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N90-21071

Low Velocity Impact Analysis with NASTRAN

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ABSTRACT

A nonlinear elastic force–displacement relationship is used to calculate the transient impact force and local deformation at the point of contact between impactor and target. The nonlinear analysis and transfer function capabilities of NASTRAN are used to define a finite element model that behaves globally linearly elastic, and locally nonlinear elastic to model the local contact behavior.

Results are presented for two different structures: a uniform cylindrical rod impacted longitudinally; and an orthotropic plate impacted transversely. Calculated impact force and transient structural response of the targets are shown to compare well with results measured in experimental tests.

INTRODUCTION

Aerospace structures are subjected to impact loading from a variety of sources, including dropped tools, runway debris, and munitions. In some advanced materials, even low velocity impact can cause significant structural damage. Therefore, development of accurate means of calculating structural response due to impact loading can be of critical importance. In this paper, a computational technique is developed to predict the dynamic response of a structure to low velocity elastic impact.

Structural damage due to impact invariably initiates in the immediate vicinity of the impact. Therefore, it is important that the local stress field in the region of contact be calculated accurately. Hertz [1] derived an elasticity–based force–displacement relationship that describes contact between two elastic bodies. The Hertzian contact law is given by:

$$F = K \alpha^n \tag{1}$$

where

F = elastic contact force
K = contact stiffness
n = exponent

and

α = relative displacement (indentation) between impactor and target
= $u_i - u_t$ (i = impactor, t = target)

The exponent n was shown in reference [1] to have the value of $^3/_2$. In dynamic applications such as this; F, u, and α are all time–varying.

During low velocity impact, where impact damage is confined to the area immediately around the point of contact, areas of the structure remote from the impact may still deform in a linear elastic manner. An efficient finite element model, therefore, would combine a linear elastic model of the global structure with a non–linearly elastic behavior at the point of contact. The nonlinear force–displacement relationship in equation (1) is incorporated into a linear elastic finite element model (MSC/NASTRAN transient solution 27, COSMIC/NASTRAN transient solution 9) by using a NASTRAN transfer function definition and nonlinear analysis capability. In the following section, the Hertz contact law is discussed in addition to a method of incorporating it into NASTRAN. Impact loading of two different structures is then analyzed. The first problem is a one–dimensional rod of uniform cross section impacted longitudinally. The second is an orthotropic plate under transverse impact.

CONTACT LAW

In reference [2] Hertz derived the force–displacement relationship for two spherical isotropic elastic bodies of radius r_1, and r_2 in contact:

$$F = K\,\alpha^{3/2} \tag{2}$$

where

$$K = \frac{4}{3}\sqrt{\frac{r_1\, r_2}{r_1 + r_2}}\;\frac{k_1\, k_2}{k_1 + k_2} \tag{3}$$

is the contact stiffness and

$$k_i = \frac{E_i}{1 - \nu_i^2} \qquad i = 1,2 \tag{4}$$

where E_i and ν_i are the Young's modulus and poisson's ratio, respectively, and the subscripts 1 and 2 refer to each of the spheres. When a spherical impactor contacts a flat target, (3) simplifies to

$$K = \frac{4}{3}\sqrt{r_i}\;\frac{k_i\, k_t}{k_i + k_t} \tag{5}$$

where i and t represent the impactor and target respectively and the k_t and k_i are given by:

$$k_t = \frac{E_t}{1 - \nu_t^2} \tag{6}$$

$$k_i = \frac{E_i}{1 - \nu_i^2} \tag{7}$$

In equation (2), α is the local indentation at the contact point, shown schematically in figure 1. We have:

$$\alpha = u_i - u_t \tag{8}$$

where α is the relative local displacement between impactor and target at the point of contact.

NASTRAN Implementation

The non–linear local behavior was incorporated into the NASTRAN finite element model as follows:

The impactor is modeled as a lumped mass just touching the target at t=0 and with an initial velocity towards the target. The difference between the displacement of this lumped mass and the displacement of the target is the indentation, α. The modeling of the contact between impactor and target is performed by utilizing the transfer function card, TF, and the nonlinear force card, NOLIN3. The TF card acts as a dynamic multipoint constraint, relating the displacement, velocity and acceleration of several independent degrees of freedom to a dependant degree of freedom. In the work discussed here, only displacement relationships were used. On the TF card coefficients of the following equation are specified [3].

$$(B_0 + B_1 p + B_2 p^2)u_{dep} + \sum_{j=1}^{n}(A_0^j + A_1^j p + A_2^j p^2)u_{ind}^j = 0 \tag{9}$$

where

B_0, B_1, B_2 = the coefficients for the dependant degree of freedom

A_0^j, A_1^j, A_2^j = the coefficients for the independent degrees of freedom

u_{dep} = the displacement of the dependant degree of freedom

u_{ind}^j = the displacements of the independent degrees of freedom

n = the number of independent degrees of freedom

p = the differential operator $\frac{\partial}{\partial t}$, and $p^2 = \frac{\partial^2}{\partial t^2}$

For this analysis, the equation would appear:

$$(1.0)u_{\text{extra point}} + \left[(-1.0)u_{\text{impactor}} + (1.0)u_{\text{target}}\right] = 0 \tag{10}$$

that is

$$n = 2$$

$$B_1, B_2, A_1^j, A_2^j = 0.0 \quad (j = 1, n)$$

$$B_0 = 1.0$$

$$A_0^1 = -1.0$$

$$A_0^2 = 1.0$$

The resulting equation defines the indentation at every time step and assigns the value to an EPOINT. The EPOINT, or extra point, is used as a nonstructural variable that provides a place to store the value of the indentation. The EPOINT is provided as input to the NOLIN3 card.

The NOLIN3 card is the means of applying the time–dependent nonlinear load based on the indentation. The NOLIN3 card has the form:

$$P(t) = \begin{cases} S(x(t))^A, & x(t) > 0 \\ 0 &, x(t) \leq 0 \end{cases} \tag{11}$$

where

$P(t)$ = is the resulting nonlinear force

S = is a scale factor

$x(t)$ = is the displacement or velocity of a degree of freedom

A = is an amplification factor

In modeling of the impact, we define $x(t)$ to be the displacement of the EPOINT, S to be the Hertzian stiffness, and A to be $^3/_2$, as given in equation (2). Recall that the displacement of the EPOINT is really the indentation as obtained from the TF card. The resulting function then has the form:

$$P(t) = \begin{cases} K(\alpha(t))^{3/2}, & \alpha(t) > 0 \\ 0 &, \alpha(t) \leq 0 \end{cases} \tag{12}$$

Note that when α is less than or equal to zero (ie. the target and the impactor are out of contact) then the force is also zero. Two NOLIN3 cards are used, one to apply the impact force to the target and the other to apply the same force to the impactor in the opposite direction of its initial velocity. This methodology allows the impactor to slow with increasing impact force and eventually to unload the target as the impactor begins to travel in the opposite direction, away from the target.

RESULTS

One Dimensional Rod

The first problem analyzed is the longitudinal impact of a steel ball on a long aluminum rod of constant cross section. Geometry and material properties of the impactor and target are given in figure 1. The problem was modeled using 144 1–D rod elements with each grid point having a single longitudinal degree of freedom. Two more degrees of freedom were used to model the impact dynamics, resulting in a total of 147 degrees of freedom. A single lumped mass with an initial velocity was used to represent the impactor. The Hertzian force–displacement relationship in equation (1) was prescribed using the NASTRAN NOLIN3 card, as shown in the example input deck in the appendix.

The calculated impact force history compares well with experimentally determined values [4], as shown in figure 2. The calculated strain response at the midpoint of the target bar is compared with measured values in figure 3. The sign reversal of the second pulse is caused by the reflected tensile stress wave generated by the incident compressive wave reaching the free end of the bar [5].

Some insight into the timing and the location of the impact–induced structural failure can be gained by tracking the distribution of energy in the impactor and the target, as shown in figure 4. The energy balance can be expressed as:

$$U_t = KE_i + SE_i + KE_t + SE_t \tag{13}$$

where

U_t = total energy in system

$$KE_i = \text{impactor kinetic energy} = {}^1/_2\, m v_i^2 \tag{14}$$

$$SE_i = \text{impactor strain energy} = \int F(\alpha)\, d\alpha = {}^2/_5\, K \alpha^{5/2} \tag{15}$$

$$KE_t = \text{target kinetic energy} \tag{16}$$

$$= \sum_{j=1}^{n-1} \frac{1}{2} m_j \left[\frac{V_j + V_{j+1}}{2}\right]^2 \quad (n = \text{number of elements})$$

$$SE_t = \text{strain energy of target} \tag{17}$$

$$= \sum_{j=1}^{n-1} \frac{1}{2} k_j \left(\delta_j - \delta_{j+1} \right)^2 \quad (n = \text{number of elements})$$

The total energy in the system, U_t, is divided between the kinetic energy and the strain energy of the target and impactor in a time–varying manner. Because damping effects are not considered, the total system energy is constant and equal to the initial kinetic energy of the impactor. The strain energy of the impactor is non–zero only during the contact interval ($0 < tC/L < 0.4$, where t = time, L = the length of the bar, and C = the wave speed in the bar) and peaks when the contact force is greatest, approximately halfway through the contact interval. The kinetic energy of the impactor decreases rapidly as the impactor slows during contact with the target. Eventually, at $tC/L = 0.25$, the impactor velocity (and therefore its kinetic energy) decreases to zero and the elastic rebound begins. The kinetic energy of the impactor never returns to its initial level because approximately 80% of the energy has been transferred to the target in the form of strain energy and kinetic energy. The strain and kinetic energies in the target both increase rapidly during the contact with the impactor and remain constant after contact has ended ($tC/L > 0.4$). Both strain and kinetic energies maintain equal and constant values until the compressive stress wave generated by the impact reaches the far end of the free–free bar ($tC/L = 1.0$). A tensile stress wave is generated when the compressive pulse reflects from the stress free boundary [5]. The superposition of the incident and reflected pulses momentarily leaves the bar stress–free which causes the strain energy to decrease to zero. The kinetic energy simultaneously increases, maintaining a conservation of total energy. The reflection process is repeated at $tC/L = 2.0$, when the reflected pulse returns to the other end of the bar. Similar energy dissipation diagrams may prove useful in analyzing dynamic failure of more complex structures.

Composite Plate

The low velocity transverse impact of a composite plate made from Scotchply 1003 prepreg [6] is now analyzed. The problem is depicted schematically in figure 5, and is described in detail in references [7,8]. A modified Hertzian contact stiffness has been proposed [9] for application to composite materials. Specifically, equation (6) is replaced by

$$k_t = E_{33t} \tag{18}$$

where E_{33t} is the transverse modulus of the plate. Plate membrane and bending stiffness material properties were calculated using the COBSTRAN (Composite Blade Structural Analyzer) computer code [10] which calculates elastic moduli of composite materials from known constituent properties and laminate ply orientations.

A uniform square mesh of QUAD4 elements was used to model the 15.24 cm × 15.24 cm (6 in × 6 in) target plate. A mesh convergence study was performed to establish the degree of mesh refinement necessary to arrive at a numerically converged solution. Three different meshes were considered, 25 × 25, 49 × 49, and 61 × 61 elements. Of these, the latter two produced essentially the same strain response for a given impact velocity and were therefore considered to be converged solutions. The results presented here were therefore calculated using the 49 × 49 element model. Five degrees of freedom (u_x, u_y, u_z, θ_x and θ_y) were used at each nodal point, giving the model a total of 11510 degrees of freedom. The problem was solved on a Cray XMP in 52 CPU minutes.

The impactor used in the tests [7,8] was a uniform 2.54 cm (1 in) long, blunt–ended steel rod of radius 0.047625 cm ($^3/_{16}$ in). In the analysis a contact radius of 0.047625 cm ($^3/_{16}$ in) was assumed in the Hertzian contact stiffness calculations. The calculated impact force history is shown in figure 6. Although no direct measurement of the impact force was obtained experimentally, the contact time was measured [8] and found to be 204 microseconds. This is in good agreement with the calculated result. Figure 6 also shows that a secondary impact occurs during the latter half of the contact interval (t = 175 μsec), probably due to the vibration of the target plate during contact with the projectile.

The resulting displacement response of the plate is shown in figure 7, where it has been assumed that no damage occurs in the target during contact with the impactor. This assumption is valid based on the available test data. Ultrasonic C–scans of the specimens after impact indicate that this level of impactor kinetic energy (10 Joules) is very near the threshold energy level required to cause damage [8] in specimens of this layup. As a result, very little damage occurs at this impactor velocity. The anisotropic bending stiffness of the target (figure 5) is evident from the elliptical displacement contours, as the flexural disturbance travels faster in the stiffer direction (figure 7).

The strain response at gage A is compared to the calculated response in figure 8. The two curves are similar in amplitude and duration but the calculated strain appears to lag the measured values by approximately 25 microseconds. This may be due to the difficulty in establishing experimentally the precise time at which contact occurs based on strain gage readings taken at some distance from the point of contact. The comparison shown in figure 9 for gage B likewise shows a time shift of approximately 25 microseconds between the measured and the calculated response. The amplitude and duration of the calculated strain response correlate quite well with the measured signal.

SUMMARY

A simple means of modeling low velocity, non–damaging impact using NASTRAN was demonstrated. A nonlinear elastic contact model was included in the finite element analysis using NASTRAN transfer function definitions and nonlinear analysis capabilities. The same contact law was used to define the force–indentation relationship for two different impactor/target combinations. Results in both cases showed that the impact force and resulting transient structural response of the target compared well with experimentally measured values.

ACKNOWLEDGEMENT

The support of the Naval Weapons Center at China Lake, CA. is gratefully acknowledged. Mr. Andrew Victor was the technical monitor.

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[10] Aiello, Robert A., Composite Blade Structural Analyzer (COBSTRAN) User's Manual, NASA Technical Memorandum 101461, April 1989.

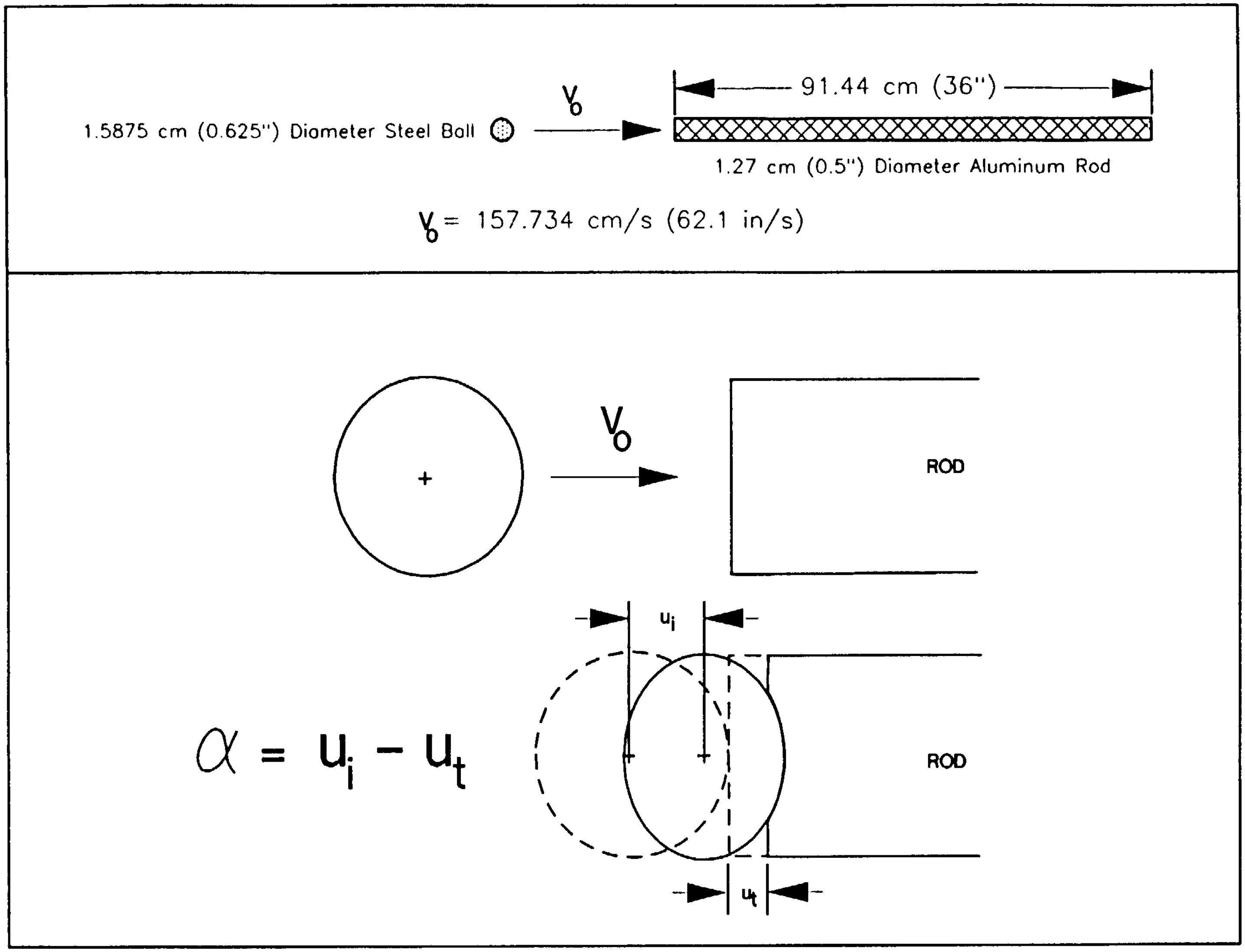

Figure 1: Longitudinal Bar Impact Problem

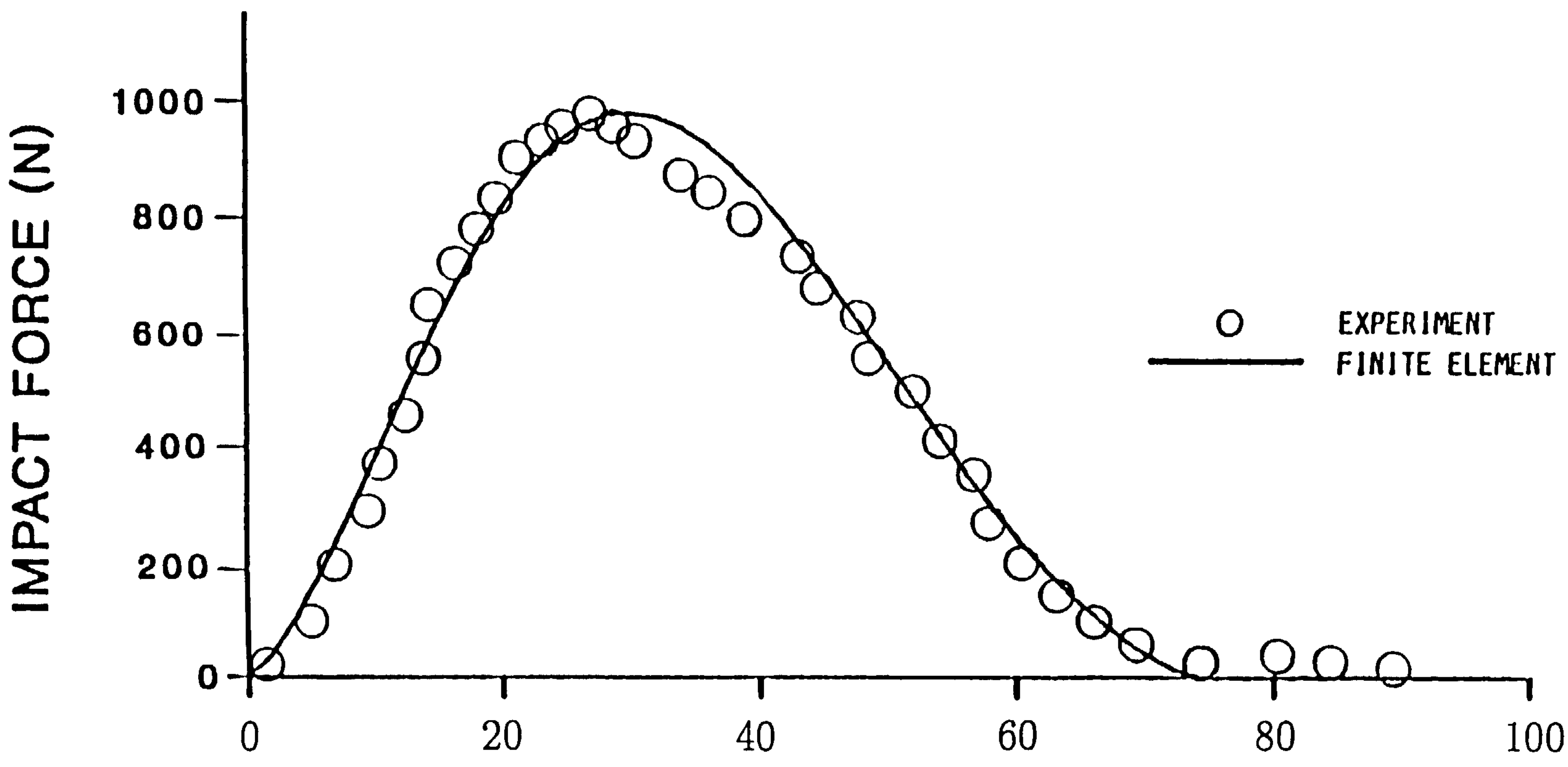

Figure 2: Impact Force for Bar Problem

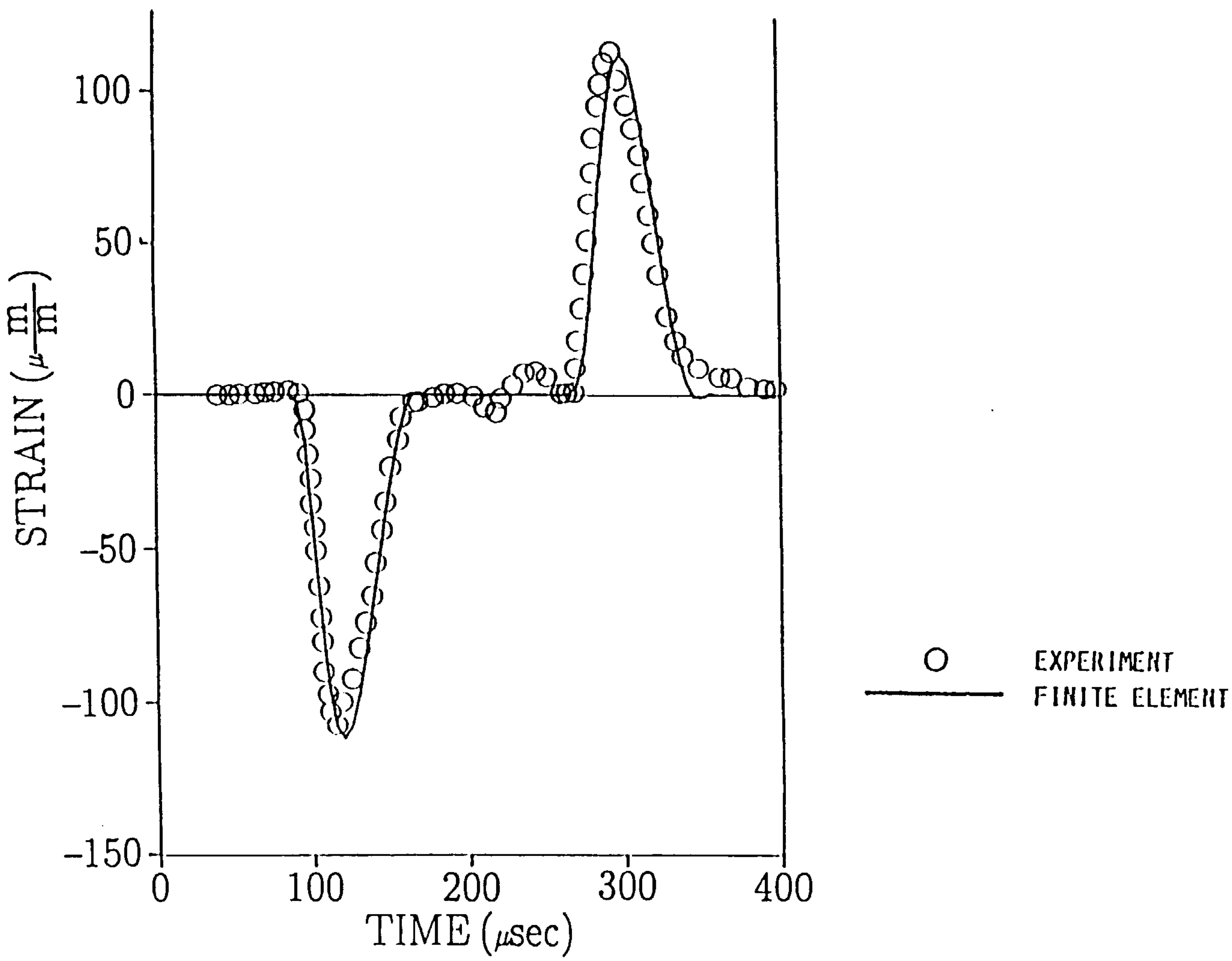

Figure 3: Strain Response at Midpoint of Impacted Bar

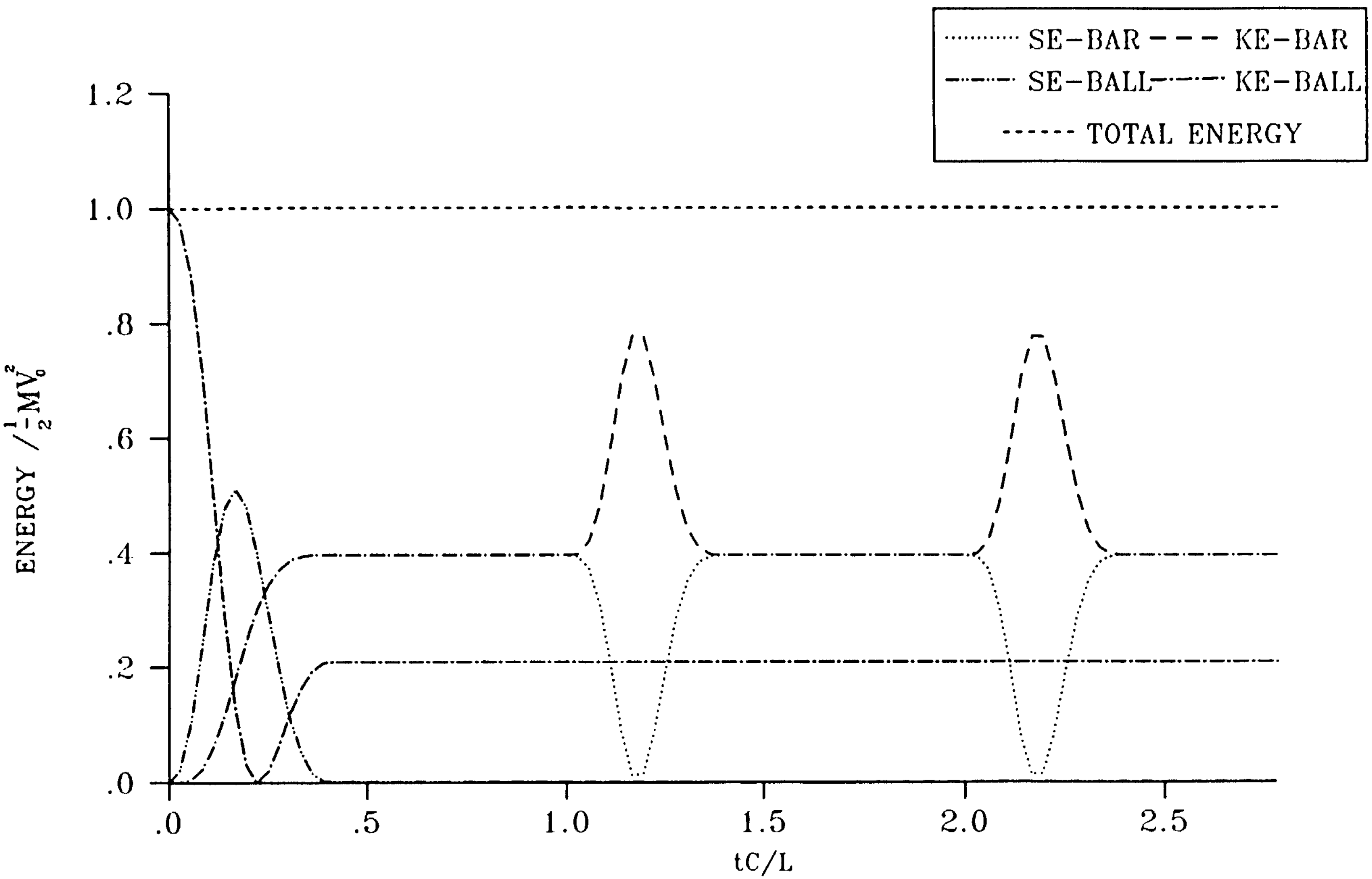

Figure 4: Energy Distribution for Longitudinal Bar Impact Problem

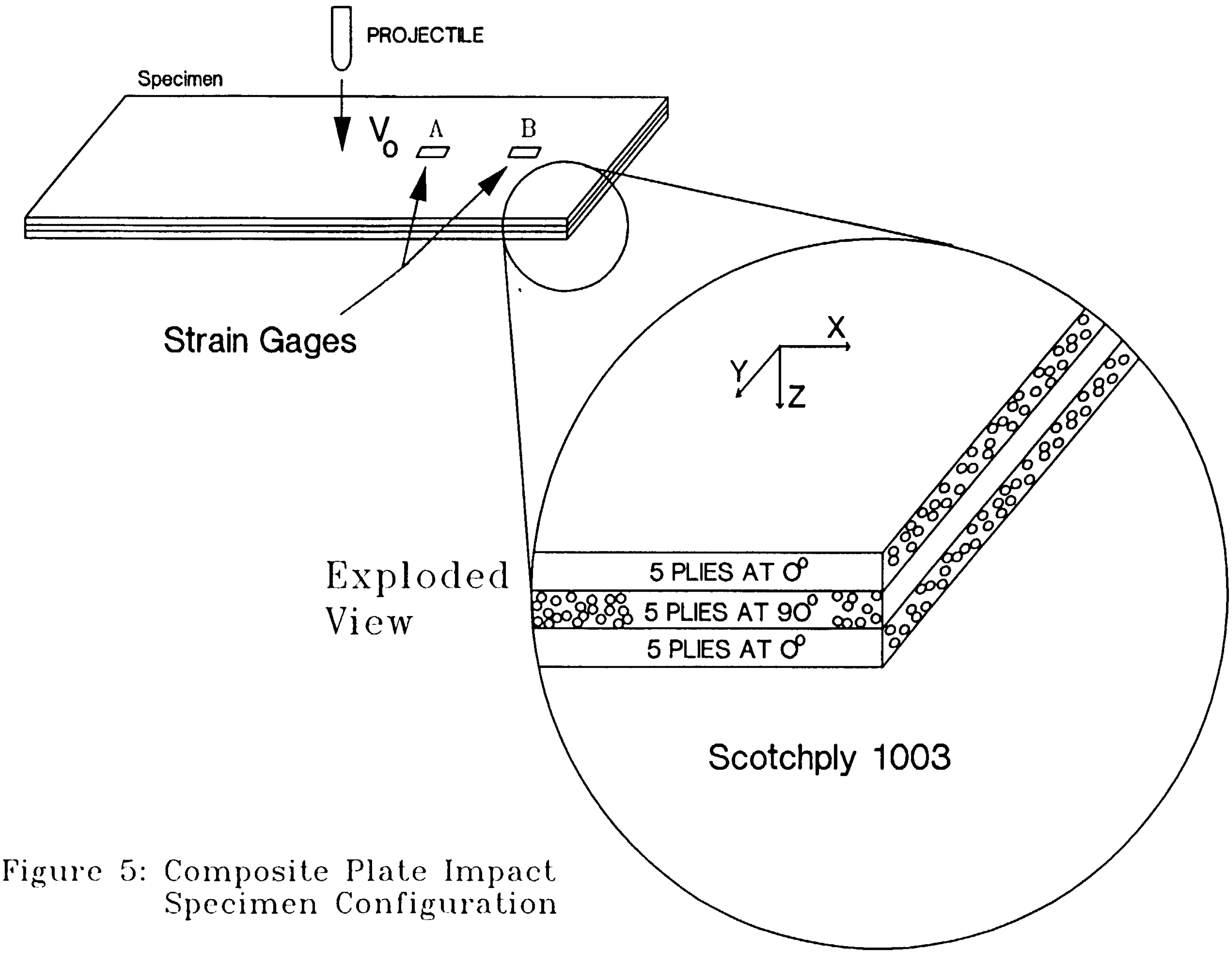

Figure 5: Composite Plate Impact Specimen Configuration

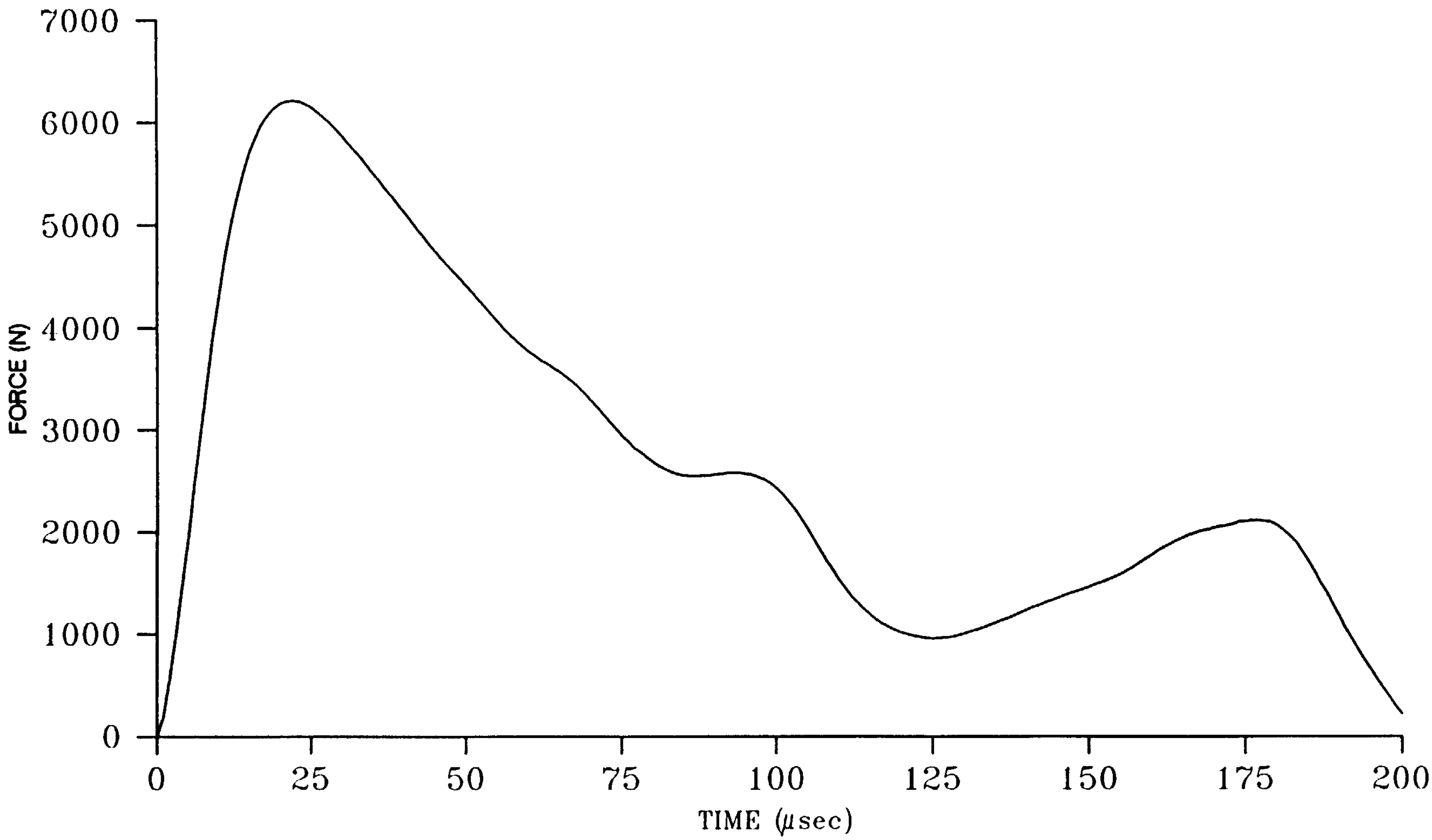

Figure 6: Calculated Force History for Transverse Impact of Composite Plate

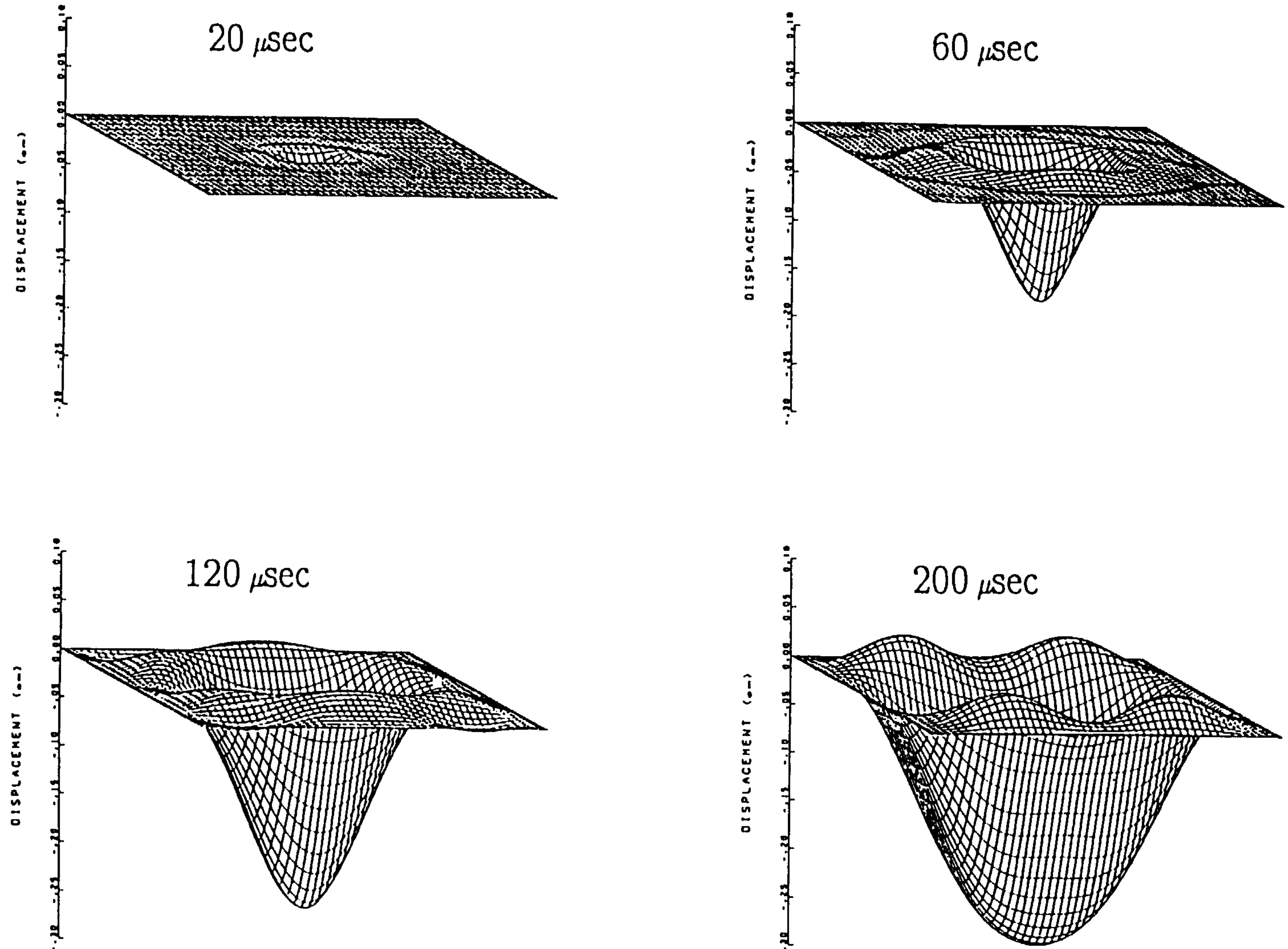

Figure 7: Calculated Displacement Response for Composite Plate

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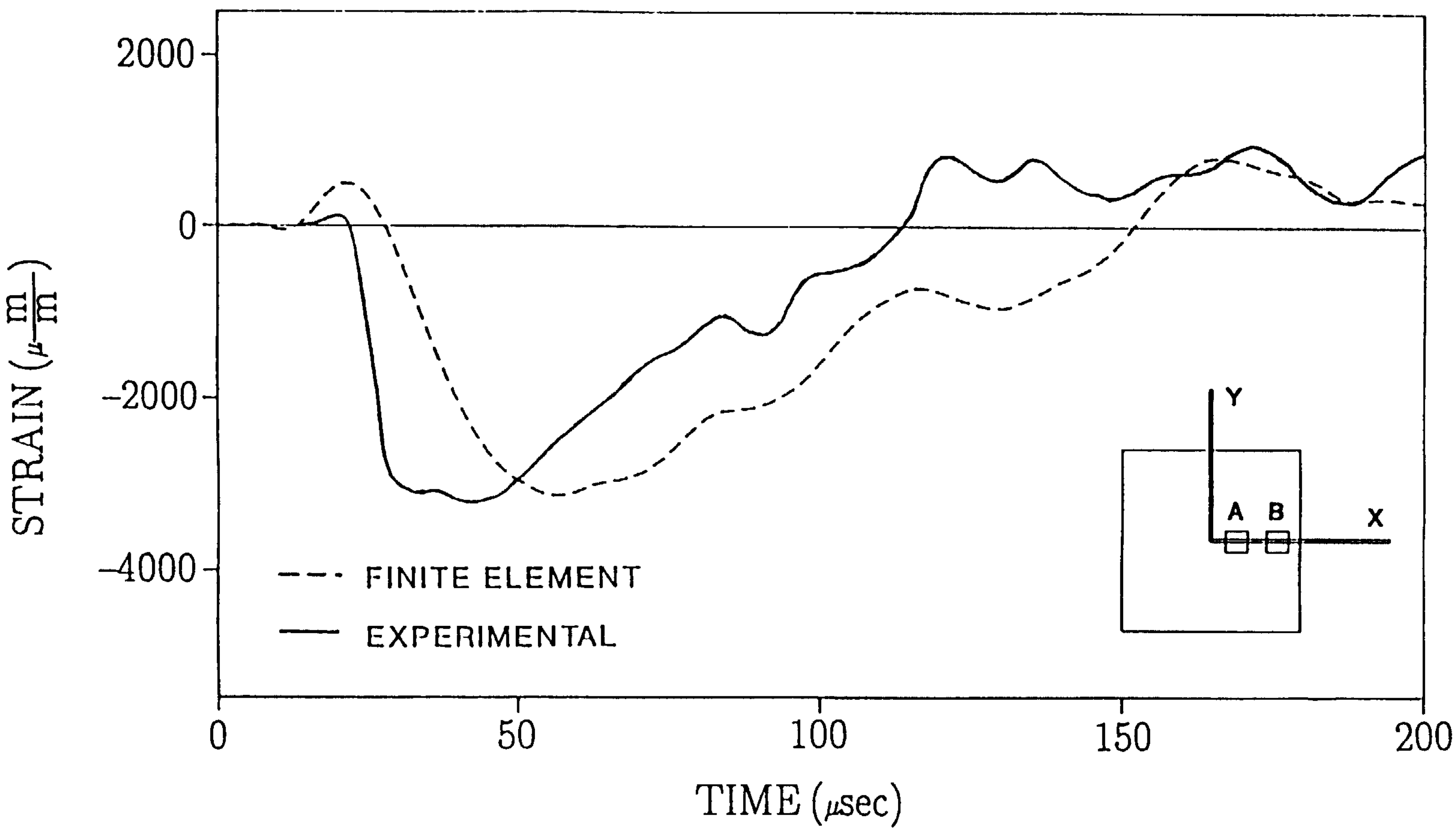

Figure 8: Strain Response at Gage Location "A"

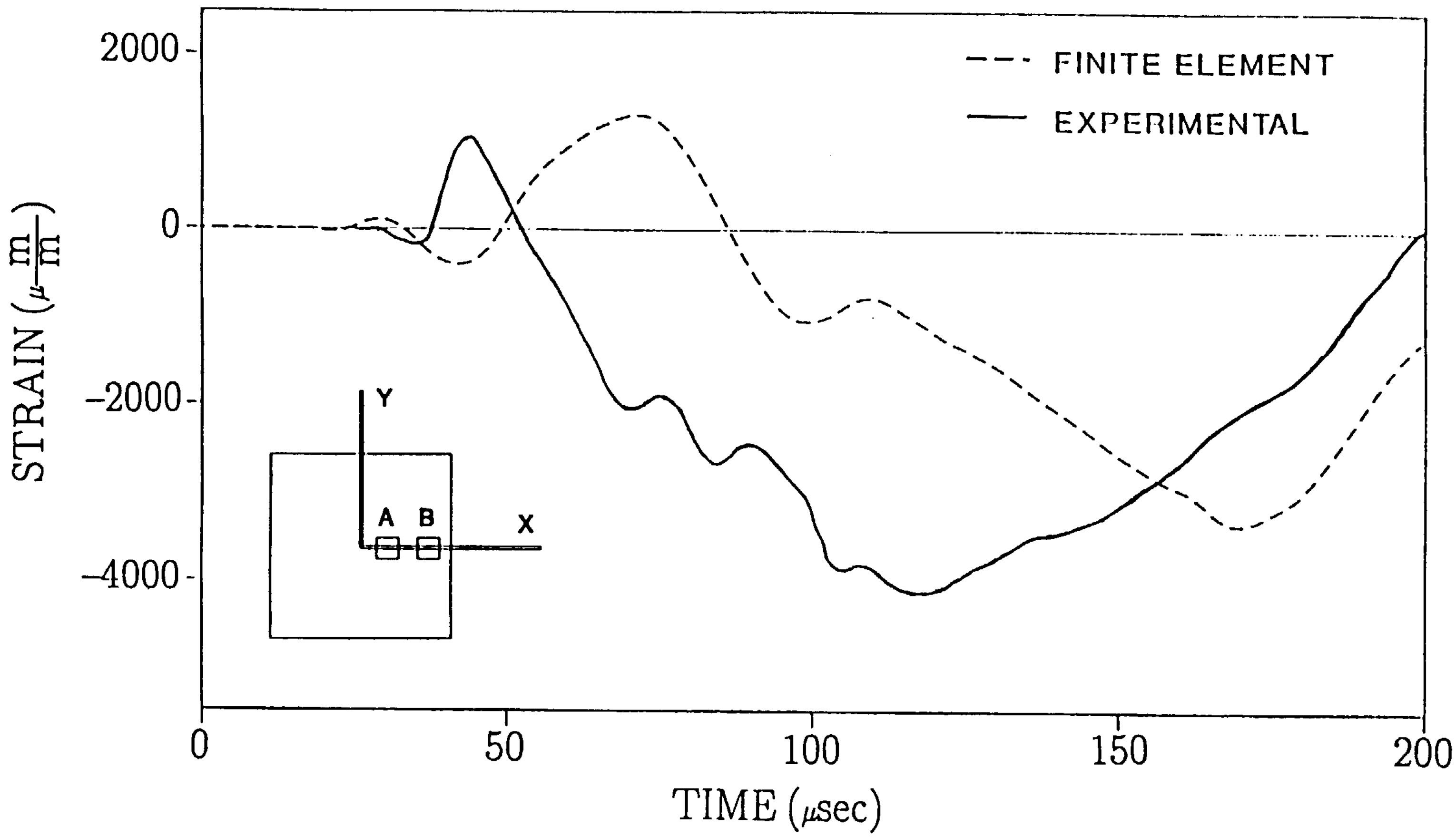

Figure 9: Strain Response at Gage Location "B"

APPENDIX

DAN TROWBRIDGE ANALEX - STRUCTRAL MECHANICS BRANCH

```
ID TRANS,LOAD
APP DISP
TIME 60
SOL 9
CEND
   TITLE = COSMIC: TRANSIENT RESPONSE ANALYSIS: HERTZIAN IMPACT FF
SUBTITLE =  36" AL. ROD   5/8 STEEL BALL  V0=62.1 IN/S
   LABEL =  ROD  ____________________     •  <--------  IMPACT
$                NONLINEAR LOAD
NONLINEAR = 5
$                INITIAL CONDITIONS SET
IC = 1
TFL=111
SPC = 4
TSTEP = 7
$                OUTPUT STUFF
SET 30 = 1,72,73,999,1001
NLLOAD = 30
STRESS(PRINT) = 30
DISP(PRINT) = 30
BEGIN BULK
$ ***************************************************************
$                EXTRA POINT = INDENTATION
EPOINT,1001
GRID,999,,-0.3125,0.0,0.0
GRID,1,,0.0,0.0,0.0
=(144),*(1),=,*(0.25),==
CROD, 1, 1, 1, 2
=(143),*(1),=,*(1),*(1)
$                LUMP MASS OF IMPACTOR
CONM2,200,999,0,9.587-5,0.0,0.0,0.0,, +CON2-2
+CON2-2,3.745-6,,3.745-6,,,3.745-6
$                MATERIAL PROPERTIES
PROD,1,11,0.196,6.14-3,0.25
MAT1,11,10.0+6,,0.33,2.5-4,,,,+MAT1-1
+MAT1-1,35.0E6,36.0E6,27.0E6
$                BOUNDRY CONDITIONS
SPC1,4,23456,1,THRU,145
$                REMOVE DEGREES OF FREEDOM FROM IMPACTOR
SPC1, 4, 23456, 999
$                TRANSFER FUNCTION TO DEFINE INDENTATION
TF,111,1001,0,+1.0,0.0,0.0,,,+TF-1
+TF-1,999,1,-1.0,0.0,0.0,,,,+TF-2
+TF-2,1,1,1.0,0.0,0.0
$                TIMING
TSTEP,7,2500,2.0-7,25
$                LOAD DEPENDENT ON DISPLACEMENT OF IMPACTOR
NOLIN3, 5, 1, 1, 6.24+6, 1001, 1, 1.5
$                SLOW DOWN IMPACTOR
NOLIN3, 5, 999, 1, -6.24+6, 1001, 1, 1.5
$                INITIAL CONDITIONS: IMPACTOR VELOCITY = 62.1 IN/SEC
TIC,1,999,1,0.0,62.1
ENDDATA
```

```
ID IMPACT,PLATE
APP DISP
TIME 120
SOL 27
CEND
   TITLE = IMPACT OF PLATE 49X49 : CENTERED ELEMENT
SUBTITLE = TRANSIENT ANALYSIS: FIXED-FIXED: NO SYMMETRY
SPC = 1
IC = 3
NONLINEAR = 5
TSTEP = 1
TFL = 111
SET 15 = 999,2525,2526,2625,2626
   NLLOAD = 15
SET 20 = 2525,3325,4125
   STRESS = 20
BEGIN BULK
$ **** EXTRA POINT TO HOLD INDENTATION ***************************
EPOINT,10001
$ **** IMPACTOR *** 3/8 IN DIAMETER ******************************
GRID,999,,0.0,0.0,-0.1875
CONM2,200,999,0,8.096-5,0.0,0.0,0.0,, +CON2-2
+CON2-2,7.459-6,,7.459-6,,,1.423-6
$  * * * * * * * GRIDS AND CQUAD4 ELEMENTS DEFINING THE PLATE GO HERE ...
$          MATERIAL PROPERTIES...  MAT2 CARDS GENERATED BY COBSTRAN
PSHELL,1,101,0.15,201,1.0
MAT2,101,4.3E+06,2.9E+05,-1.7E-03,2.8E+06,-3.4E-02,5.7E+05,1.8E-04,+A101
+A101,5.8E-06,8.9E-06,5.0E-13
MAT2,201,5.7E+06,2.9E+05,-1.9E-04,1.4E+06,-3.8E-03,5.7E+05
$                BOUNDRY CONDITIONS
SPC1, 1, 123456, 101, THRU, 150
SPC1, 1, 123456, 5001, THRU, 5050
SPC1, 1, 123456, 101
=,=,=,*100
=48
SPC1, 1, 123456, 150
=,=,=,*100
=48
SPC1, 1, 12456, 999
GRDSET,,,,,,,6
$                TIME STEP INFO
TSTEP, 1,2000, 1.0-7, 10
$                LOAD DEPENDENT ON RELATIVE DISPLACEMENT OF IMPACTOR
NOLIN3, 5,2525, 3,+1.945+5, 10001, 0, 1.5
NOLIN3, 5,2526, 3,+1.945+5, 10001, 0, 1.5
NOLIN3, 5,2625, 3,+1.945+5, 10001, 0, 1.5
NOLIN3, 5,2626, 3,+1.945+5, 10001, 0, 1.5
$                SLOW DOWN IMPACTOR
NOLIN3, 5, 999, 3,-7.779+5, 10001, 0, 1.5
$                TRANSFER FUNCTION TO CALCULATE INDENTATION
TF,111,10001,0,+1.0,00.0,00.0,,,+TF-1
+TF-1,999,3,-1.0,00.0,00.0,,,,+TF-2
+TF-2,2525,3,+0.25,00.0,00.0,,,,+TF-3
+TF-3,2526,3,+0.25,00.0,00.0,,,,+TF-4
+TF-4,2625,3,+0.25,00.0,00.0,,,,+TF-5
+TF-5,2626,3,+0.25,00.0,00.0
$             INITIAL CONDITIONS: IMPACTOR VELOCITY = 1470 IN/SEC (122.5 FT/SEC)
TIC,3,999,3,0.0,1470.0
ENDDATA
```