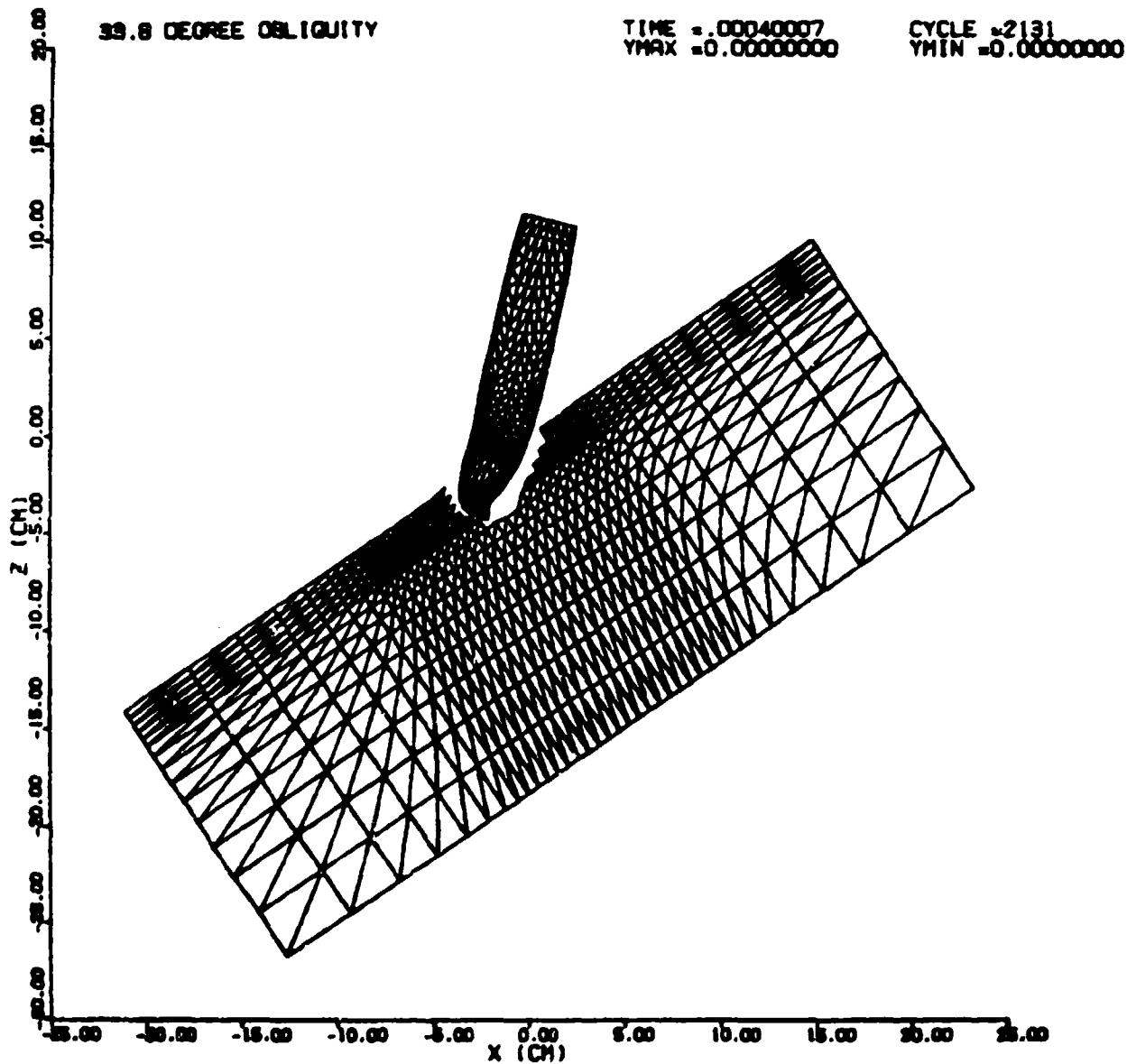


Figure A10. Deformation Profile for 33.8° Obliquity at $T = 40 \mu s$

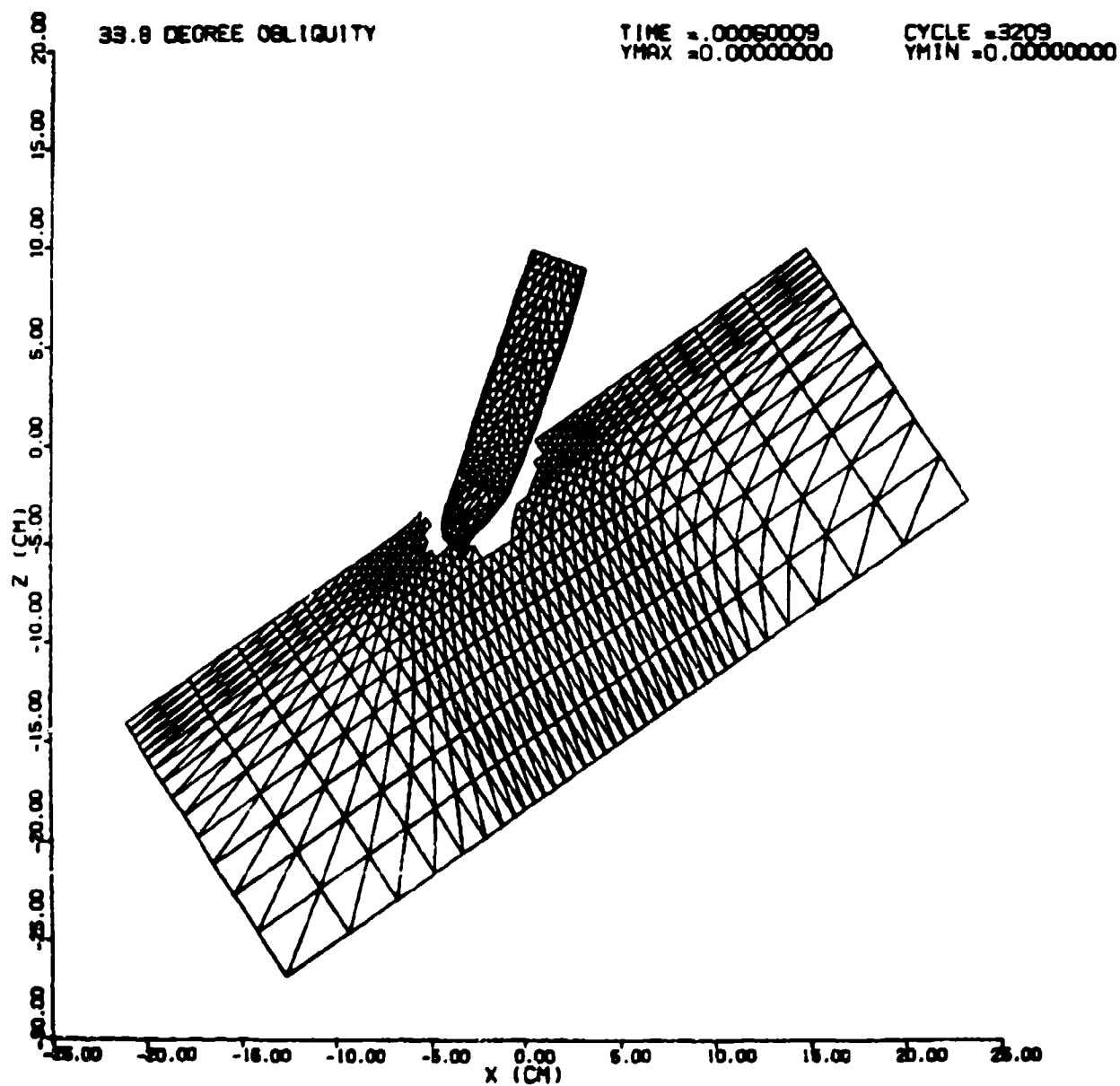


Figure A11. Deformation Profile for 33.8° Obliquity at $T = 60 \mu s$

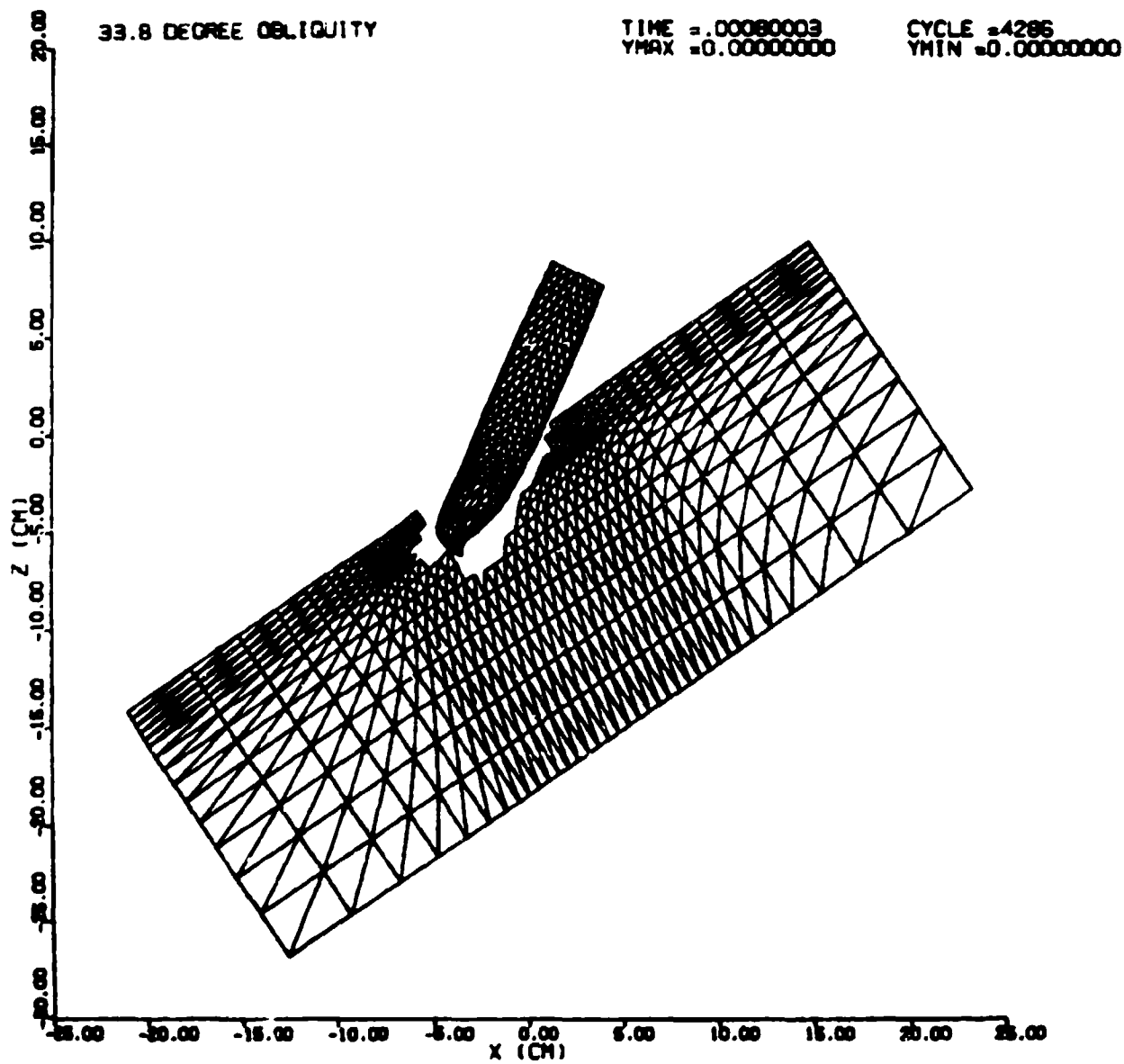


Figure A12. Deformation Profile for 33.8° Obliquity at $\tau = 80 \mu s$

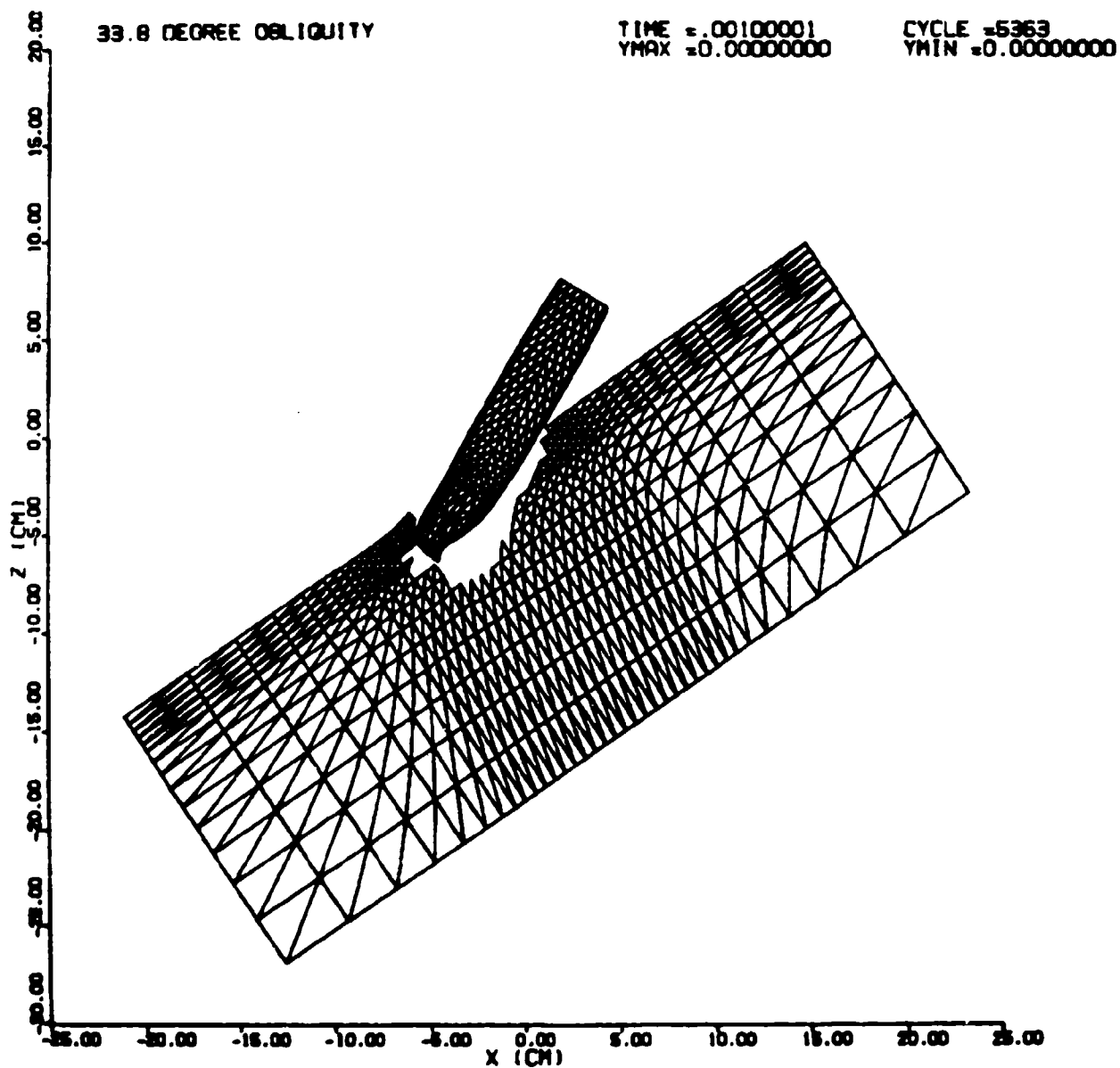


Figure A13. Deformation Profile for 33.8° Obliquity at $T = 100 \mu s$

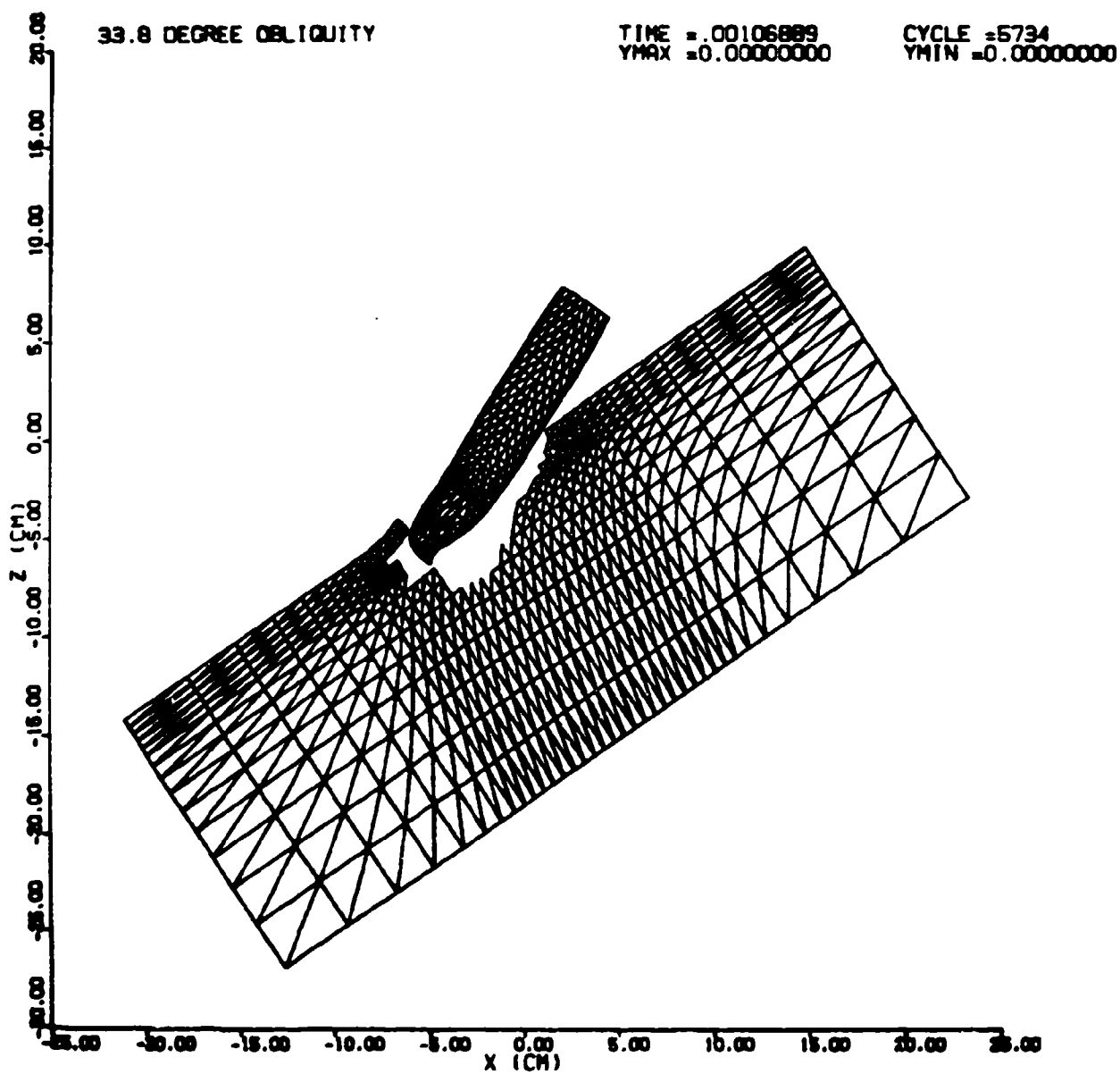


Figure A14. Deformation Profile for 33.8° Obliquity at $T = 106.9 \mu s$

APPENDIX B

Input Data for EPIC-3 Preprocessor for 33.8° Obliquity

.080 PROJECTILE. V=750 FPS. IMPACT ANGLE=56.2 DEG (FROM HORIZONTAL)

606	1	0	1	1	0	0	0	1	4	0	15
1	11045 STEEL RC 29										
.000725	830000.	2303000.	42693000.	72513000.				1.2			.2
11500000.	180000.	240000.	.04	1000000.				0.			1.
999.	999.	999.	70.								
2	TRITONAL EXPLOSIVE SIMULANT										
.000136	999999.	20143.	0.	0.				0.			.2
15048.	309.	309.	1.	1000000.				0.			1.
999.	999.	999.	70.								
3	CONCRETE (OSBORN REPORT) 6300 PSI COMPRESSIVE STRENGTH										
.000204	560000.	70.	999.	999.				0.40			.2
1542000.	0.	0.	999.	430.				0.			1.
4112.	.002	116000.	.1	305000.				.2			875000.
11364000.	.2	6300.	-.03333	1.				.3333			30.47
1.	1.	1.	0.	0.				0.0			0.
2											
4	0	2	1	6.733	6.363			1.			
.162	.325			.487	.567						
.170	.341			.511	.591						
6.733	6.733			6.733	6.733						
6.363	6.363			6.363	6.363						
2											
4	0	2	1	6.000	5.627			1.			
.176	.353			.529	.609						
.180	.360			.540	.620						
6.000	6.000			6.000	6.000						
5.627	5.627			5.627	5.627						
2											
4	0	5	1	5.260	3.766			1.			
.182	.363			.545	.625						
.182	.363			.545	.625						
5.260	5.260			5.260	5.260						
3.766	3.766			3.766	3.766						
2											
4	0	2	1	3.451	3.132			1.			
.181	.362			.543	.623						
.177	.355			.532	.612						
3.451	3.451			3.451	3.451						
3.132	3.132			3.132	3.132						
2											
4	0	2	1	2.428	2.539			1.			
.171	.343			.514	.594						
.164	.328			.492	.572						
2.428	2.428			2.428	2.428						
2.539	2.539			2.539	2.539						
2											
4	0	2	1	2.263	2.000			1.			
.157	.313			.470	.550						
.148	.296			.444	.524						
2.263	2.263			2.263	2.263						
2.000	2.000			2.000	2.000						
3											
4	0	3	1	.524	0.			2.		0.	
.148	.296			.444	.524						
1.000	.600			.156	0.						
1.	1.			1.	-1.5			0.		-33.8	0.
4	2										
37	13	13	9	12	1			1.30	.35294	1.02	.4
-8.5	0.			0.				8.5	5.6	-6.	1.20

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