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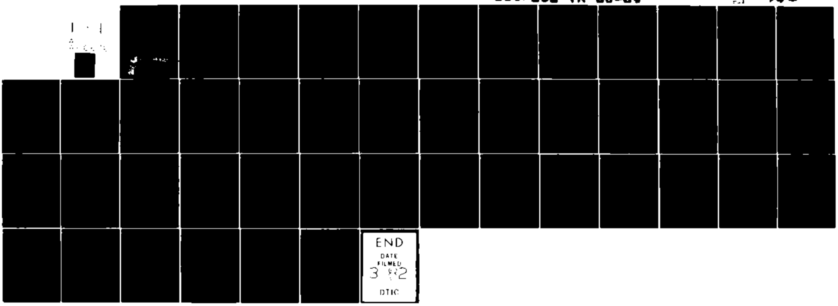

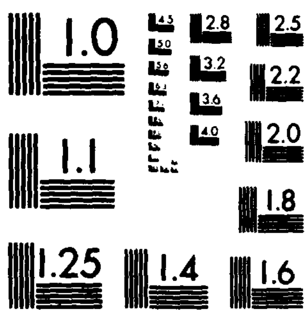

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BOMB DAMAGE REPAIR CODE FOR PREDICTION OF REPAIRED CRATER PERFORMANCE

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A nonlinear, finite-element computer code was developed for use in predicting the performance of repaired bomb craters. The code is capable of calculating the stresses, strains, and deflections produced by single- and multiple-wheel aircraft gear configurations. The apparent crater profile can be input as a series of linear approximations that is used by the code to modify material properties to reflect pushback and fallback crater debris from in situ native materials.

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PREFACE

This report was prepared by the New Mexico Engineering Research Institute, University of New Mexico, at the Eric H. Wang Civil Engineering Research Facility, Kirtland Air Force Base, New Mexico under Contract F29601-76-C-0015, Job Order 21042B47 for the Rapid Runway Repair Branch, Engineering and Services Laboratory, Headquarters Air Force Engineering and Services Center, Tyndall Air Force Base, Florida.

This report summarizes work done between September 27, 1978 and September 30, 1980. The author wishes to thank Ms. Georgine Durka of the New Mexico Engineering Research Institute (NMERI) Computer Support Division for her extensive programming effort in the development of the NMERI Bomb Damage Repair (BDR) code. Appreciation is extended to Mr. John Crawford of the Control Data Corporation, Los Angeles, CA for the reorganization and modifications performed on the AFPAV code that allowed NMERI to develop the BDR code for AFESC/RDCR. Mr. Phillip Nash was the Project Officer.

This report has been reviewed by the Information Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I
INTRODUCTION

BACKGROUND

Runways and taxiways have become the weakest link in the chain of defense for a military air base. Due to the improved technology in the area of aircraft protective shelter design, aircraft and shelters are no longer considered primary targets. Attack efforts have been redirected to the runways and taxiways with the thinking being that a severely damaged runway must be repaired before aircraft can operate, thereby decreasing the defensive and offensive strength of the opponent. As a result the U.S. Air Force has initiated an extensive program in rapid runway repair (RRR) emphasizing bomb damage repair (BDR) to evaluate and improve repair techniques and materials. The ultimate goals of the RRR program are (1) assess the damage and repair the runway in the least amount of time so that aircraft will be able to operate, and (2) utilize techniques and materials in the repair process such that the runway will remain operational for the longest possible time without deterioration of the repair (i.e., rutting, roughness, or excessive deflection under load).

The Air Force has studied repair techniques and materials by performing field tests on scaled bomb craters. Field testing is a valuable tool for evaluation of techniques and materials. This method is expensive, requires construction personnel and equipment, and is time consuming. Consequently, when a large number of variables needs to be studied field testing becomes prohibitive with respect to funding and time. Therefore, included in the RRR program was the development of computer codes to evaluate the performance of repaired bomb craters.

With the onset of the space program, electronic components have been significantly improved and have directly affected the computer industry. Computers have greater capabilities and can be operated at a lower cost than ever before. This has caused increased use of the computer to solve and analyze problems in minutes that otherwise would have taken hours or days. A computer code that could predict the performance of a repaired bomb crater would reduce the cost and time required to evaluate different variables pertaining to the repair process.

A finite-element computer program was developed by the Civil Engineering Laboratory, formerly NCEL, in Port Hueneme, California, for analyzing repaired bomb craters (References 1, 2, and 3). This code (NCEL BDR) is an axisymmetric, nonlinear, finite-element code composed of two main programs, GEN2D and WINDAX. GEN2D is a preprocessor program that generates the data (i.e., nodal point coordinates, element definition, load representation, and material property definition) pertinent to the finite-element mesh for the problem. The output from GEN2D is input to WINDAX which solves the problem and outputs the computer displacements, stresses, and strains for the finite-element mesh. The NCEL BDR code has been used to analyze scale and full-size crater repairs but has not been extensively utilized in RRR research due to several disadvantages of the code.

The first disadvantage concerns the method by which a finite-element mesh is input or generated utilizing GEN2D and how the crater profile and element material properties are defined. To develop a finite-element mesh for a specific problem the user has two options: (1) use a scale drawing of the problem from which all nodal point coordinates and element locations can be obtained for input on cards to GEN2D, or (2) use the nodal point and element generator in GEN2D to calculate coordinates and location of the nodes and elements. Method 1 requires that the user specify each nodal point with an X and Y coordinate and define each element according to its connectivity (i.e., node points at the corners of the elements) and material property identification. A problem with 400 elements would require approximately 400 nodal point cards and 400 element definition cards. Method 2 requires less work, but not significantly less. With Method 2 the user must specify points in the mesh that are

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1. Forrest, James B., and Shugar, T.A., *A Structural Evaluation of Rapid Methods of Backfilling for Bomb Damage Repair*, AFWL-TR-73-29, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, March 1974.
2. Crawford, John, and Forrest, James B., *A Structural Evaluation of Rapid Methods of Backfilling for Bomb Damage Repair - Phase II*, AFWL-TR-74-272, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, August 1975.
3. Baird, Glenn T., *Evaluation of Sustitute Input for NCEL Bomb Damage Repair Code*, AFCEC-TR-76-4, Air Force Civil Engineering Center, Tyndall Air Force Base, Florida, March 1976.

transition points according to crater geometry or material property identification. Between these points the GEN2D generator can be used to complete the finite-element mesh. This method still requires a scale drawing and does not significantly reduce the work required by the user. Both methods are prone to input errors due to the tedious nature of the procedure.

The second characteristic of the NCEL BDR code that caused difficulty is the manner by which the stress-strain behavior of the material is defined. Material properties, specifically the bulk and shear moduli, K and G, respectively, are input to the code as a function of the volumetric strain the material undergoes. The bulk modulus of a soil material is determined in the laboratory test by measuring the volumetric strain--the volume of expelled pore water from a saturated sample--as it is hydrostatically (i.e., vertical stress, σ_1, and horizontal stress, σ_2 and σ_3, are equal) compressed. This test is typically performed on a triaxial test specimen before the sample is sheared. A plot of volumetric strain versus hydrostatic pressure is known as a hydrostat or hydrostatic compression curve and the slope of the curve is the bulk modulus, K.

The shear modulus, G, is evaluated by means of a more complicated test known as the constant mean normal stress test. Mean normal stress is defined as the sum of the principal stresses divided by 3,$(\sigma_1 + \sigma_2 + \sigma_3)/3$. For a conventional triaxial test specimen the vertical stress, σ_1, must increase twice the amount that the horizontal stress, σ_3, is decreased. Similarly, if σ_1 is decreased σ_3 must be increased such that the mean normal stress remains a constant. The test is performed by initially placing the sample under a hydrostatic state of stress corresponding to a selected value of mean normal stress. The vertical stress and horizontal stress are then simultaneously adjusted according to the previous technique. Measurements of the volumetric and vertical strains are recorded and are used with the stresses to calculate the shear modulus, G, for the selected mean normal stress. Additional tests are performed at different values of mean normal stress to determine the variation of the shear modulus with mean normal stress.

Finally, the NCEL BDR code, an axisymmetric finite-element code, is most accurately utilized to model and analyze problems that have axisymmetric geometry. That is, there is no change in the material properties, boundary conditions, or loading configuration in the circumferential direction. Relating this to the RRR problems, a crater would have approximately the same properties and geometry independent of what profile was analyzed. However, when the analysis involves a multiple-wheel landing gear configuration, the problem deviates significantly from the axisymmetric situation. For example, the C5A main landing gear consists of 6 tires. It would be impossible to input this configuration into an axisymmetric computer code and obtain reasonable output results. A single-wheel landing gear produces a tire contact area that is ellipsoidal in shape but is represented by a rectangular area. If the stresses in the immediate vicinity of the load are not to be considered, the rectangular contact area can be approximated by an equivalent circular area without significant error being introduced to the results at distances removed from the load. This is the principle of Saint Venant which states that the stresses and strains at some distance from the point of application of the load are relatively unaffected by the manner in which the load is applied. Therefore, to accurately model both single-wheel and multiple-wheel gear configurations, two computer codes would be required.

OBJECTIVE

The objective of this subtask was to develop a New Mexico Engineering Research Institute (NMERI) BDR code that would consist of the NCEL BDR code (i.e., GEN2D and WINDAX) and the AFPAV code, a prismatic solid finite-element code that is presently utilized to analyze multiple-wheel aircraft pavement problems. The merging of the two codes would allow single-wheel problems to be analyzed using AFPAV. However, after a significant effort was made to combine the codes it was discovered that the amount of computer core required to compile the programs and solve relatively simple problems bordered on the capacity of the Eglin AFB computer. The objective was changed to perform modifications on the AFPAV computer code to allow solution of axisymmetric single-wheel problems while retaining the multiple-wheel capability of the AFPAV code. The resulting BDR code would include the AFPAV preprocessor programs that allow the user to input the minimum amount of aircraft characteristics, crater geometry, and material property identification necessary to define the problem and generate a finite-element mesh for analysis.

SCOPE

The scope included development of a method to estimate the shear modulus and stress-strain behavior of repair materials using Hardin's (Reference 4) nonlinear stress-strain constitutive model. In so doing the only properties required to characterize the repair materials behavior are plasticity index, dry density, water content, gradation, and unified soil classification. The crater geometry would be input to the code to define the boundary between backfill materials and disturbed in situ materials. The code would be verified by comparing computer responses with data from field tests. Output from the code would be displayed both graphically and in tabular form.

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4. Hardin, Bobby O., *Constitutive Relations for Airfield Subgrade and Base Course Materials*, Technical Report UKY 32-71-CE5, Soil Mechanics Series No. 4, University of Kentucky.

SECTION II
CODE MODIFICATIONS AND OPERATION

The NMERI BDR computer code that has been developed for the Air Force Engineering Services Center (AFESC/RDCR) is a nonlinear finite-element code with the capability to solve both axisymmetric and prismatic solid problems. As stated earlier the original NCEL BDR computer code could not be utilized as originally proposed in the statement of work for the subtask. The NCEL BDR code, specifically WINDAX, utilized an in-core equation solver to evaluate the stiffness matrix of the entire finite-element mesh. The amount of core necessary to compile the code and solve simple problems approaches the limit of core available on the Eglin AFB computer system. To perform more complicated problems would require additional core which would exceed the capabilities of the Eglin AFB computer. Therefore it was decided to utilize the AFPAV pavement code (Reference 5) with an out-of-core solver that minimizes the core requirements. To solve axisymmetric problems it was necessary to perform modifications to the AFPAV code. These modifications pertain to the incorporation of an axisymmetric stiffness array and constitutive equations that define the loading conditions and stress-strain relationships.

The soil constitutive equations are those for basic elastic materials. Nonlinear stress-strain behavior as defined by Hardin's nonlinear hyperbolic shear strain relationship (Reference 4) is incorporated into the computer code. In this approach a series of calculations is performed and the resulting shear strain is compared with a normalized shear strain curve for the material, based on inputted material properties and soil indexes. Successive calculations are performed utilizing decreasing shear moduli values to account for the shear strain. The procedure can be thought of as performing a series of linear calculations using various secant shear moduli until the calculated shear strain and shear stress agree with the normalized curve.

The crater profile is input as a series of six points starting at the bottom center of the crater and progressing upward to the surface and lip of the crater. The X-coordinates (horizontal distance) and Y-coordinates (vertical depth) are input as positive and negative values respectively in units of

5. Nielsen, John P., *AFPAV Computer Code for Structural Analysis of Airfield Pavements*, AFWL-TR-75-151, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1975.

inches. A subroutine has been developed that utilizes these coordinates to determine if an element is inside or outside the crater. If the element is outside the crater the material identification of the element is changed to agree with the native material, the last inputted material. This causes the crater profile to be stepped rather than piecewise linear (Figure 1). This, however, has an insignificant effect on the calculated stresses, strains, and displacements.

Both single-wheel and multiple-wheel aircraft effects can be analyzed using the NMERI BDR code. The aircraft presently included in the code are presented in Table 1 (Reference 6). The code allows for standard default values of tire pressure and individual tire loads to the basic mission aircraft weight. However, tire pressure and tire load can be input, and these will override the default values. Included in Table 1 are the default values for each aircraft that is incorporated into the code.

In many BDR applications the user may not have any knowledge of the strength or stiffness of the materials in the crater. For this reason two options have been incorporated into the code. The first option is a list of default elastic modulii and Poisson's ratios according to the type of material that could be used in the solution of the problem. The second option requires knowledge of the material's unit weight, water content, plasticity index, and gradation. This information can then be used to generate an elastic modulus based on the void ratio and in situ stresses. Details on how these options are selected are given in Appendix A.

The generation of the elastic modulus for a material is based on the torsional resonant column (Reference 4). The specific equation incorporated in the code is

$$G = \frac{1230\ (2.973 - e)^2}{1 + e} \qquad (1)$$

where

G = shear modulus (lb/in^2)

e = void ratio

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6. Hay, D. R., *Aircraft Characteristics for Airfield Pavement Design*, AFWL-TR-69-54, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1969.

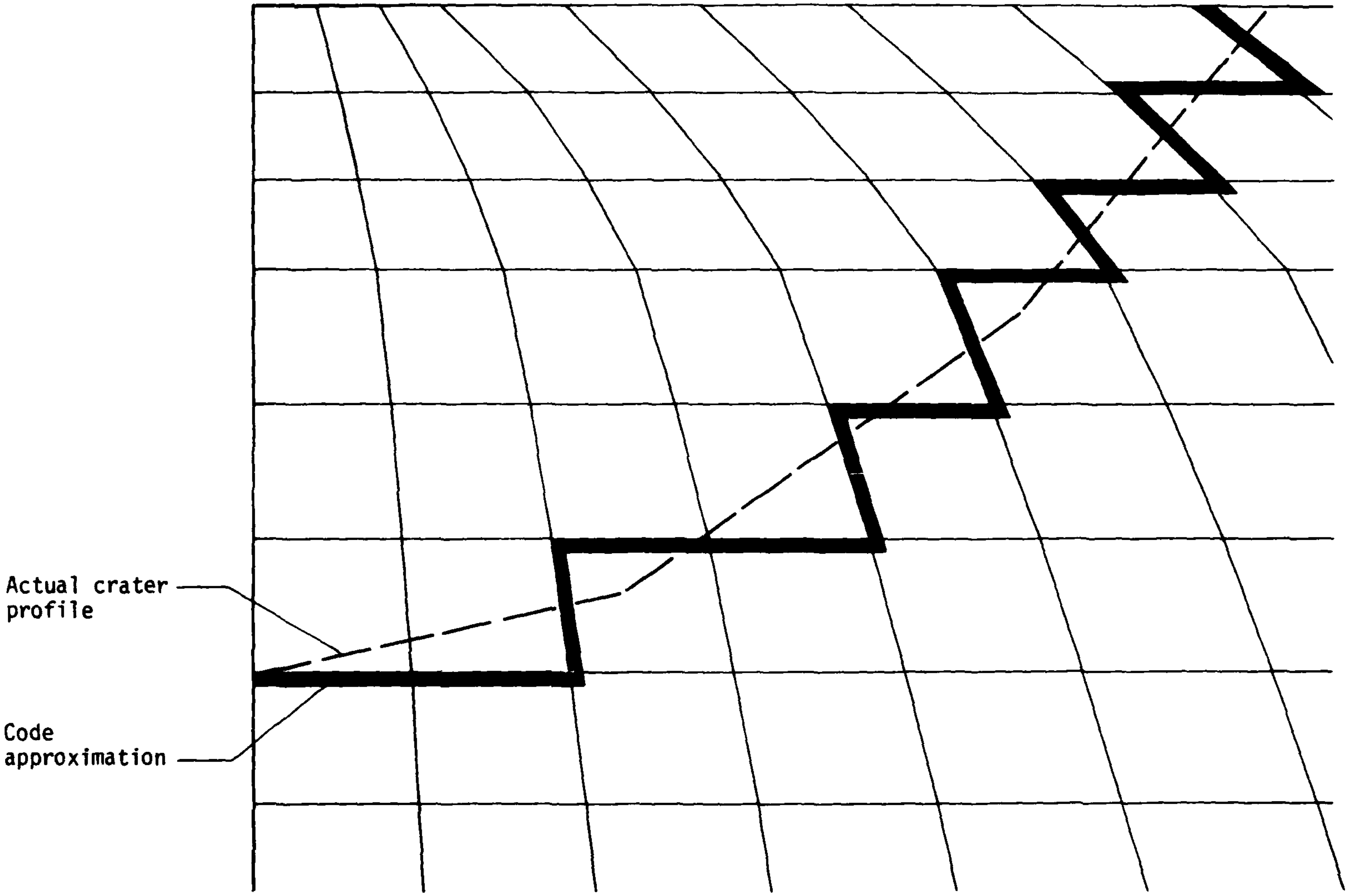

Figure 1. Code crater profile approximation.

TABLE 1. AIRCRAFT DEFAULT CHARACTERISTICS

Aircraft	Wheel configuration*	Tire pressure, lb/in^2	Wheel load, lb
A10	S W	213	20,600
F4	S W	265	27,000
F15	S W	260	23,400
F16	S W	275	15,000
F105	S W	220	23,400
F111	S W	150	47,000
FB111A	S W	215	54,000
T38	S W	250	5,650
T43	S W	148	27,000
B1	M W	195	40,500
B52	M W	285	67,100
B57	M W	152	27,700
B747	M W	204	41,600
C5	M W	115	30,100
C9A	M W	148	25,800
C130	M W	95	41,900
C141	M W	180	37,400
KC97	M W	180	44,500
KC135	M W	155	35,500

*S W--single-wheel main gear
M W--multiple-wheel main gear

The void ratio is calculated from the material's wet unit weight and water content using the equations

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + w} \tag{2}$$

$$e = \frac{G\gamma_w}{\gamma_{dry}} - 1 \tag{3}$$

where γ_{dry} = dry unit weight (lb/ft^3)

γ_{wet} = wet unit weight (lb/ft^3)

W = water content

G = specific gravity of solids

γ_w = unit weight of water

The specific gravity of solids is preset in the program to 2.65 and the unit weight of water to 62.4 lb/ft^3. These values can be changed by modifying the data statements in the program.

To characterize the material nonlinear behavior it is necessary to input a value for the variable STYPE, soil type. A general description of the materials and values for STYPE is given in Appendix A. A linear material is defined as STYPE equal to zero. All materials are assumed to be linear unless another value is input independent of whether the elastic moduli are default values, are generated from the void ratio, or are input onto the material property card. Default values for the types of crater materials are presented in Table 2. The default values can be changed in the data statements if other values are desired.

TABLE 2. MATERIAL PROPERTY DEFAULT VALUES

	Material identification code (MATID)	Elastic modulus, lb/in^2	Poisson's ratio
Concrete	C	3,000,000	0.15
Asphalt	A	700,000	0.43
Crushed limestone	L	100,000	0.25
Landing mat	M	100,000	0
Stabilized material	S	50,000	0.30
Base course material	B	10,000	0.30
Compacted pushback	P	5,000	0.37
Native material	N	5,000	0.43
Special material	X	5,000	0.40
Fallback/pushback	F	3,000	0.40

The NMERI BDR code output consists of (1) nodal point deflections at the surface and at each material layer interface; and (2) stresses and strains for those elements vertically along the centerline of the crater, elements beneath the tire load, and elements at the top and bottom of the material layers. These data are printed out for nodal points and elements sequentially. Plotting routines have been developed that provide the following types of plots: (1) stress versus depth along the centerline, (2) stress versus depth beneath the load, (3) stress versus horizontal distance for the elements at the top and bottom of the material layers, and (4) plots of strain similar to (2) and (3) and displacement versus horizontal distance at material layer interfaces.

Algorithms are incorporated into the code that allow the user to estimate the repair capacity in terms of aircraft coverages. The algorithms are the result of best least squares linear fit to data obtained from Figure 2 (Reference 7). The equations are

$$\log A = C_1 + C_2 \log PSI + C_3 WLOAD + C_4 (WLOAD) \log PSI$$

$$\log COV = C_5 + C_6 \log A + C_7 \log CBR + C_8 \log A \log CBR$$

where

A = parameter based on tire pressure and wheel load

PSI = tire pressure (lb/in^2)

WLOAD = wheel load (lb)

COV = coverages

CBR = California bearing ratio

$C_1, C_2 \ldots C_8$ = regression analysis constants

C_1 = -0.36479866

C_2 = 0.88933751

C_3 = 9.2262945E-6

C_4 = -5.7010068E-7

C_5 = 5.79949030

C_6 = -5.94366123

C_7 = 6.24183530

C_8 = -0.10033645

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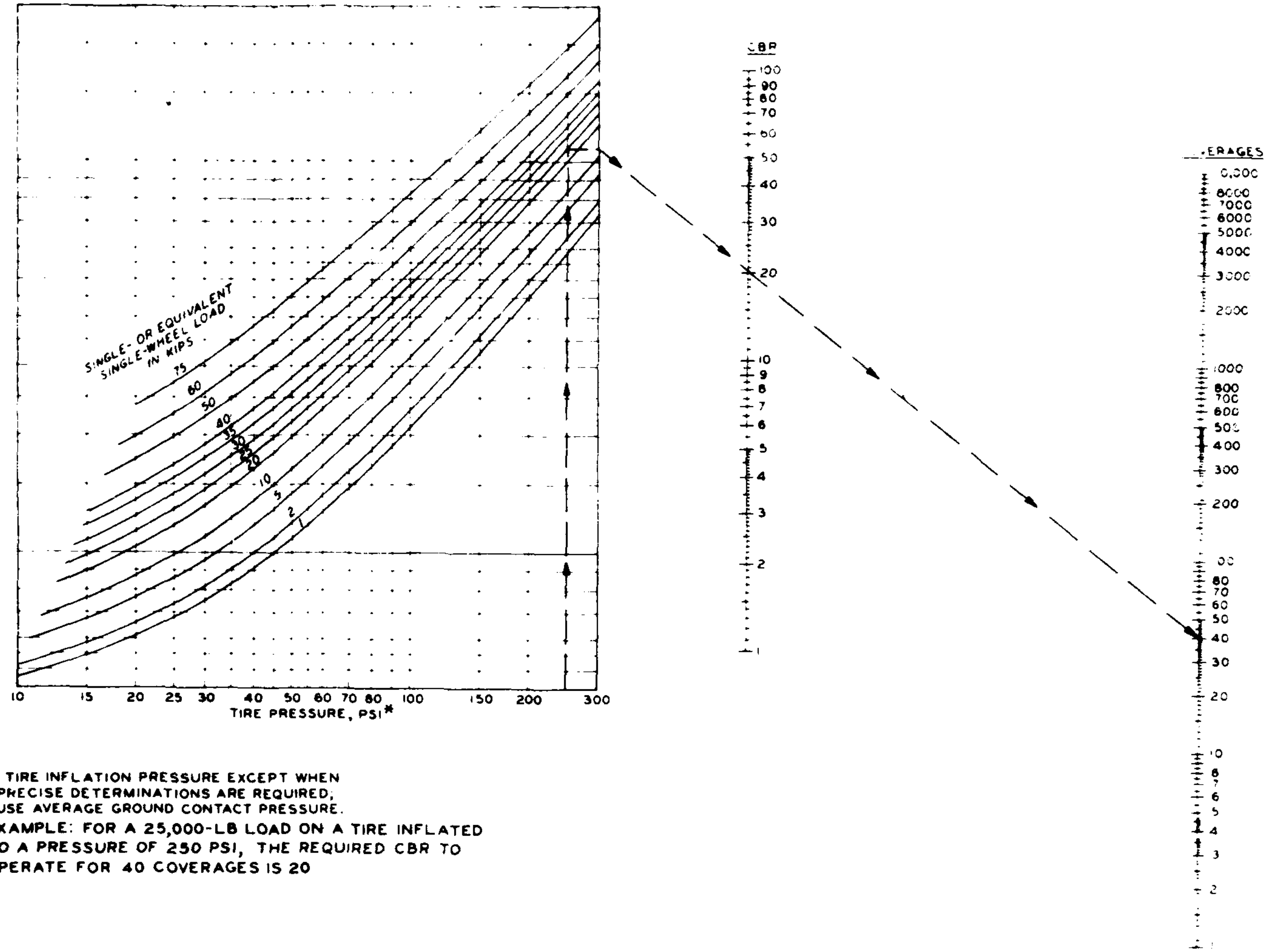
7. Ladd, D. M., *Soil Strength Criteria for Operation of Fighter Aircraft on Unsurfaced Airfields, Bare Base Support*, Miscellaneous Paper S-70-24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi; sponsored by U.S. Air Force, Project 3782-65, September 1970.



* USE TIRE INFLATION PRESSURE EXCEPT WHEN MORE PRECISE DETERMINATIONS ARE REQUIRED; THEN USE AVERAGE GROUND CONTACT PRESSURE.

EXAMPLE: FOR A 25,000-LB LOAD ON A TIRE INFLATED TO A PRESSURE OF 250 PSI, THE REQUIRED CBR TO OPERATE FOR 40 COVERAGES IS 20

Figure 2. CBR required for operation of aircraft on unsurfaced soils (Reference 7).

The estimated repair capacity is based on the CBR of the surface material. The algorithms were developed from Figure 2 with an r^2-value of greater than 97 percent. However, comparison of data using the algorithms with the graphical technique of the nomograph indicates the algorithms are conservative and underestimate the repair capacity coverage level.

If the CBR-value is not input an estimate is calculated using the following equation

$$CBR = \frac{G - 1150}{586}$$

where

G = shear modulus (lb/in^2)

This equation was developed from a correlation study (Reference 8) involving the elastic modulus, E, from nondestructive wave propagation techniques for pavement and CBR as determined by conventional destructive testing. The shear modulus, G, has been substituted into the equation for two reasons. First, the correlation study utilized wave propagation techniques that are performed at very low strain levels as opposed to a rutting phenomenon that occurs at large strain levels. Secondly, the problem is more appropriately a shear problem than a compressibility problem. This method is included in the code only as an estimate of repair capacity. As with all the calculated data provided by the code, the repair capacity algorithm needs to be verifed before adoption. Other failure criteria should be reviewed as they become available for their applicability to BDR.

---

8. Steedman, David, "A Correlation Study Between Non-Destructive and Conventional Test Data on Flexible Airfield Pavements," problem submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, University of New Mexico, Albuquerque, New Mexico, May 1979.

SECTION III
CODE VERIFICATION

To verify the results of the computer code a series of elastic layered solutions was developed. The first and simplest is the homogeneous half-space Boussinesq problem with a circular plate load. Figure 3 shows the NMERI BDR code vertical stress results along with the vertical stress calculated by the Boussinesq equation. The BDR code appears to calculate slightly lower stresses than Boussinesq but the difference is insignificant. The average vertical deflection of the loaded area according to Boussinesq should be 0.0994 inch. The BDR code calculated an average vertical deflection of 0.122 inch, approximately 22.7 percent greater deflection.

A second problem consisted of a single layer overlying a semi-infinite half-space. The top layer had an elastic modulus of 20,000 lb/in^2 and Poisson's ratio of 0.5. The semi-infinite half-space had an elastic modulus of 5,000 lb/in^2 and Poisson's ratio of 0.5. The properties input to the code were 20,000 lb/in^2 and 0.48 and 5,000 lb/in^2 and 0.48 for the top layer and semi-infinite half-space respectively. Figure 4 shows the calculated vertical stress profiles with depth. The differences between the two calculations in the top layer is less than 20 percent and less than 13 percent in the half-space. Elastic two-layer theory predicts a deflection of 0.0972 inch while the BDR code estimates 0.0614 inch average loaded area deflection, approximately 36.7 percent less.

Using plate load test results on crater materials [Figures 5 and 6 (Reference 9)] moduli were calculated by elastic layered theory for the pushback, compacted pushback, and crushed limestone layers of Tyndall crater 1-2. The first problem in this series was 13 inches of compacted pushback on 82 inches of pushback/fallback material. Moduli values of 5000 lb/in^2 and 1500 lb/in^2 were calculated for the compacted pushback and pushback/fallback materials respectively. These data were input to the BDR code. The actual measured deflection was 0.44 inch, and the average calculated deflection of the nodal points under the load was 0.483 inch, approximately 10 percent greater.

---

9. Hokanson, Lawrence D., *Tyndall AFB Bomb Damage Repair Field Test, Documentation and Analysis Final Report*, AFWL-TR-74-226, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1975.

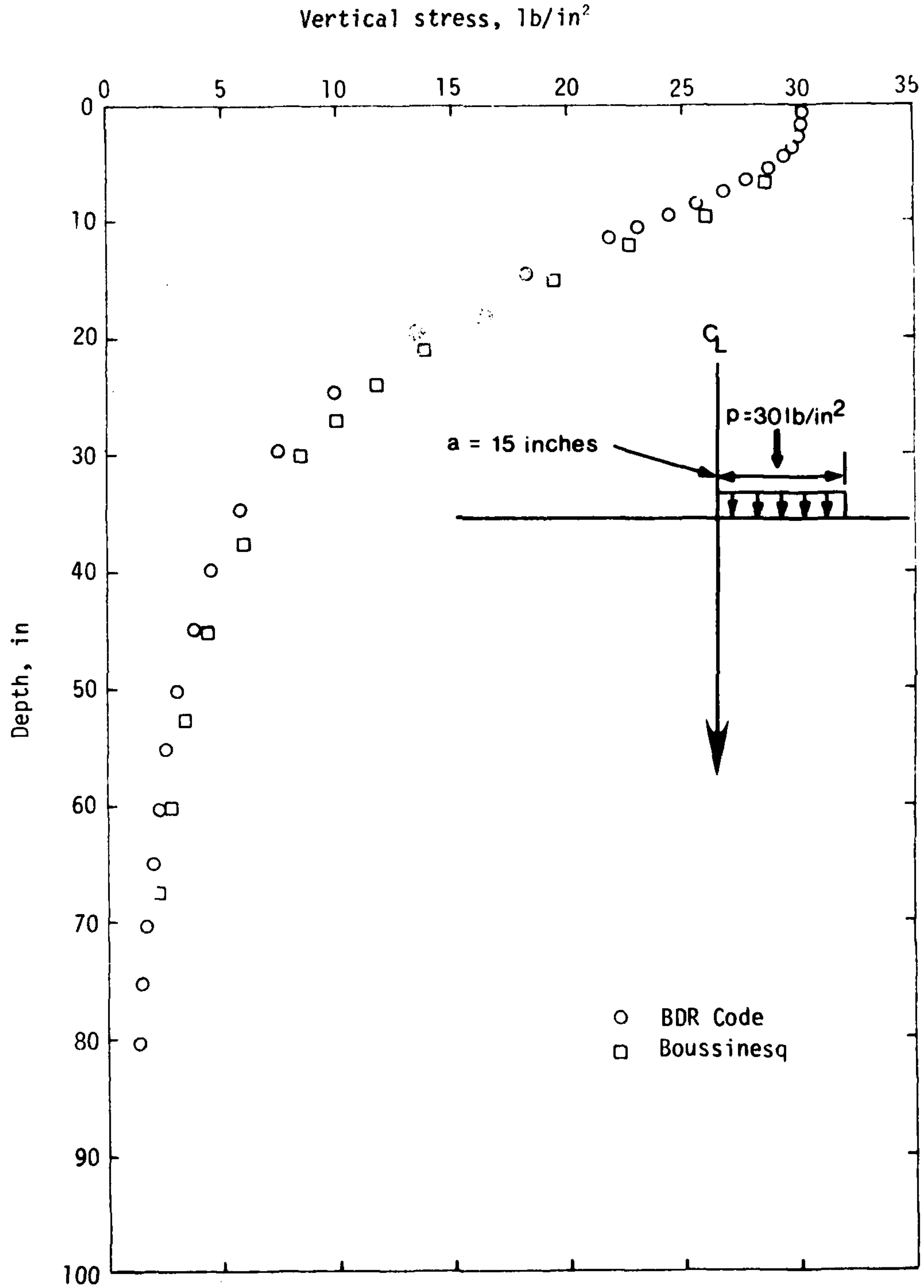


Figure 3. Boussinesq and BDR code vertical stress profiles.

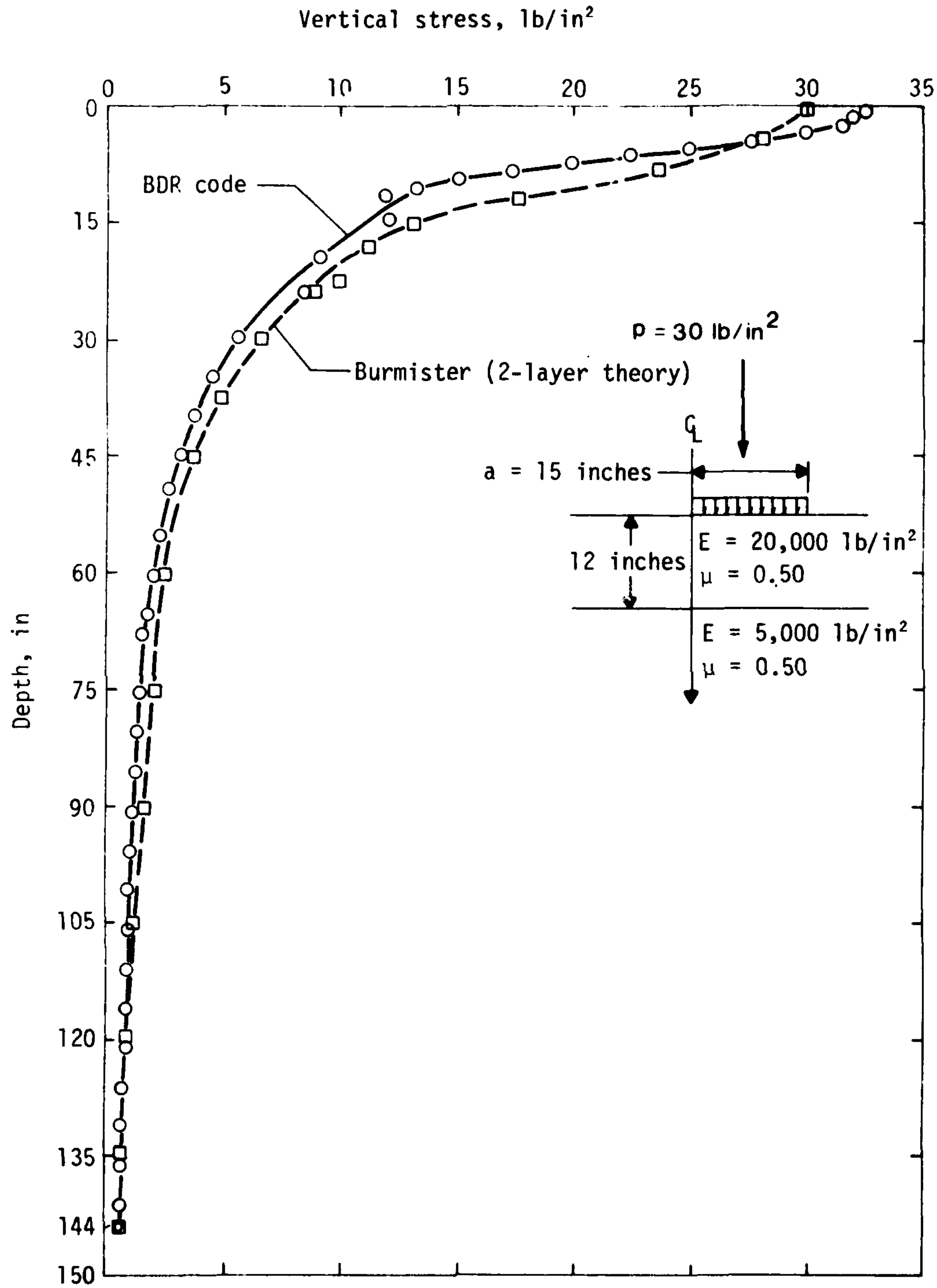


Figure 4. Two-layer theoretical and BDR code vertical stress profiles.

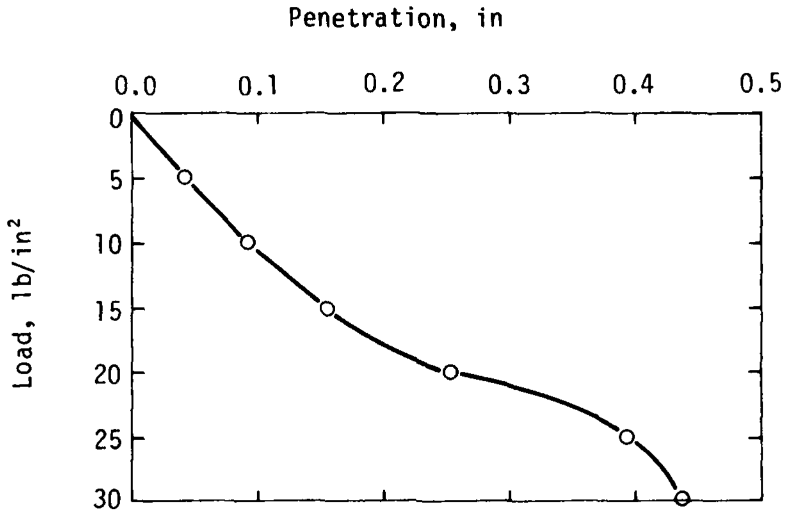


Figure 5. Plate bearing on compacted pushback material.

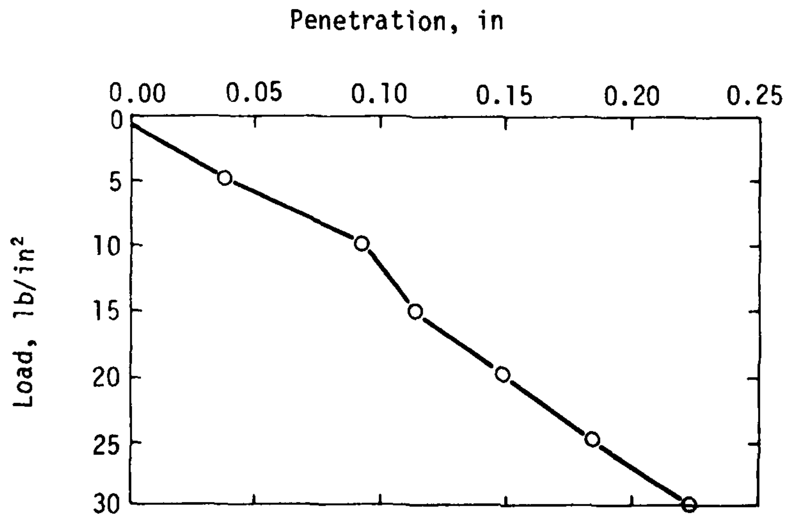


Figure 6. Plate bearing on crushed limestone material.

A second problem in this series consisted of 24 inches of crushed limestone, 24 inches of compacted pushback, and 82 inches of pushback/fallback material. The elastic moduli of the materials were 90,000, 5000, and 1500 lb/in^2 respectively. The actual measured deflection at 30 lb/in^2 load (Figure 6) was 0.223 inch, and the average loaded area deflection from the code was 0.325 inch, approximatley 46 percent greater deflection.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

Due to limitations of the Eglin AFB computer system hardware it was necessary to redirect the task to allow operation of a computer code for bomb damage repair calculations. WINDAX, an axisymmetric finite-element code, utilizes an in-core solving routine which requires the entire finite-element mesh and associated element stiffnesses to be simultaneously solved for the problem. This placed large core memory requirements for basic BDR problems. It was decided to modify the PREDIC pavement analysis code which utilizes an out-of-core solver to perform axisymmetric analyses of a repaired bomb crater. Subroutines were developed that account for the geometry of the crater and differences in material properties. If material properties are not known, the user has the option to use default values or generate properties based on density, water content, and void ratio.

A series of verification problems was performed that indicates the code can calculate stress levels and deflections to within 50 percent of the values estimated using elastic layered theory. Comparisons were made with predicted and measured deflections for typical crater materials and agreement was within 50 percent. This indicates that the NMERI BDR code can be used to analyze repaired bomb crater performance if the material properties and crater profile information are known. If quantitative data are not required, qualitative information can be obtained through comparison of repaired crater profiles and material properties. To utilize the code as a prediction tool for the BDR program would require additional verifications where the material properties, crater profile, and crater performance (i.e. stress, strain, or deflection) are known with reasonable accuracy.

It is recommended that the TAXI code not be incorporated into the NMERI BDR code due to the amount of core memory that would be required. It is much simpler to operate the TAXI code using the output from the BDR code than to merge the two codes. The NMERI BDR code calculates the stresses, strains, and deflections due to a static aircraft load. The calculated deflection at the surface is essentially a static deflection basin and static deflection profile. To input a static deflection profile into the TAXI code would be inappropriate. A dynamic deflection profile, if input to the TAXI code, would provide a closer approximation to the profile actually felt by the aircraft.

If, however, a correlation could be established between the calculated static deflection and a roughest criteria or final crater profile after a number of passes or coverages of an aircraft, it would be possible to input the correlated crater profile to TAXI for prediction of aircraft response.

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9. Hokanson, Lawrence D., *Tyndall AFB Bomb Damage Repair Field Test, Documentation and Analysis Final Report*, AFWL-TR-74-226, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1975.

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APPENDIX A

NMERI BDR CODE

USER'S MANUAL

A. TITLE AND SOLUTION TYPE CARD (A8, 15A4, 2A2, 1X, A2, 1X, I2, 1X)

Column	Variable	Description
1-8	TITLE(1)	Aircraft name (left justified) F4, B52, F111, FB111A, B57, C130, C141, B747, B1, C5, T38, F105, KC135, C9A, F15, F16, KC97, T43, A10
9-72	TITLE(2)	Problem identification
74-75	LRWTP	Traffic type always = RR
78	NPLOT	Plot output 0 = no plots 1 = plots
80	SOLTYPE	Solution type A = axisymmetric P = prismatic solid

B. LOAD FACTORS AND PRINT CONTROL CARD (I2, 1X, F3.0, 2(1X, I1), 5X, 2F10.0, I5)

Column	Variable	Description
1-2	NUMLAY	Number of materials maximum = 10
4-6	PSI	Tire pressure (lb/in^2) 0 = default value
8	KPPRE	Print control for APRE output always = 1
10	KPPAV	Print control for APPAV output always = 1
16-25	WLOAD	Wheel load (lb) 1 = default value
26-35	CBR	Surface material CBR 0 = default value (CBR generated from shear modulus)
36-40	LCONCOP	Split tensile strength of material (lb/in^2) (must be LE 1500)

C. CRATER PROFILE COORDINATES CARD (6 F10.0)

	Column	Variable	Description
C1.	1-10	XCP(1)	X-coordinate of point 1
	11-20	YCP(1)	Y-coordinate of point 1
	21-30	XCP(2)	X-coordinate of point 2
	31-40	YCP(2)	Y-coordinate of point 2
	41-50	XCP(3)	X-coordinate of point 3
	51-60	YCP(3)	Y-coordinate of point 3
C2.	1-10	XCP(4)	X-coordinate of point 4
	11-20	YCP(4)	Y-coordinate of point 4
	21-30	XCP(5)	X-coordinate of point 5
	31-40	YCP(5)	Y-coordinate of point 5
	41-50	XCP(6)	X-coordinate of point 6
	51-60	YCP(6)	Y-coordinate of point 6

Note: Coordinates must be input beginning at the bottom centerline of the crater and progressing vertically to the crater edge. Therefore XCP(1) will always equal zero, YCP(1) will correspond to the depth of the true crater, XCP(6) will correspond to the crater radius, and YCP(6) will always equal zero. All X-coordinates must be positive and all Y-coordinates must be negative. All coordinates are in inches. If no profile is desired, insert two blank cards.

D. MATERIAL PROPERTY CARDS (F4.0, 1X, A1, I1, F8.0, 1X, F3.2, 5X, F1.0, 5X, F10.3, F5.3, 2X, F3.0, 3I1)

Column	Variable	Description
1-4	THICK	Material layer thickness (inches)
6	MATID	Material identification code C = concrete A = asphalt L = crushed limestone M = landing mat F = fallback/pushback P = compacted pushback S = stabilized material N = native material B = base course X = special material
7	MATCHSR	Modulus generation option 0 = PROPTY(1) is input. 1 = PROPTY(1) is generated from void ratio. [STYPE (column 25) must be 1, 2, 3, 4, or 5.] 1 = PROPTY(1) is default value for material. (STYPE must equal 0.)
8-15	PROPTY(1)	Elastic modulus (lb/in^2)
17-19	PROPTY(2)	Poisson's ratio 0 = default value User value must be GT.0 and LT 0.48.

Column	Variable	Description
25	STYPE	Material type 0 = linear stress-strain material 1 = nonplastic with fines, low plasticity 2 = high plasticity, LL > 50 3 = clean sands 4 = clean gravels, poorly graded sand/ gravel mixtures 5 = well-graded sand/gravel mixtures
31-40	WETDEN	Wet unit weight (lb/ft^3)
41-45	WATCON	Water content (percent)
48-50	PI	Plasticity index (percent)
51	KHARDN	Type of Hardin law 0 = shear modulus is a function of confining stress and shear strain and used to calculate new stiffness and stress output. 1 = shear modulus is a function of station pressure and station shear strain and used to calculate stress output only. 2 = shear modulus is a function of the shear strain only and used for calculation of new stiffness and stress output.
52	KGAMMA	Shear strain calculation 0 = shear strain used in stiffness matrix is maximum of station strains. 1 = shear strain used in stiffness matrix is average of station shear strains. 2 = shear strain used in stiffness matrix is minimum of station shear strains.
53	KCPRES	Confining pressure calculation 0 = maximum of station pressures is used to calculate stiffness. 1 = average of station pressures is used to calculate stiffness. 2 = minimum of station pressures is used to calculate stiffness.

Note: Confining pressure is negative for compression. Tensile confining pressures (positive) are not allowed in stiffness calculation. Material layers are input beginning at the surface. No thickness specification is required for the last material layer (i.e., native material).

E. END CARD (A3)

Column	Variable	Description
1-3	TITLE(1)	End of data identification Set = END for last card in data deck.

Repeat cards A-D for each problem. Only 1 E-card required per data deck.

MATERIAL PROPERTY DEFAULT VALUES

F	Fallback/pushback	3,000 lb/in^2	μ = 0.40
X	Special material	5,000	0.40
N	Native material	5,000	0.43
P	Compacted pushback	5,000	0.37
B	Base course material	10,000	0.30
S	Stabilized material	50,000	0.30
M	Landing mat	100,000	0
L	Crushed limestone	100,000	0.25
A	Ashpalt	700,000	0.43
C	Concrete	3,000,000	0.15

If default values are used, linear behavior is assumed unless variable STYPE is input.

AIRCRAFT DEFAULT VALUES

Aircraft	Wheel load, lb	Tire pressure, lb/in^2
A10	20,600	213
B1	40,500	195
B52	67,100	285
B57	27,700	152
B747	41,600	204
C5	30,100	115
C9A	25,800	148
C130	41,900	95
C141	37,400	180
F4	27,000	265
F15	23,400	260
F16	15,000	275
F105	23,400	220
F111	47,000	150
FB111A	54,000	215
KC97	44,500	180
KC135	35,500	155
T38	5,650	250
T43	27,000	148

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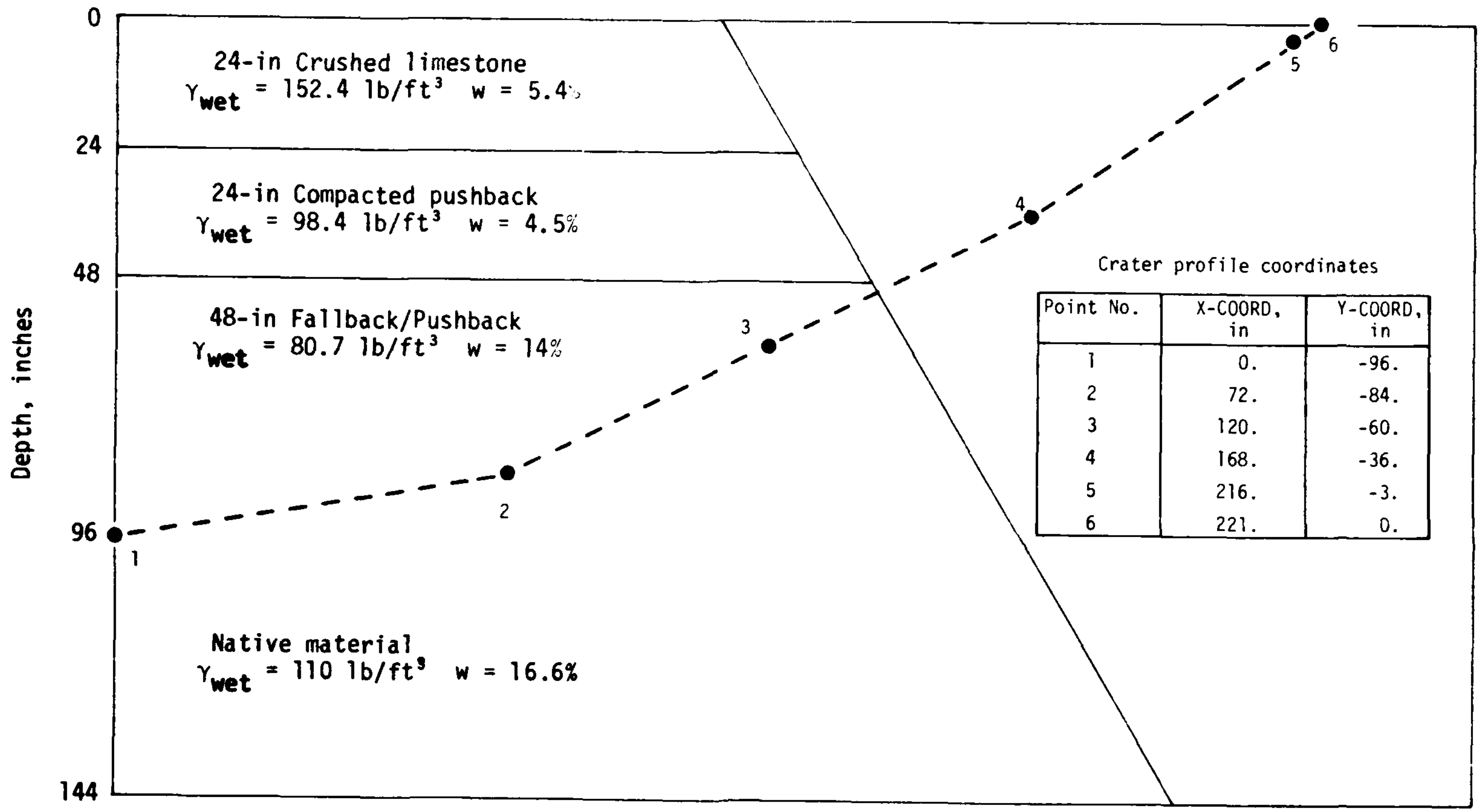
APPENDIX B
SAMPLE PROBLEM--INPUT/OUTPUT



Point No.	X-COORD, in	Y-COORD, in
1	0.	-96.
2	72.	-84.
3	120.	-60.
4	168.	-36.
5	216.	-3.
6	221.	0.

Figure B-1. Sample problem input data.

IBM FORTRAN Coding Form

NMERI BDR CODE SAMPLE PROBLEMS

```
F1:1      SAMPLE SINGLE WHEEL PROBLEM                             RR   O A
 4          1 1               1
0.              -96.      72.        -84.       120.       -60.
168.            -36.      216.       -3.        221.       0.
24.  L1                              152.4      5.4        002
24.  P2                              98.4       4.6        002
48.  F2                              80.7       14.        002
     N2                              110.       16.6       002
C130      SAMPLE MULTI-WHEEL PROBLEM                              RR   O P
 4          1 1               1
0.              -96.      72.        -84.       120.       -60.
168.            -36.      216.       -3.        221.       0.
24.  L1                              152.4      5.4        002
24.  P2                              98.4       4.6        002
48.  F2                              80.7       14.        002
     N2                              110.       16.6       002
END
```

Figure B-2. NMERI BDR code sample problems.

NODAL DISPLACEMENTS

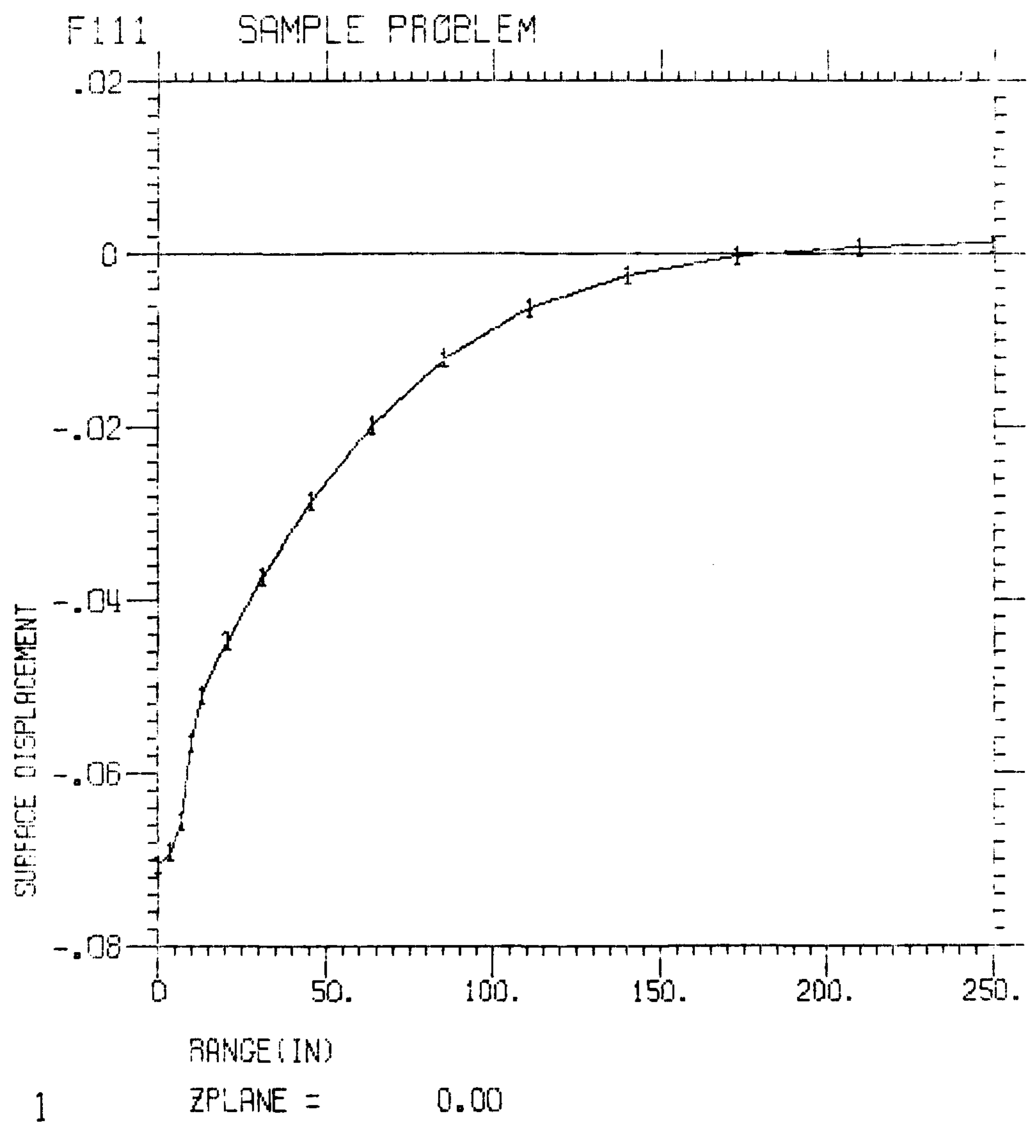
NODE POINT	U-X	U-Y	U-Z	Z-POSITION
1	0.	-.678E-01	0.	0.00
2	-.262E-02	-.664E-01	0.	0.00
3	-.495E-02	-.630E-01	0.	0.00
4	-.595E-02	-.538E-01	0.	0.00
5	-.584E-02	-.485E-01	0.	0.00
6	-.624E-02	-.422E-01	0.	0.00
7	-.612E-02	-.347E-01	0.	0.00
8	-.559E-02	-.262E-01	0.	0.00
9	-.447E-02	-.177E-01	0.	0.00
10	-.309E-02	-.104E-01	0.	0.00
11	-.178E-02	-.489E-02	0.	0.00
12	-.772E-03	-.147E-02	0.	0.00
13	-.132E-03	.282E-03	0.	0.00
14	.186E-03	.988E-03	0.	0.00
15	.278E-03	.124E-02	0.	0.00
16	0.	-.661E-01	0.	0.00
31	0.	-.640E-01	0.	0.00

Figure B-3. Nodal displacements.

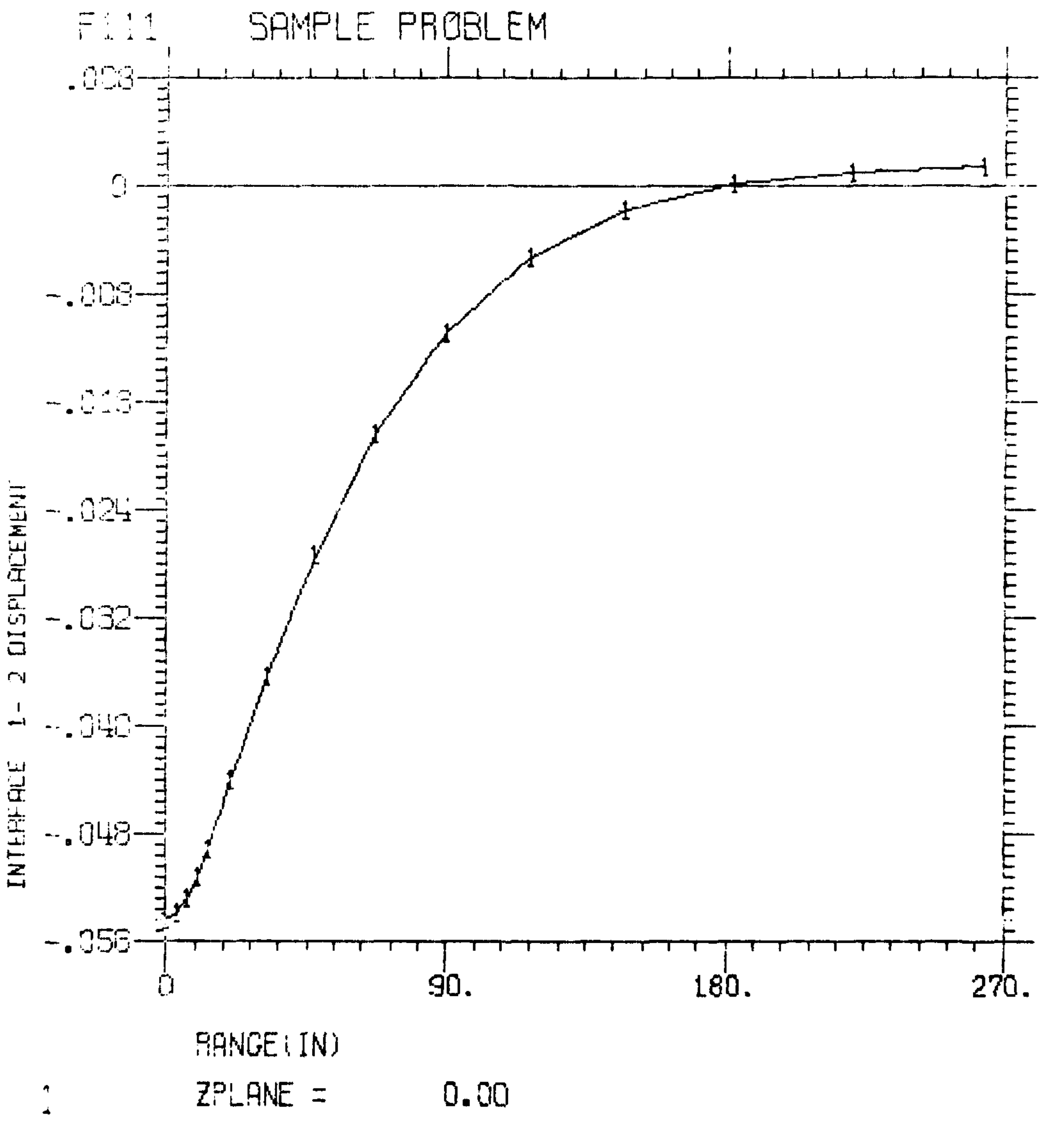
ELEMENT RESPONSE

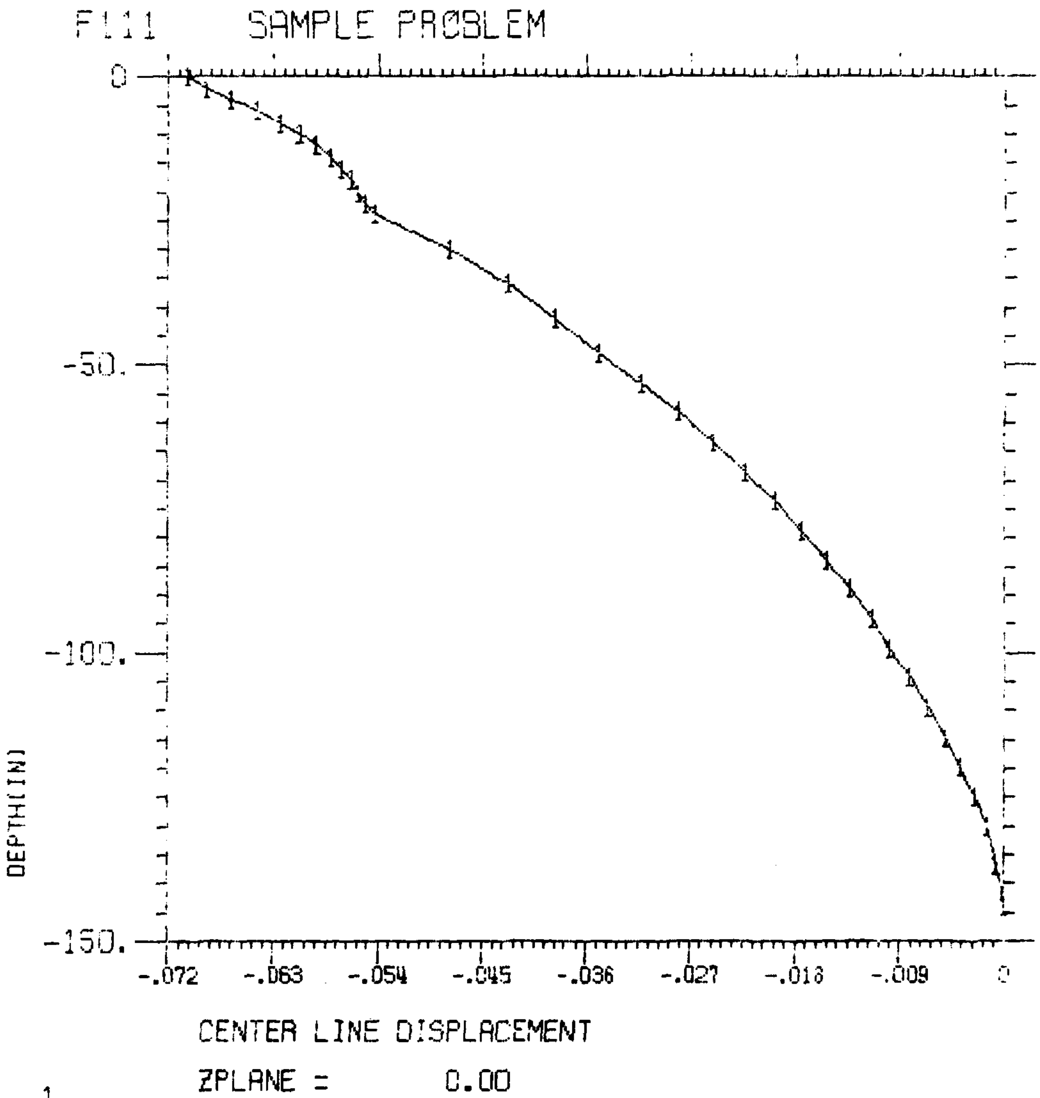
EL.NO.	Z-COORD OF STATION(S)	S-MAXIMUM S-GMAX	E-PRESR S-PRESR	E-GAMMA S-GAMMA	X-STRESS X-STRAIN	Y-STRESS Y-STRAIN	Z-STRESS Z-STRAIN	XY-STRESS XY-STRAIN	XZ-STRESS XZ-STRAIN	YZ-STRESS YZ-STRAIN
1	0.00				-127.2 -.000580	-149.7 -.000951	-127.0 -.000578	3.3 .000092	0.0 0.000000	0.0 0.000000
2	0.00				-115.4 -.000459	-155.7 -.000962	-122.6 -.000549	1.3 .000034	0.0 0.000000	0.0 0.000000
3	0.00				-71.1 -.000276	-90.6 -.000519	-83.4 -.000430	35.2 .000880	0.0 0.000000	0.0 0.000000
4	0.00				-27.5 -.000130	-9.9 .000091	-48.3 -.000365	12.5 .000262	0.0 0.000000	0.0 0.000000
5	0.00				-15.7 -.000072	-.0 .000123	-37.9 -.000300	1.3 .000032	0.0 0.000000	0.0 0.000000
6	0.00				-7.5 -.000018	.2 .000076	-22.9 -.000210	1.3 .000032	0.0 0.000000	0.0 0.000000
7	0.00				-.4 .000030	.2 .000039	-13.8 -.000130	1.1 .000029	0.0 0.000000	0.0 0.000000
8	0.00				3.8 .000055	.3 .000012	-7.3 -.000084	.7 .000016	0.0 0.000000	0.0 0.000000
9	0.00				5.0 .000056	.3 -.000022	-3.3 -.000046	.3 .000007	0.0 0.000000	0.0 0.000000
10	0.00				4.5 .000047	.2 -.000007	-1.1 -.000022	.0 .000001	0.0 0.000000	0.0 0.000000
11	0.00				3.2 .000032	.0 -.000007	-.1 -.000009	-.1 -.000003	0.0 0.000000	0.0 0.000000
12	0.00				1.6 .000018	-.1 -.000006	.2 -.000002	-.1 -.000003	0.0 0.000000	0.0 0.000000
13	0.00				.8 .000008	-.1 -.000004	.2 .000000	-.1 -.000003	0.0 0.000000	0.0 0.000000
14	0.00				.2 .000002	-.1 -.000002	.1 .000001	-.1 -.000002	0.0 0.000000	0.0 0.000000
15	0.00				-80.6 -.000238	-146.2 -.001058	-81.2 -.000245	7.5 .000188	0.0 0.000000	0.0 0.000000
29	0.00				-46.5 -.000025	-130.1 -.001070	-45.9 -.000019	12.3 .000307	0.0 0.000000	0.0 0.000000
43	0.00				-25.4 .000078	-108.5 -.000961	-24.4 .000091	13.1 .000327	0.0 0.000000	0.0 0.000000
57	0.00				-11.8 .000127	-87.2 -.000815	-10.8 .000140	12.0 .000300	0.0 0.000000	0.0 0.000000
71	0.00				-1.9 .000154	-66.2 -.000674	-1.1 .000164	10.4 .000259	0.0 0.000000	0.0 0.000000
85										

Figure B-4. Element response.


F111 SAMPLE PRØBLEM
.02
0
-.02
-.04
-.06
-.08
SURFACE DISPLACEMENT
0
50.
100.
150.
200.
250.
RANGE(IN)
ZPLANE = 0.00

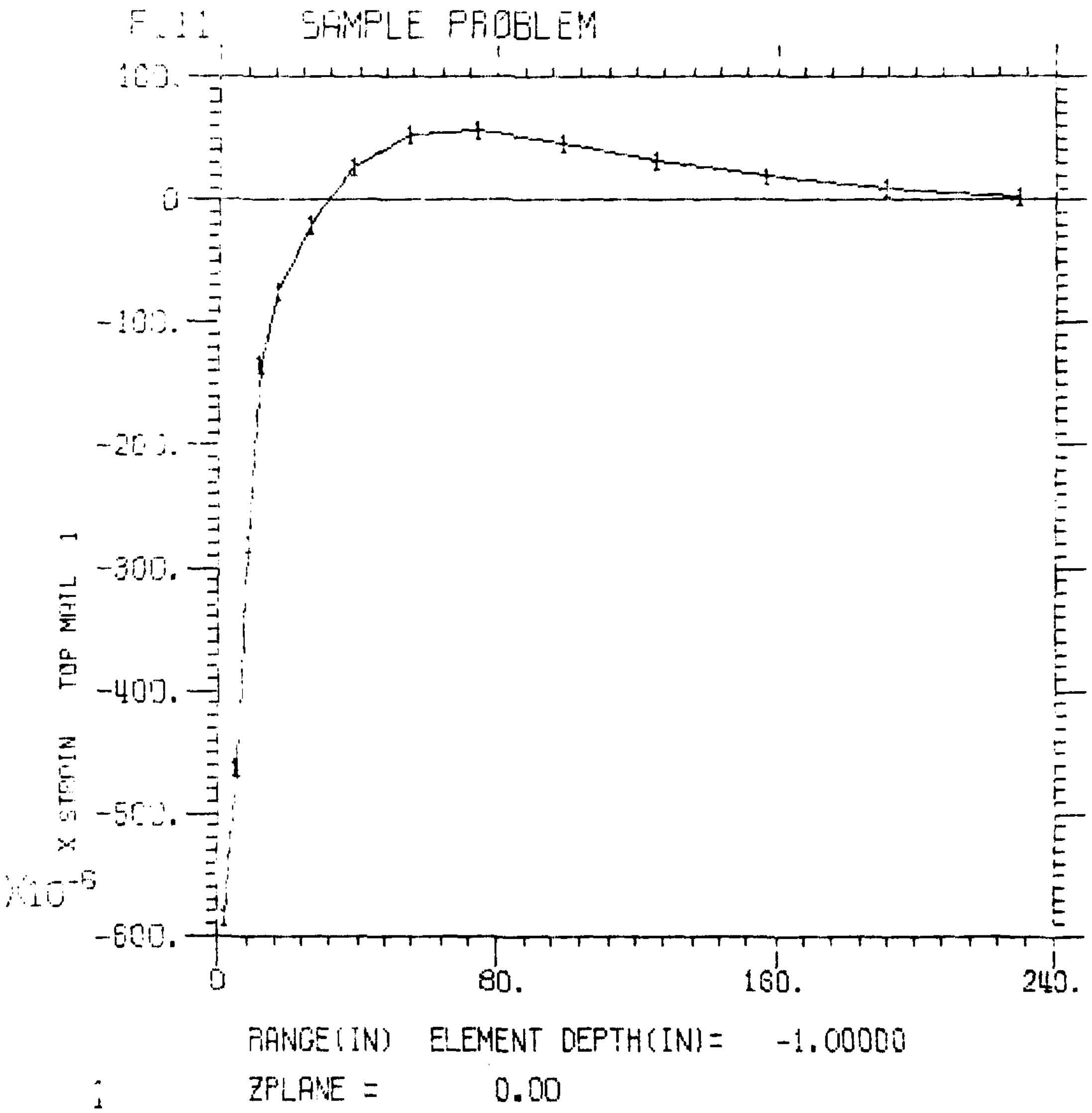
1


F111 SAMPLE PRØBLEM
.008
0
-.008
-.016
-.024
-.032
-.040
-.048
-.056
INTERFACE 1- 2 DISPLACEMENT
0
90.
180.
270.
RANGE(IN)
ZPLANE = 0.00

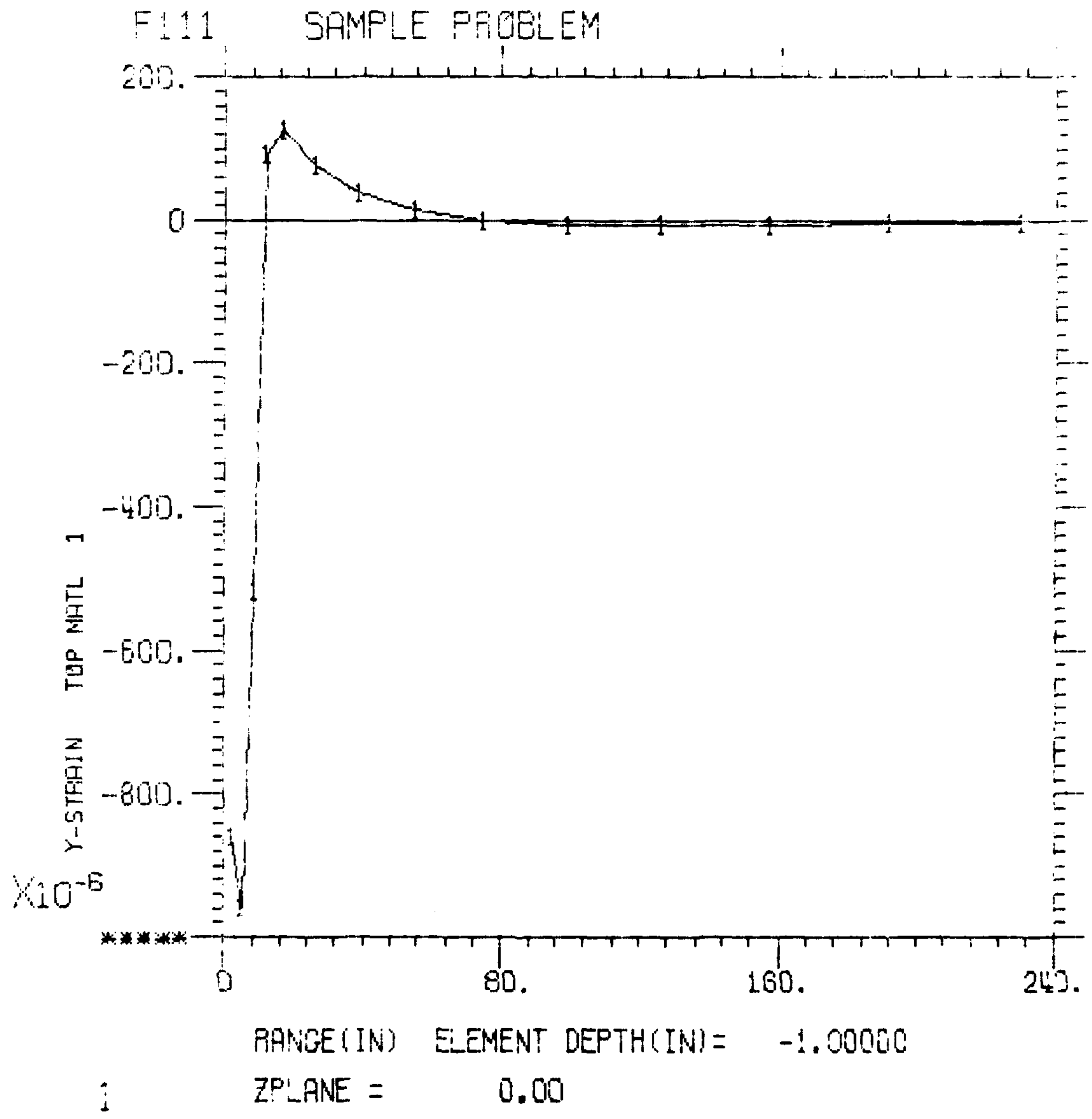


F111 SAMPLE PRØBLEM
0
-50.
-100.
-150.
DEPTH(IN)
-.072
-.063
-.054
-.045
-.036
-.027
-.018
-.009
0
CENTER LINE DISPLACEMENT
ZPLANE = 0.00

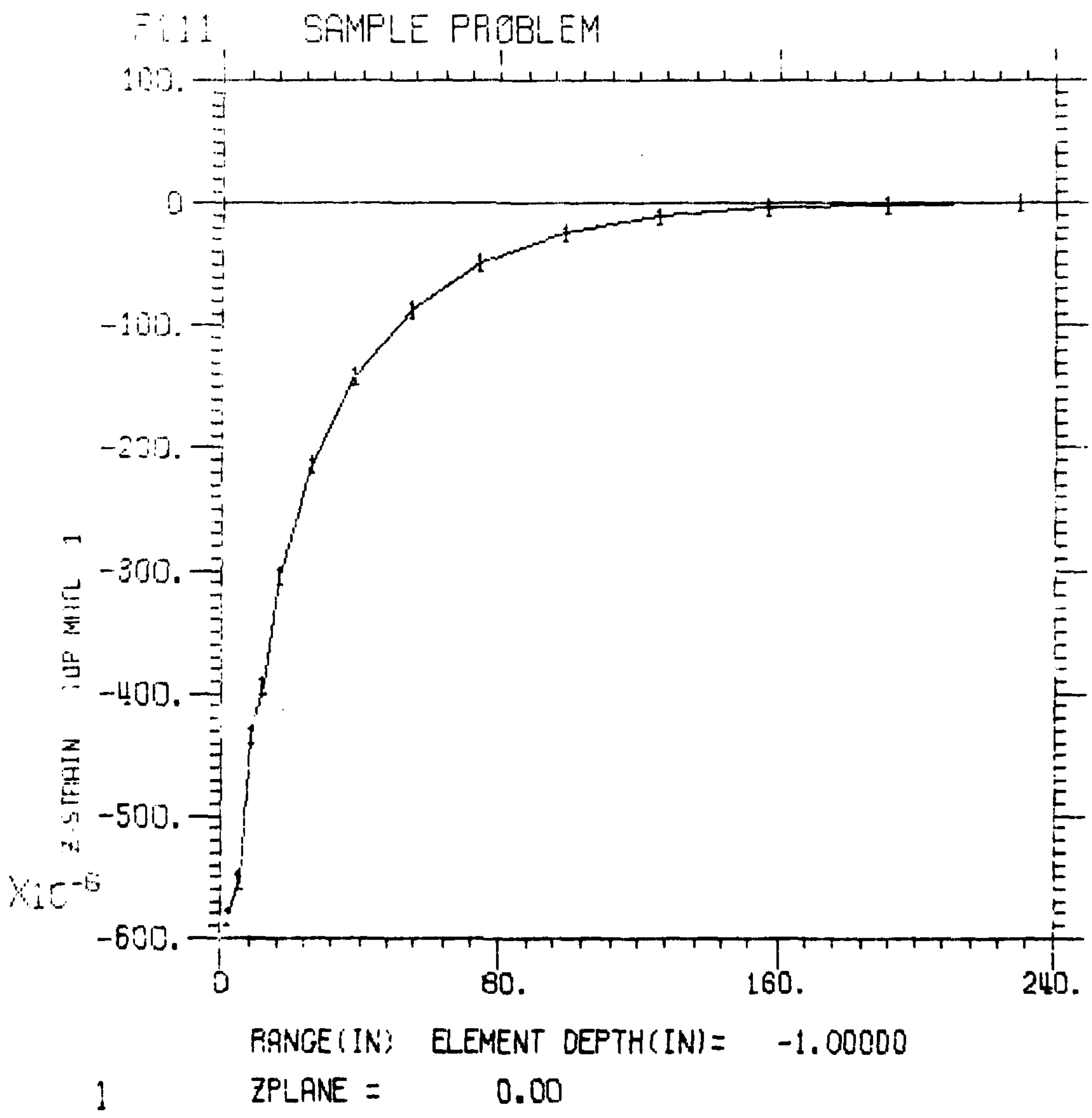
1

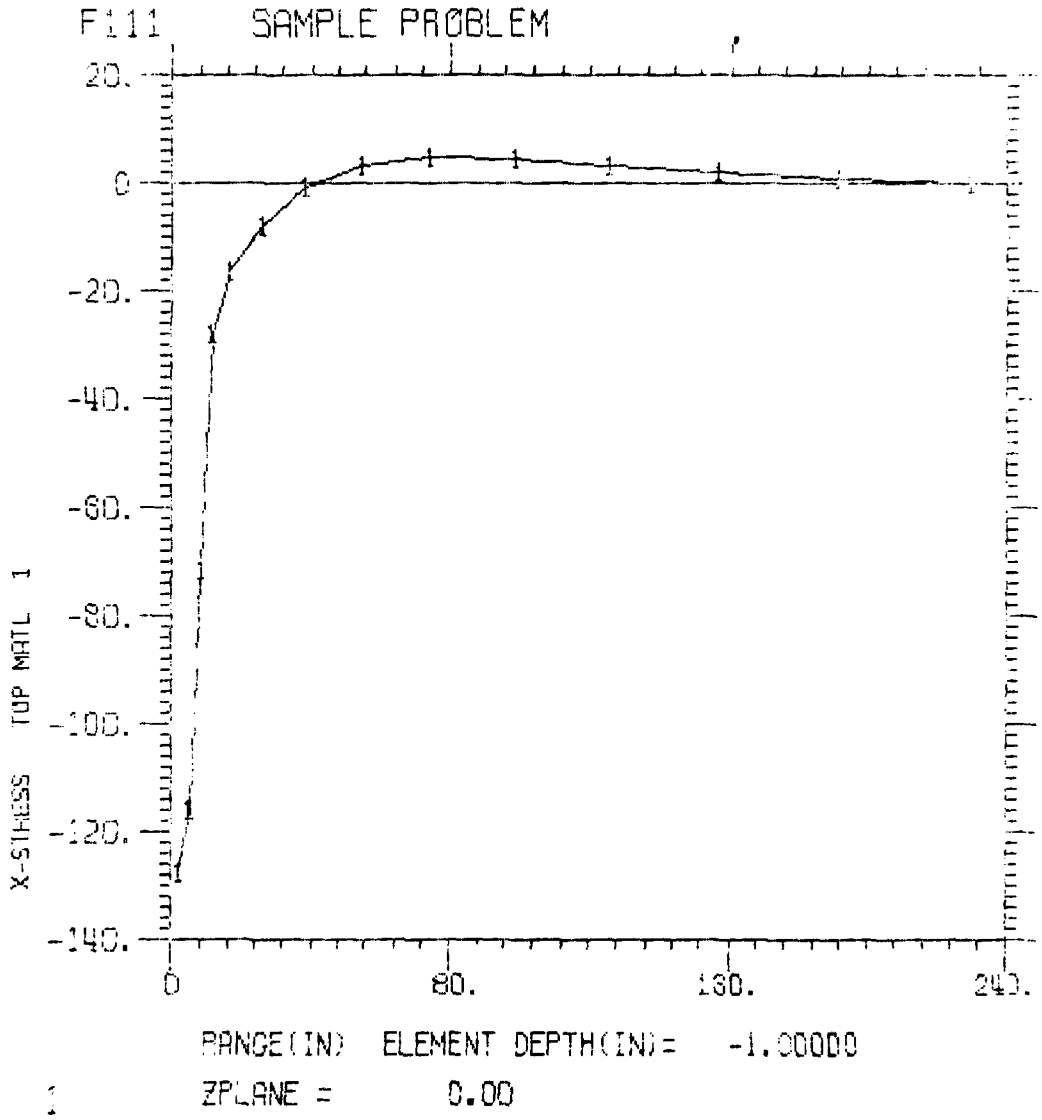


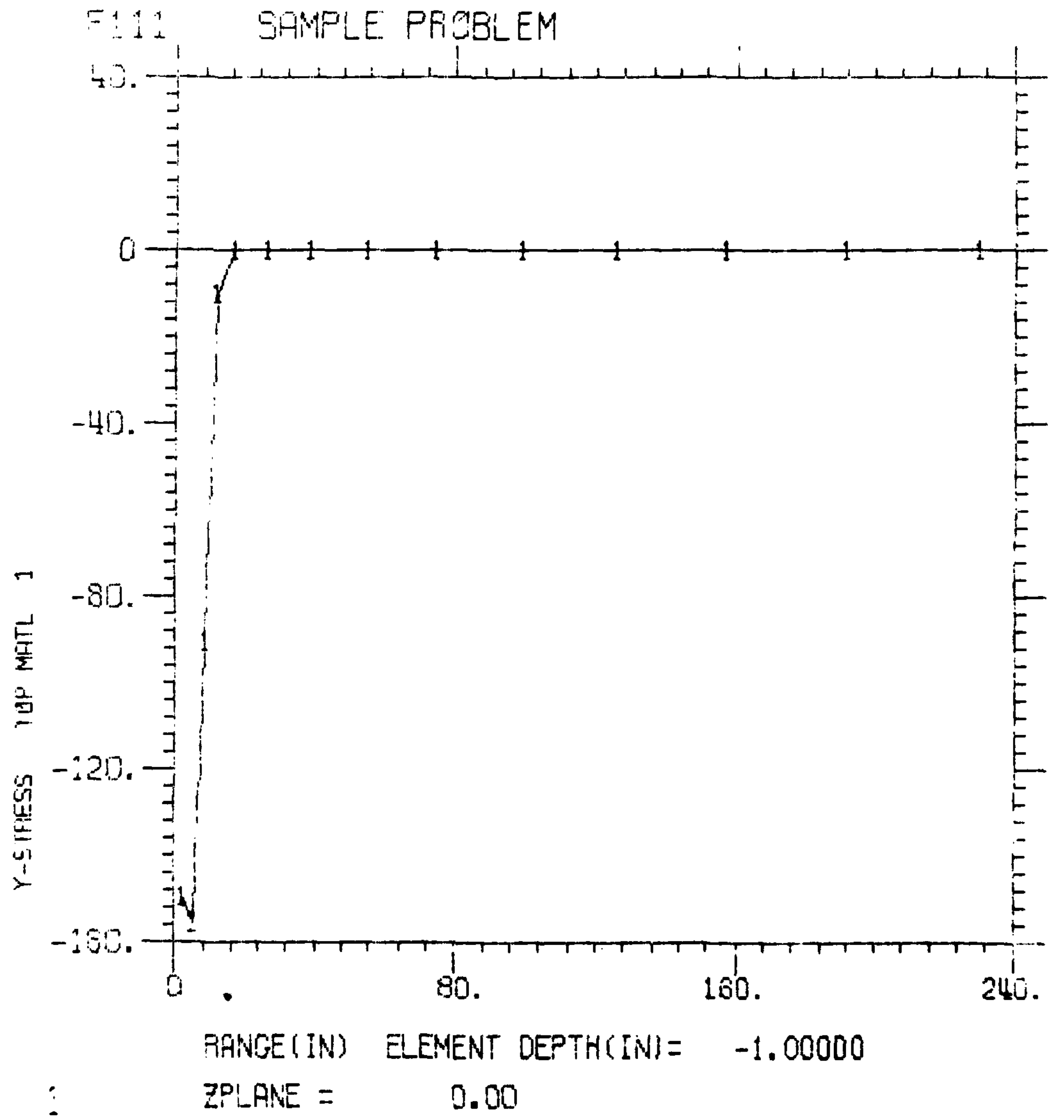
F.11 SAMPLE PROBLEM
100.
0
-100.
-200.
-300.
-400.
-500.
-600.
X STRAIN TOP MAIL 1
X10^-6
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00

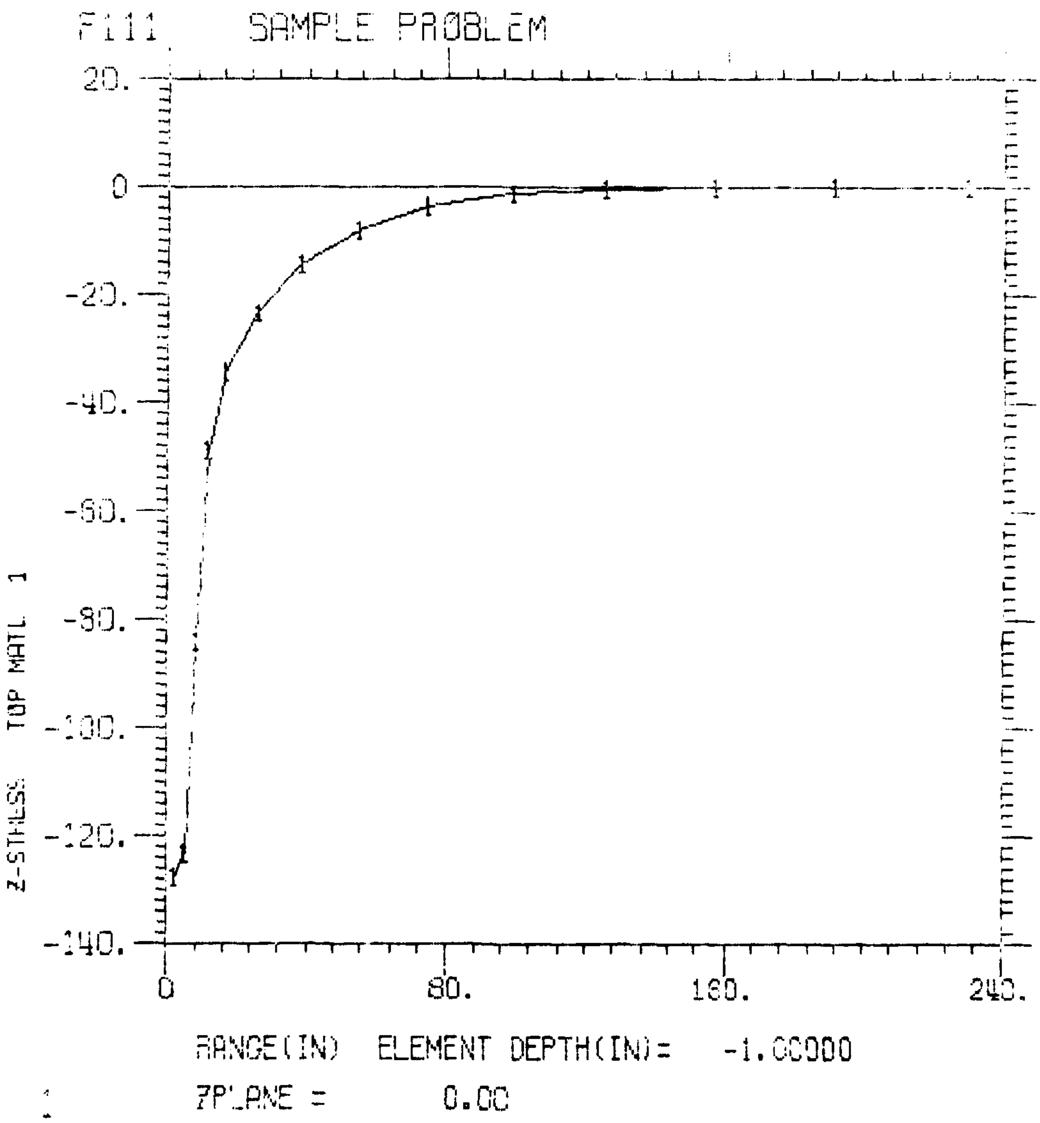


F111 SAMPLE PRØBLEM
200.
0
-200.
-400.
-600.
-800.
X10^-6
*****
Y-STRAIN TØP MATL 1
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00


SAMPLE PRØBLEM
100.
0
-100.
-200.
-300.
-400.
-500.
-600.
X10^-6
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00


F111 SAMPLE PRØBLEM
20.
0
-20.
-40.
-60.
-80.
-100.
-120.
-140.
X-STRESS TOP MATL 1
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00


F111 SAMPLE PRØBLEM
40.
0
-40.
-80.
-120.
-160.
Y-STRESS TØP MATL 1
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00


F111 SAMPLE PROBLEM
20.
0
-20.
-40.
-60.
-80.
-100.
-120.
-140.
Z-STRESS TOP MATL 1
0
80.
160.
240.
RANGE(IN) ELEMENT DEPTH(IN)= -1.00000
ZPLANE = 0.00

END

DATE

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