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NAVAL SURFACE WEAPONS CENTER SILVER SPRING MD
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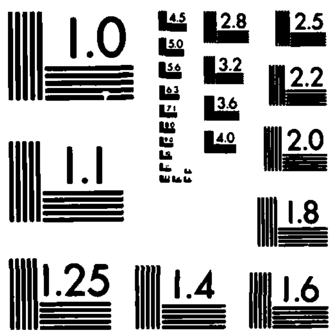

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NSWC TR 82-94

AD A122288

UNDERWATER SHOCK ANALYSIS OF A MISSILE LAUNCH TUBE

BY KENNETH C. KIDDY

RESEARCH AND TECHNOLOGY DEPARTMENT

20 MAY 1982

NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSWC/TR 82-94	2. GOVT ACCESSION NO. AD-A122288	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) UNDERWATER SHOCK ANALYSIS OF A MISSILE LAUNCH TUBE		5. TYPE OF REPORT & PERIOD COVERED Final March - October 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Kenneth C. Kiddy		8. CONTRACT OR GRANT NUMBER(s) N0002481WR10233
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center (Code R14) White Oak, Silver Spring, Maryland 20910		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 64567N, 0, 22659, 0
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 20 May 1982
		13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Underwater Shock
Fluid-Structure Interaction
Transient Response

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the results of a non-linear, elastic-plastic, structural response analysis of a missile launch tube to underwater shock. The analysis was performed with the structural response code USA-STAGS. This code employs the finite element method for the structure and the Doubly Asymptotic Approximation (DAA) for the fluid-structure interaction. This analysis was performed in support of a General Dynamics/Electric Boat Division design development for an upcoming shock test to be conducted by the Navy. This report is intended to document results to date in this support effort.

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FOREWORD

This report documents the results of a non-linear, elastic-plastic, structural response analysis of a missile launch tube to underwater shock. The analysis was performed with the structural response code USA-STAGS. This code employs the finite element method for the structure and the Doubly Asymptotic Approximation (DAA) for the fluid-structure interaction. This analysis was performed in support of a General Dynamics/Electric Boat Division design development for an upcoming shock test to be conducted by the Navy. This report is intended to document results to date in this support effort. Additional analyses may be required in the future.

Funding for this work has been provided by the Naval Sea Systems Command (SEA-322).

J. F. PROCTOR
By direction

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CHAPTER 1

INTRODUCTION

This report documents the results of a non-linear, elastic-plastic, structural response analysis of a missile launch tube to underwater shock. The analysis was performed with the structural response code USA-STAGS. This code is a combination of the Underwater Shock Analysis (USA)[1] code and the Structural Analysis of General Shells code (STAGS).[2] In USA, the fluid is assumed to be an infinite acoustic medium whose response to the motion of the structure is described by the Doubly Asymptotic Approximation (DAA).[3,4,5] STAGS is a general purpose non-linear finite element code intended for analysis of shell type structures. The analytical formulation of USA-STAGS is described in Chapter 2.

This analysis was performed in support of a General Dynamics/Electric Boat Division design development for an upcoming shock test to be conducted by the Navy. This report is intended to document results to data in this support effort. Additional analysis may be required in the future.

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1 DeRuntz, J. A., Geers, T. L., Fellipa, C. A., "The Underwater Shock Analysis (USA) Code, A Reference Manual," LMSC-D624328, Contract No. DNA 001-76-C-0285, 28 Feb 1978.

2. Almroth, B. O., Brogan, F. A., "The STAGS Computer Code," Report No. LMSC-DS58853, Structural Mechanics Laboratory, Lockheed Palo Alto Research Lab, Palo Alto, CA.

3 Geers, T. L., "Transient Response Analysis of Submerged Structures," in Finite Element Analysis of Transient Non-Linear Behavior, AMD Vol. 14, ASME, New York, 1975.

4 Geers, T. L., "Response of an Elastic Cylindrical Shell by a Transient Acoustic Shock Wave in a Light Fluid Medium," J. Acoust. Soc. Am., Vol. 48, No. 3, Sep 1970, pp. 692-701.

5 Geers, T. L., "Excitation of an Elastic Cylindrical Shell by a Transient Acoustic Wave," J. Appl. Mech., Vol. 36, No. 3, Sep 1969, pp. 459-469.

Prior to the dynamic structural analysis, a bifurcation buckling analysis of the launch tube was performed using STAGS. This is discussed in Chapter 3.

CHAPTER 2

ANALYTICAL FORMULATION

STRUCTURAL RESPONSE EQUATION

As STAGS is based upon the finite element method, the discretized differential equation of motion for the non-linear structure is expressed as

$$\underset{\sim}{M}_s \ddot{\underline{x}} + \underset{\sim}{C}_s \dot{\underline{x}} + \underset{\sim}{K}_s \underline{x} = \underline{f} \qquad (1)$$

where $\underline{x}$ is the structural displacement vector. $\underset{\sim}{M}_s$ and $\underset{\sim}{C}_s$ are the structural mass and damping matrices. $\underset{\sim}{K}_s$ is the non-linear stiffness matrix and $\underline{f}$ is the external force vector. Generally $\underset{\sim}{M}_s$, $\underset{\sim}{C}_s$ and $\underset{\sim}{K}_s$ are highly banded symmetric matrices of large order. In particular, STAGS considers $\underset{\sim}{M}_s$ to be diagonal and $\underset{\sim}{C}_s$ to be a linear combination of $\underset{\sim}{M}_s$ and $\underset{\sim}{K}_s$.

For the excitation of a submerged structure by a transient acoustic wave, $\underline{f}$ is a given by

$$\underline{f} = -\underset{\sim}{G}\, \underset{\sim}{A}_f \, (\underline{P}_I + \underline{P}_s) + \underline{f}_D \qquad (2)$$

where $\underline{P}_I$ is the modal incident pressure vector (a known) and $\underline{P}_s$ is the modal scattered pressure vector (unknown). The dry structure dynamic load vector is given by $\underline{f}_D$; additionally, $\underset{\sim}{A}_f$ is an area matrix and $\underset{\sim}{G}$ is a transformation matrix.

FLUID RESPONSE EQUATION

USA makes use of the DAA to describe the response of the scattered pressure at the fluid structure interface.[6,7] The DAA exhibits both excellent high frequency accuracy and excellent low frequency accuracy as well as offering a smooth transition between the two asymptotes.

The differential equation governing the fluid response is

$$\underset{\sim}{M}_f \dot{\underline{P}}_s + \rho c \underset{\sim}{A}_f \underline{P}_s = \rho c \underset{\sim}{M}_f \dot{\underline{U}}_s \tag{3}$$

where $\underline{P}_s$ is the scattered pressure vector; $\underline{U}_s$ is the vector of the scattered wave particle velocities; ρ and c are the fluid density and sound speed. The added mass matrix, $\underset{\sim}{M}_f$, is produced by a boundary element treatment of the irrotational fluid by the motions of the structure's wetted surface.[8]

The above equation (3) is subject to the following kinematic compatibility equation

$$\underset{\sim}{G}^T \dot{\underline{x}} = \underline{U}_I + \underline{U}_s \tag{4}$$

where the superscript T represents the matrix transposition. The compatibility equation (4) constrains the normal fluid particle velocity ($\underline{U}_I + \underline{U}_s$) to the normal structural velocity at the wet interface. The transformation matrix, $\underset{\sim}{G}$, relates the structural freedoms to the fluid freedoms and it follows from the invariance of virtual work with respect to either coordinate system.

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6 Geers, T. L., "Residual Potential and Approximate Methods for Three-Dimensional Fluid-Structure Interaction Problems," J. Acoust. Soc. Am., Vol. 49, No. 5, (Part 2), May 1971, pp 1505-1510.

7 Geers, T. L., "Doubly Asymptotic Approximations for Transient Motions of Submerged Structures," J. Acoust. Soc. Am., Vol. 64, No. 5, November 1978, pp 1500-1508.

8 DeRuntz, J. A., and Geers, T. L., "Added Mass Computation by the Boundary Integral Method," Int. J. Num. Meth. Eng., Vol. 12, 1978, pp 531-550.

FLUID STRUCTURE INTERACTION EQUATION

Substitution of equation (2) into equation (1) and equation (4) into equation (3) yields the coupled fluid structure interaction equations.

$$\underset{\sim}{M}_s \ddot{\underline{x}} + \underset{\sim}{C}_s \dot{\underline{x}} + \underset{\sim}{K}_s \underline{x} = \underline{f}_D - \underset{\sim}{G}\, \underset{\sim}{A}_f (\underline{P}_I + \underline{P}_s)$$

$$\underset{\sim}{M}_f \dot{\underline{P}}_s + \rho c\, \underset{\sim}{A}_f \underline{P}_s = \rho c\, \underset{\sim}{M}_f (\underset{\sim}{G}^T \ddot{\underline{x}} - \dot{\underline{U}}_I) \qquad (5)$$

The above equation (5) may be solved simultaneously at each time step by the transfer of $-\underset{\sim}{G}\, \underset{\sim}{A}_f \underline{P}_s$ and $\rho c\, \underset{\sim}{M}_f \underset{\sim}{G}^T \ddot{\underline{x}}$ to the left side of their respective equation. Such a procedure is exceedingly difficult for larger systems because of the large connectivity of the coefficient matrices. Therefore, a staggered solution procedure has been developed that is unconditionally stable with respect to the time step for the linear problem.[9]

The computational strategy for the staggered solution procedure is embodied in the following steps assuming the solution is known at time t.

(1) Estimate the unknown structural restoring force vector at $t + \Delta t$ from the extrapolation of current and past values.

(2) Transform this extrapolation into fluid node values and form the right-hand side of the fluid equation, which also involves the unknown incident pressure at $t + \Delta t$.

(3) Transform fluid pressures into structural nodal forces.

(4) Solve the structural equation for the displacement and velocity vectors at $t + \Delta t$.

(5) Transform the computed structural restoring force vector at $t + \Delta t$ into fluid node values and reform the right-hand side of the fluid equation.

9 Park, K. C., Felippa, C. A., and DeRuntz, J. A., "Stabilization of Staggered Solution Procedures for Fluid-Structure Interaction Analysis," pp 95-124 of Computational Methods for Fluid-Structure Interaction Problems, AMD-Vol. 26, ASME, New York, 1977.

(6) Resolve the fluid equation and obtain refined values for the total pressures at $t + \Delta t$.

(7) Save system response.

Steps (1), (3) and (5) constitute the basic staggered solution technique, while Steps (2) and (4) are required because of the difference between the fluid and structural surface meshes. The iteration of the fluid solution reflected in Steps (6) and (7) has been added to enhance accuracy. Inasmuch as the computation time is overwhelmed by the structural solution requirements, this requires only a small increase in total run time. The use of a three-point extrapolation method in Step (1) also improves accuracy, as discussed in reference 9.

NON-LINEAR RESPONSE

Structural non-linearities arise from two sources; first geometric considerations and secondly, material considerations. Geometric non-linearities arise from retaining the non-linear terms in the strain-displacement relationship as:

$$\varepsilon_{ij} = 1/2 \{u_{i,j} + u_{j,i} + u_{k,i}\, u_{k,j}\} \qquad (6)$$

The non-linearity in the above equation (6) is the product term, $u_{k,i}\, u_{k,j}$, and physically represents the square of the rotations. For the linear case it is assumed that the squares of the rotations are small and may be neglected. However, for shell type structures, the rotations may not be small and neglecting their effect may not be prudent.

On the other hand, non-linearities may arise from material considerations. Such non-linearities in the stress-strain relationships are commonly referred to as plasticity. Once a material is loaded beyond its elastic limit, it no longer satisfies the generalized Hooke's law. The effective stress now becomes a function of the integral of the plastic strain increment as:

$$\bar{\sigma} = H [\int d \varepsilon^{p}] \tag{7}$$

The functional form of the above equation is quite complicated. It requires a yield criterion and an associated flow rule. In STAGS the Von Mises yield criterion is used. For the analysis described subsequently, the Mechanical Sub-Layer or White-Besseling method has been used. No attempt will be made here to describe its implementation. The reader is referred to References 10 and 11 for a further discussion.

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10 Besseling, J. F., "A Theory of Elastic, Plastic, and Creep Deformation of an Initially Isotropic Material Showing Strain Hardening, Creep Recovery and Secondary Creep," J. Appl. Mech., Vol. 25, No. 4, December 1958, pp 529-536.

11 Hunsaker, B., Vaughan, D. K., and Sticklin, J. A., "A Comparison of the Capability of Four Hardening Rules to Predict a Material's Plastic Behavior," Texas Engineering Experiment Station, Proc. of the Office of Naval Research Plasticity Workshop, June 1975, pp 27-65.

CHAPTER 3

BUCKLING ANALYSIS

A bifurcation buckling analysis of the missile tube is performed using STAGS. The finite element model of the one-inch nominal thickness missile tube is shown in Figure 1. Due to symmetry, only one-half (180^o) of the tube need be modeled. This model has 3002 degrees of freedom (d.o.f) and is radially restrained at two locations along the longitudinal axis representing foundation support plates. It is also constrained at three points at the end of the "skirt" area which represents a rigid pin connection between the tube and the foundation. The foundation is the SSTV (Submarine Shock Test Vehicle), to which the missile tube will be connected for the underwater shock tests.

The first three buckling modes were calculated using STAGS. These modes correspond to buckling pressures of 5498, 6948, and 10425 psi. The exaggerated mode shapes for these pressures are shown in Figures 2, 3, and 4.

CHAPTER 4

DYNAMIC SHOCK ANALYSIS

MODEL DESCRIPTION

A non-linear underwater shock analysis of the one-inch nominal thickness missile tube is now performed using USA-STAGS. Again due to symmetry, only one-half (180^{0}) of the tube is modeled. The discretized finite element mesh is shown in Figure 5. The 3270 d.o.f model is supported with three stiffened plates as well as a round bar connected at the bottom or "skirt" area of the tube. The upper two foundation supports are attached to the tube directly, while the bottom support plate is tied to the round bar through the use of partial compatibility constraints. The three support plates and the round bar are assumed to be connected to a rigid foundation. Figure 6 presents the finite element model in a different view, illustrating the rigid foundation as well as the charge axis. HY 80 is used in the tube, the foundation support plates and the round bars.

STRUCTURAL RESPONSE CALCULATION

The dynamic structural response calculation is done for a 250 pound HBX operational fore-aft shock geometry, with the charge axis located midway between the upper and middle tube support plates (see Figure 6). The input pressure-time history for USA-STAGS is shown in Figure 7. The pressure-time history is calculated from the shock empirically. A typical pressure-time history is obtained from data and compared to its corresponding empirically determined similitude pressure-time history. The resulting scale factors are applied to the empirical similitude pressures for the explosive configuration of interest and highly accurate pressures are obtained.

USA-STAGS calculations have been carried out for 10 milliseconds or about 22 transit times (the time for the incident wave front to traverse the distance of the tube diameter). The 3-step implicit Park[12] method is used to numerically integrate the coupled system of Eqs. (5). An initial timestep of 1/18 transit time was used. The timestep is subsequently increased as the analysis proceeds. In all, 130 time steps were required to perform the analysis.

USA-STAGS RESULTS

Plots of the deformed tube model versus time are shown in Figures 8 and 9. From these plots, it is evident that the most serious deformations are taking place around the top support plate and in the skirt area where the round bar connection is located. Table 1 lists all the elements and the times at which yielding (Von Mises criterion) has occurred. (Only the elements which have satisfied the yield criterion at more than one time are inlcuded). Branch 1, row 3 and branch 2, row 1 are the two rows of elements just above the top support plate. Branch 7 is the skirt area.

A strain-time history is shown for branch 2, row 1, column 1 in Figure 10. This element is the first one above the top support plate and on the side opposite the charge. The strain component that is plotted is the outer fiber axial strain. There are two things to note about this strain history. One is that the strain exceeds the yield strain (2.56 millistrain). The other is that the strain is oscillating between tension and compression. The reason for this

12 Park, K. C., "An Improved Stiffly Stable Method for Direct Integration of Non-Linear Structural Dynamics," J. Appl. Mech. Vol.42, 1975, pp. 464-470.

is that the tube above the top support plate is unconstrained and also carries a rather large concentrated mass to account for the closure hatch, etc. Figures 11 and 12 show displacement-time histories of two points (0^{o} and 180^{o}, where 180^{o} is the charge side) at the end of the tube. Figures 13 and 14 show the velocity-time histories of the same two points. These figures clearly indicate the tube's oscillatory behavior above the top support plate, corresponding to the strain oscillations.

As seen from Table 1, the skirt area of the tube near the round bar connection exhibits the greatest amount of yielding. Two strain-time histories in this area are shown in Figures 15 and 16. Figure 15 is the outer fiber hoop strain for the element where the round bar is connected on the opposite side of the charge. Figure 16 is the same strain component on the element on the charge side, where the other round bar connection is made. It is evident that these strains well exceed yield. However, the skirt area of the model may not adequately represent the round bar-tube connection, leading to misleading predictions for yielding. Therefore, the plastic strains in this area are suspect. The reason for this suspicion is that the tube-round bar connection is made at only one point on each side of the tube. In reality, the round bar connections occur at several points on each side of the tube and therefore may not permit large distortions in the skirt area.

CONCLUSIONS

The structural response calculations of the missile launch tube model were carried out to 10 milliseconds. For this period of time, the results show that the response of the tube remains basically elastic. The only areas which exhibit yielding are in the tube just above the upper foundation and in the skirt area where the round bar attachment to the tube is made.

The large concentrated mass of the tube's free end causes the tube to begin oscillating back and forth when loaded. The momentum from this mass causes the velocity and displacement to increase with each oscillation. Thus the strains in the area of tube support also increase with each oscillation, eventually exceeding yield. This may be a possible trouble spot when the tests are conducted.

It is believed that the skirt area of the finite element model may not adequately represent the round bar-tube connections. Therefore, the plastic strain predictions in this area may be misleading. It is recommended that the round bar-tube connection be more accurately modeled in any future analyses.

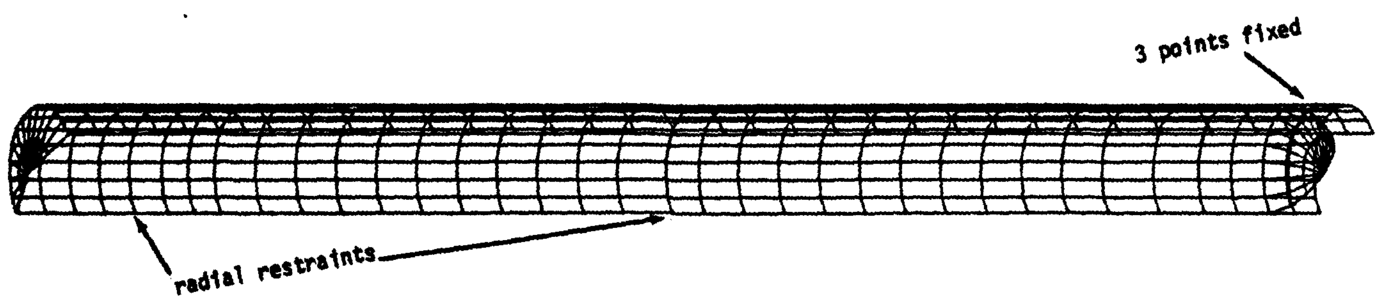

FIGURE 1. FINITE ELEMENT MODEL FOR BUCKLING

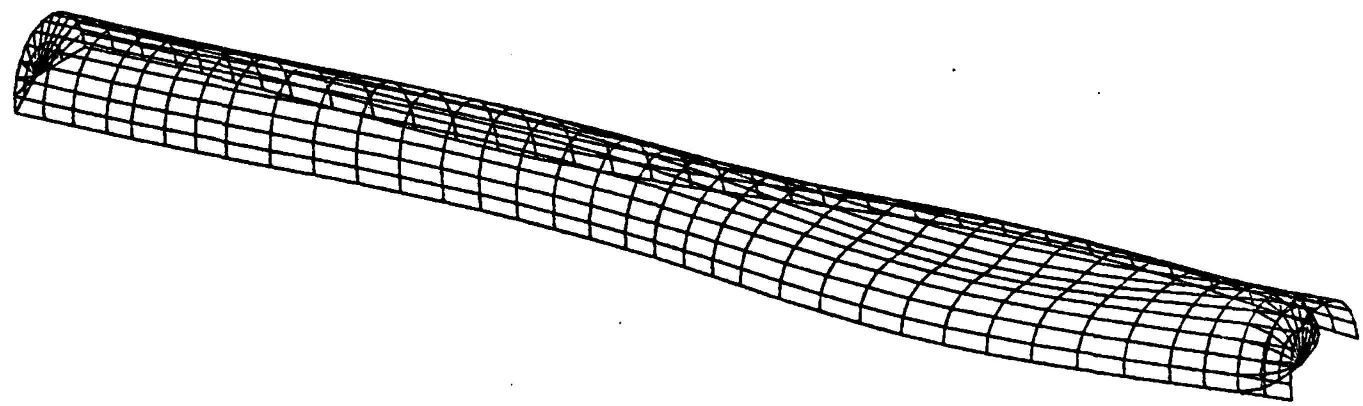

FIGURE 2. MODE SHAPE FOR p = 5498 psi

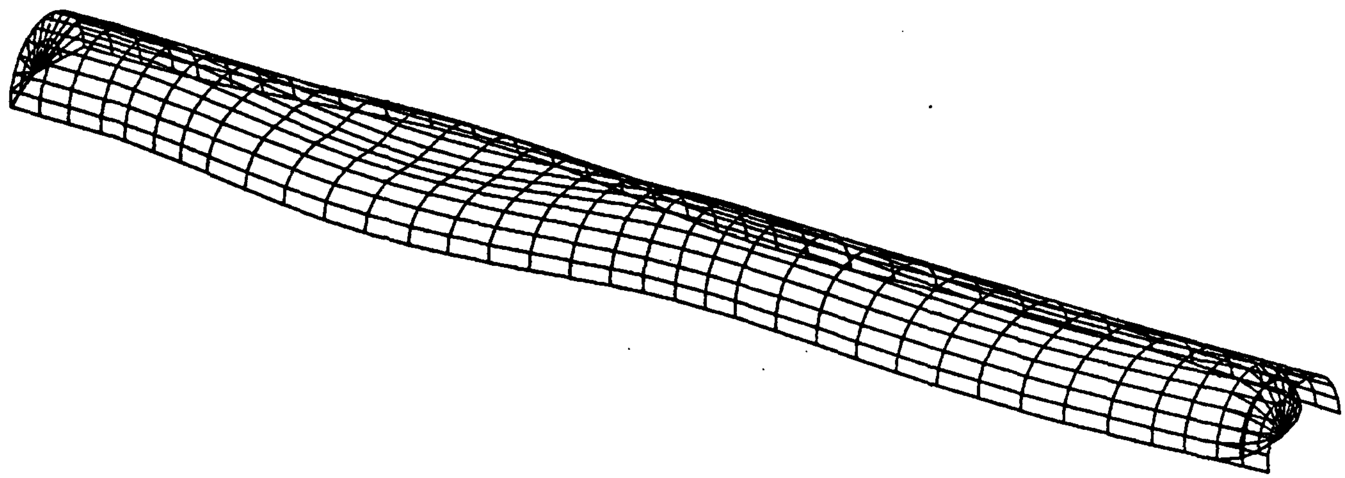

FIGURE 3. MODE SHAPE FOR p = 6948 psi

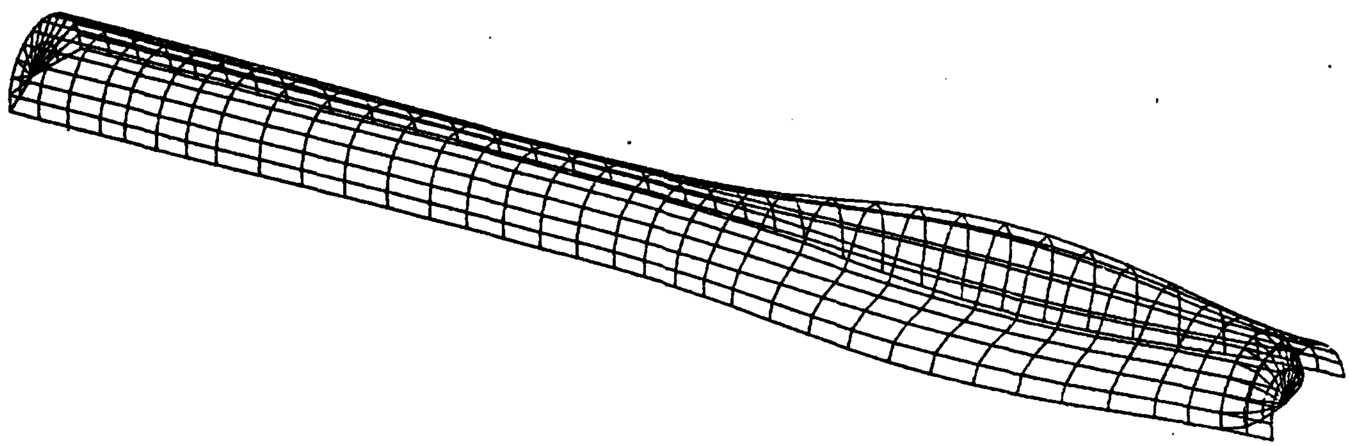

FIGURE 4. MODE SHAPE FOR p = 10425 psi

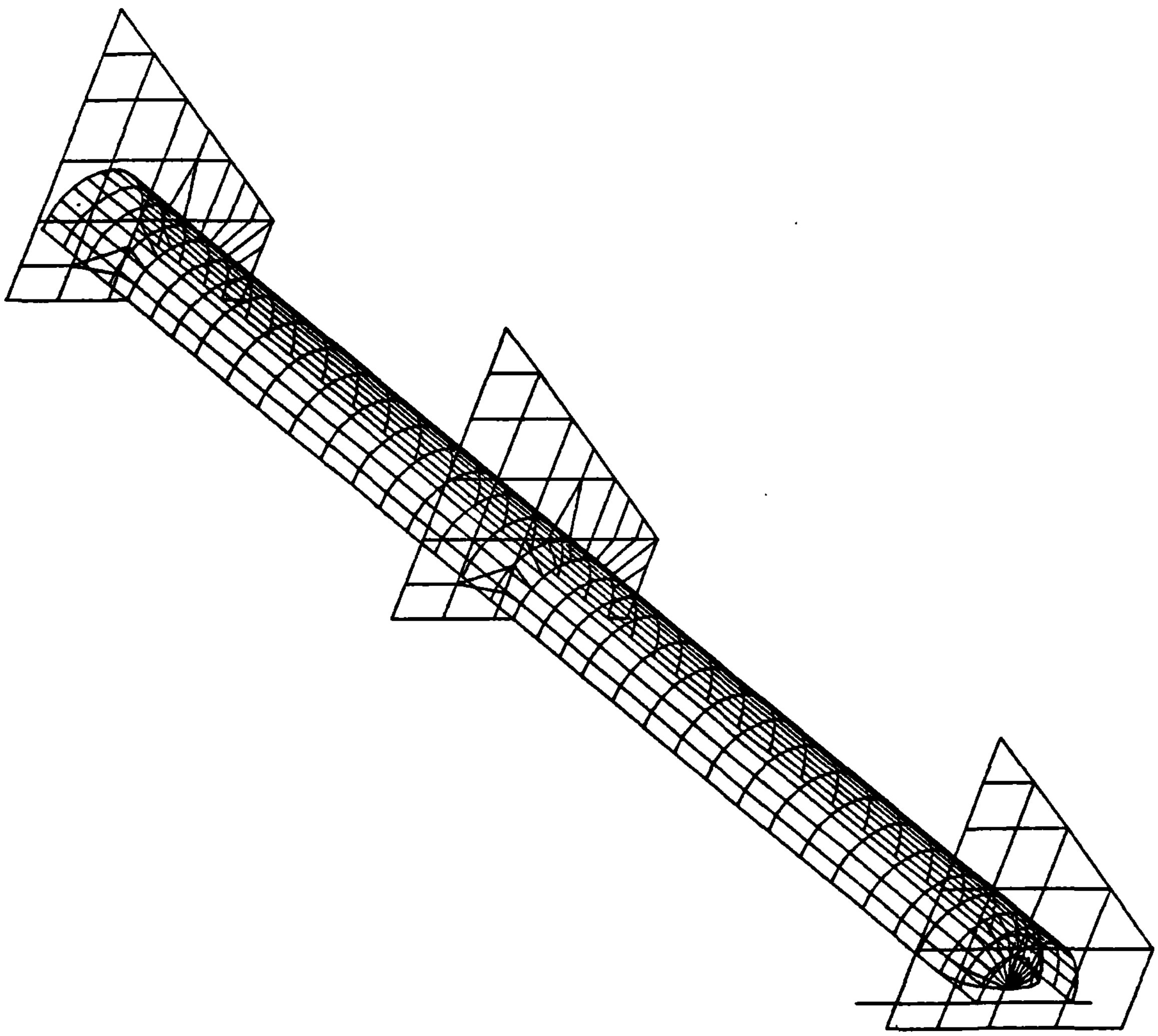

FIGURE 5. FINITE ELEMENT MODEL OF MISSLE TUBE

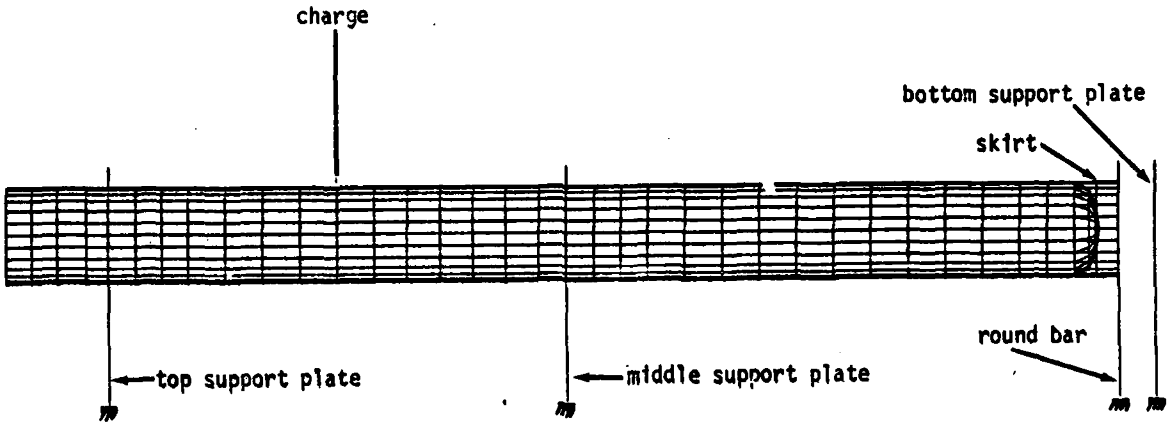

FIGURE 6. PLAN VIEW OF FINITE ELEMENT MODEL

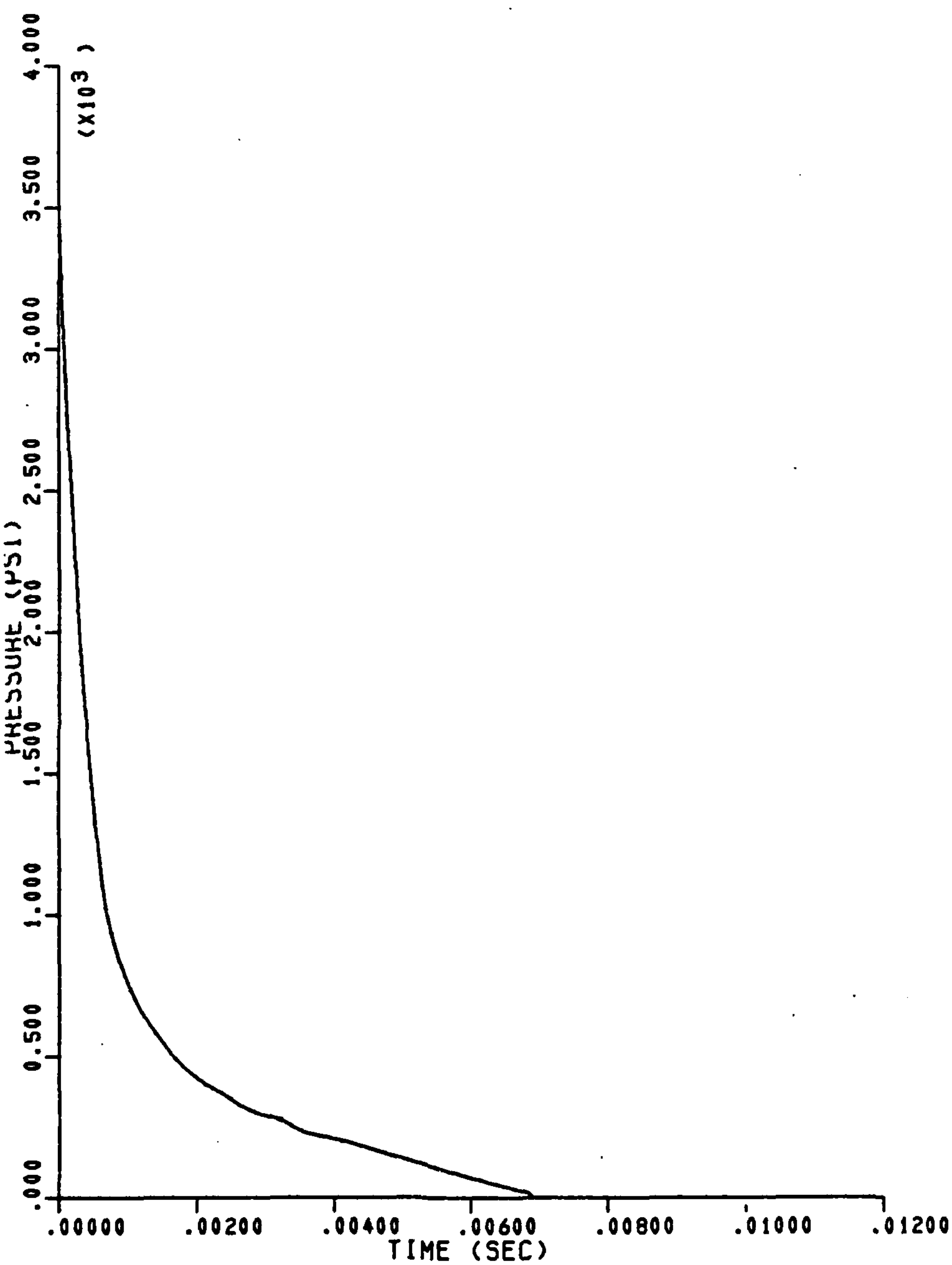

FIGURE 7. INPUT PRESSURE-TIME HISTORY

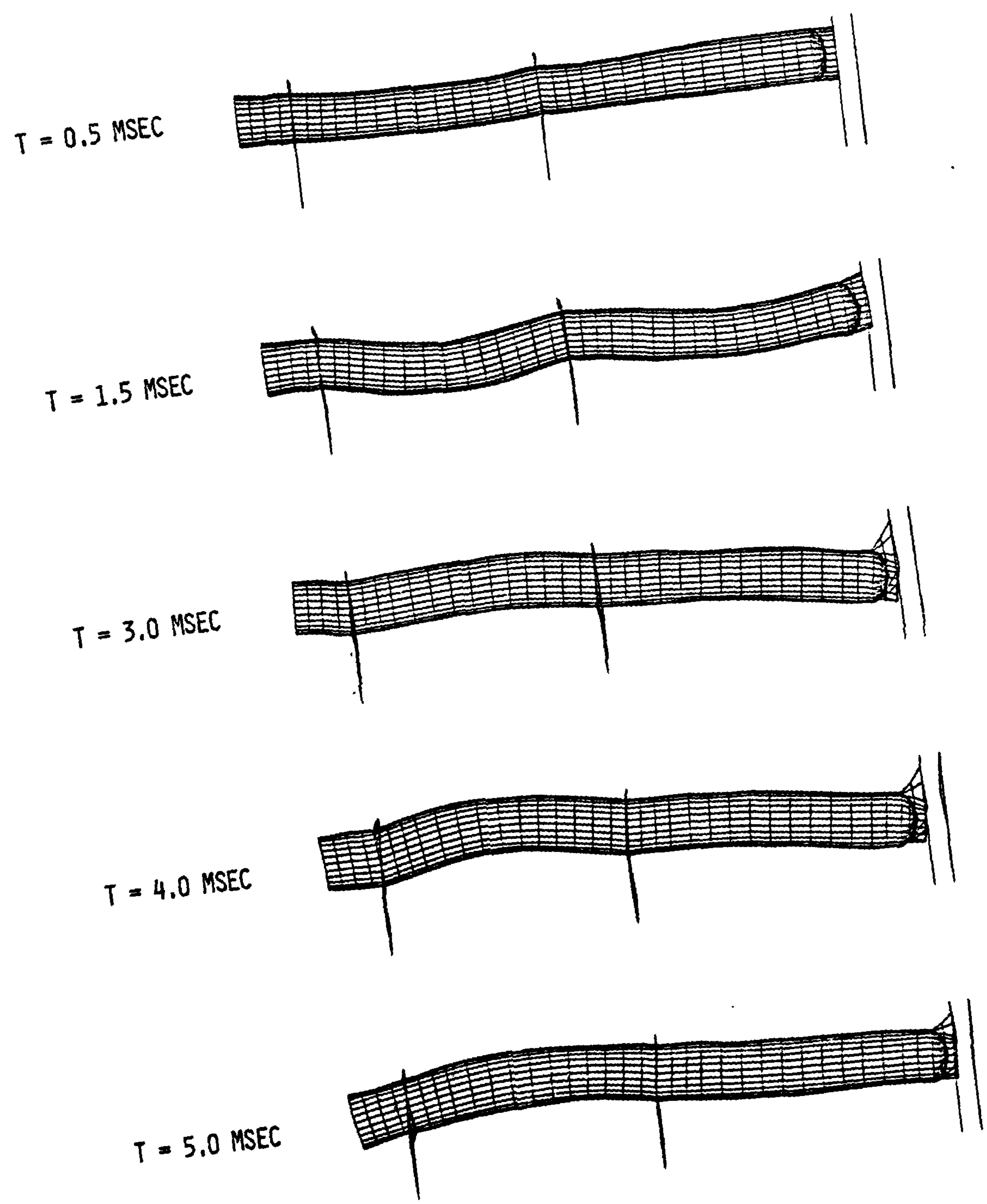

FIGURE 8. DEFORMED TUBE MODEL (T = 0-5 MSEC)

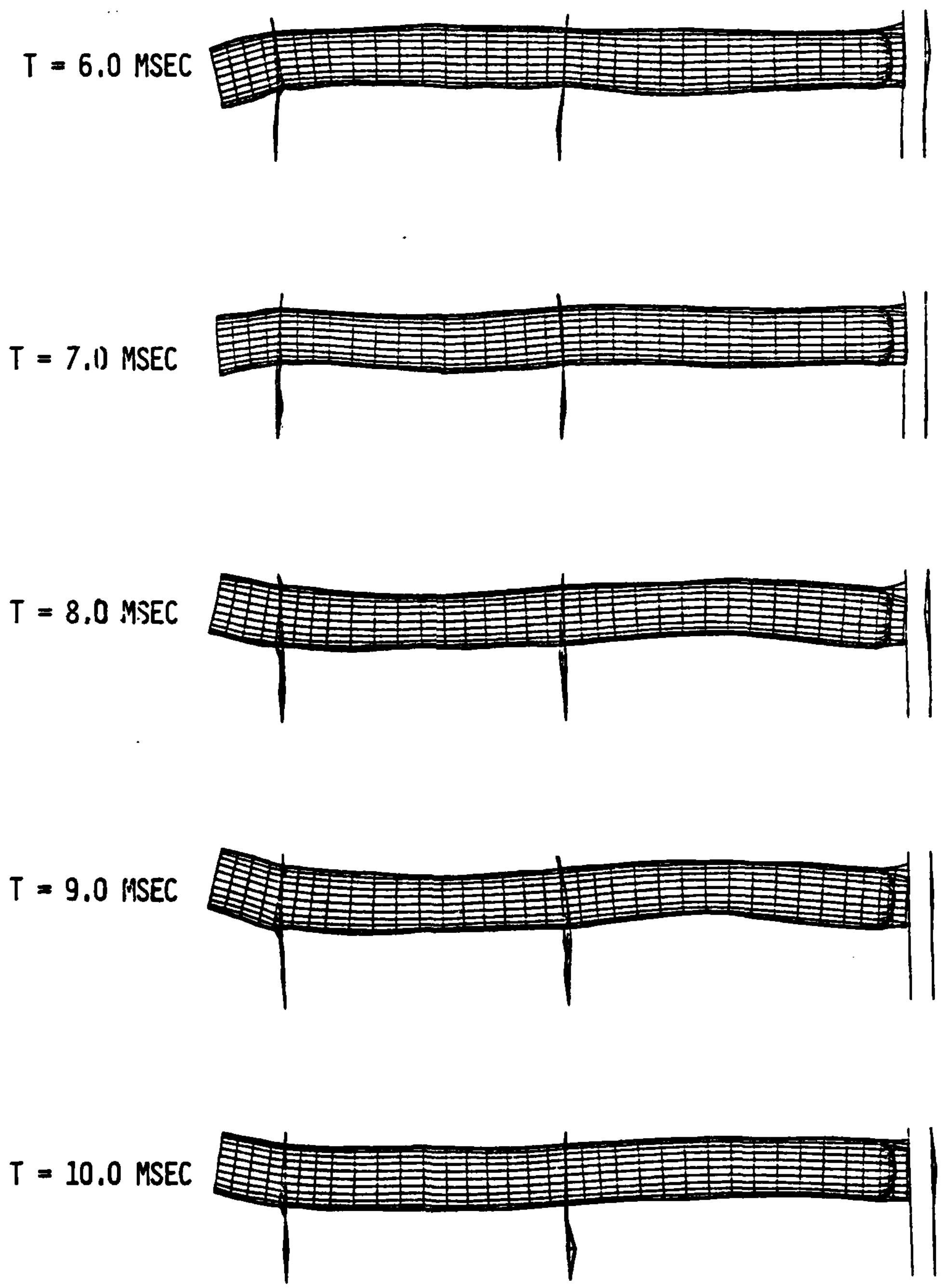

FIGURE 9. DEFORMED TUBE MODEL (T = 6-10 MSEC)

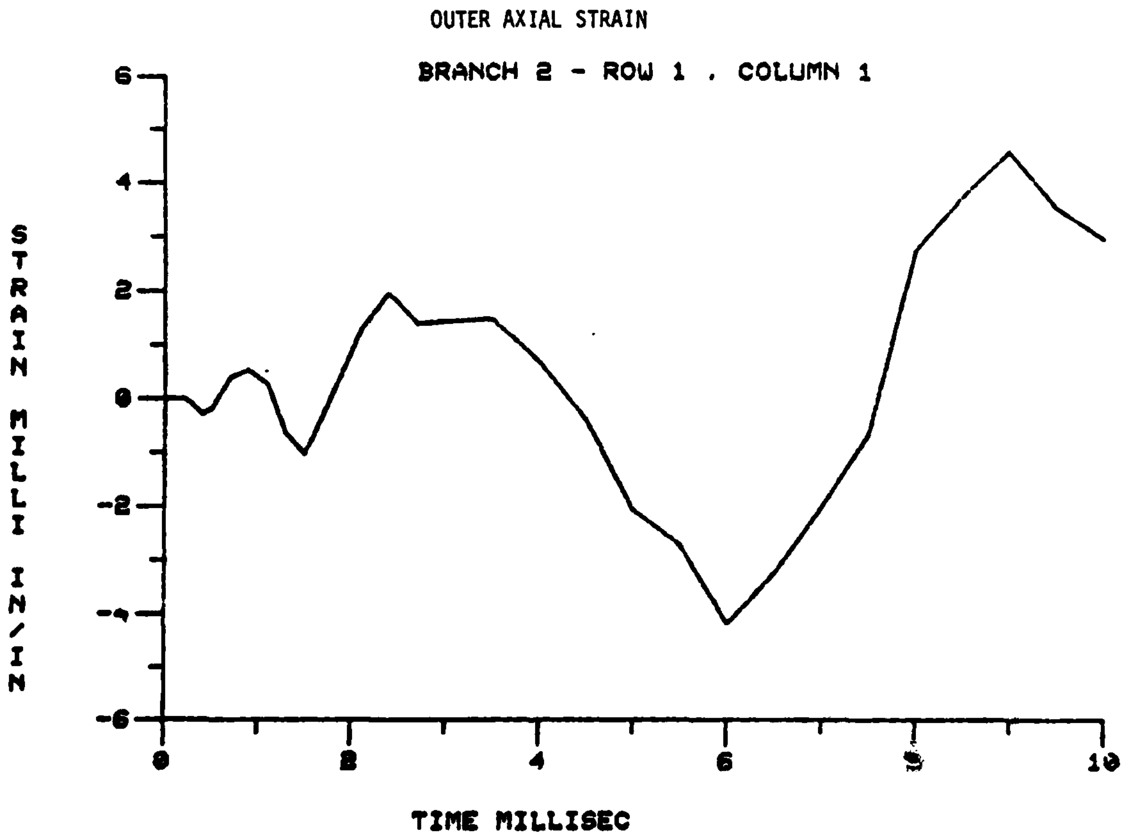

FIGURE 10. STRAIN-TIME HISTORY

BRANCH 2 - ROW 1, COLUMN 1

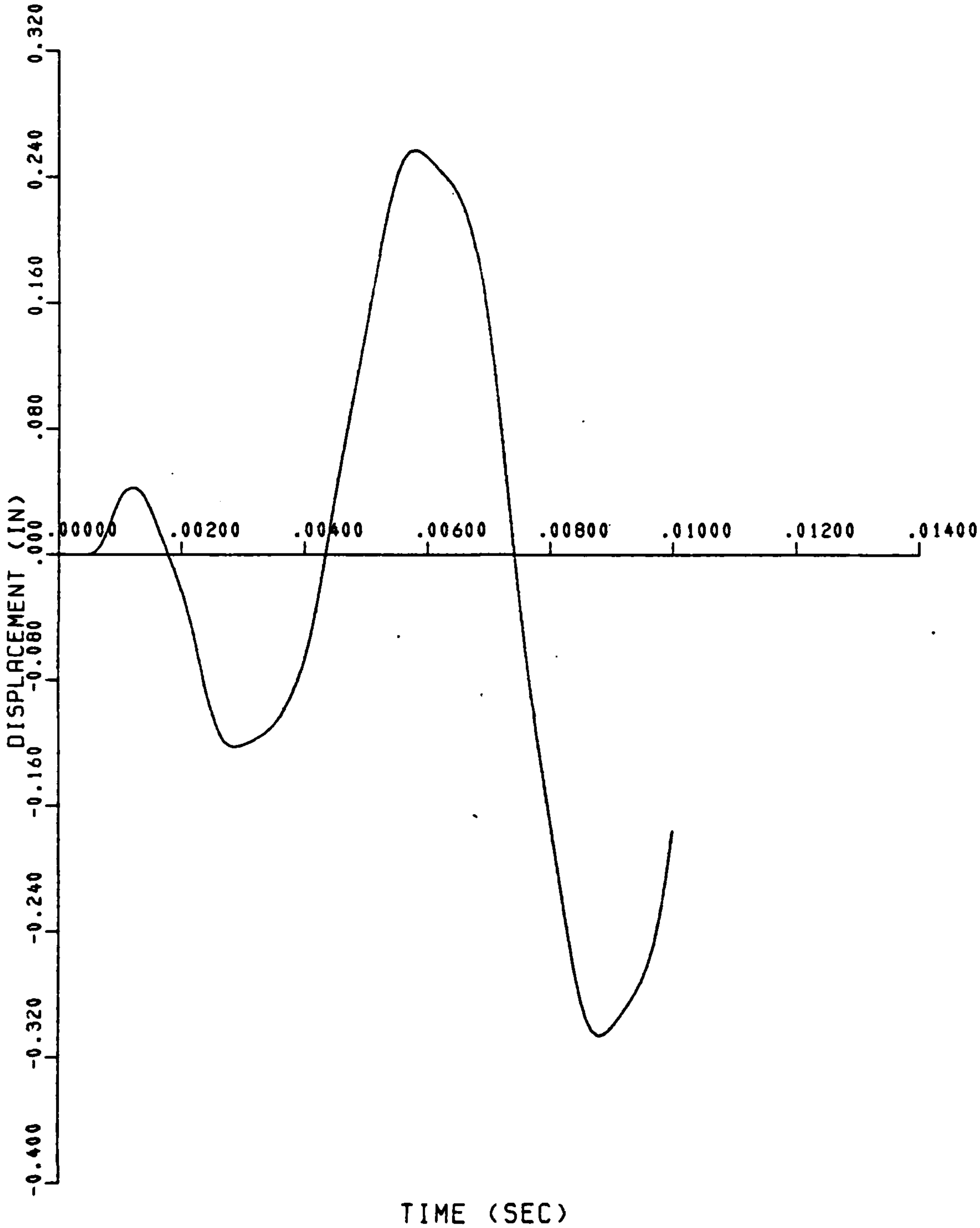

FIGURE 11. DISPLACEMENT-TIME HISTORY AT 0^0

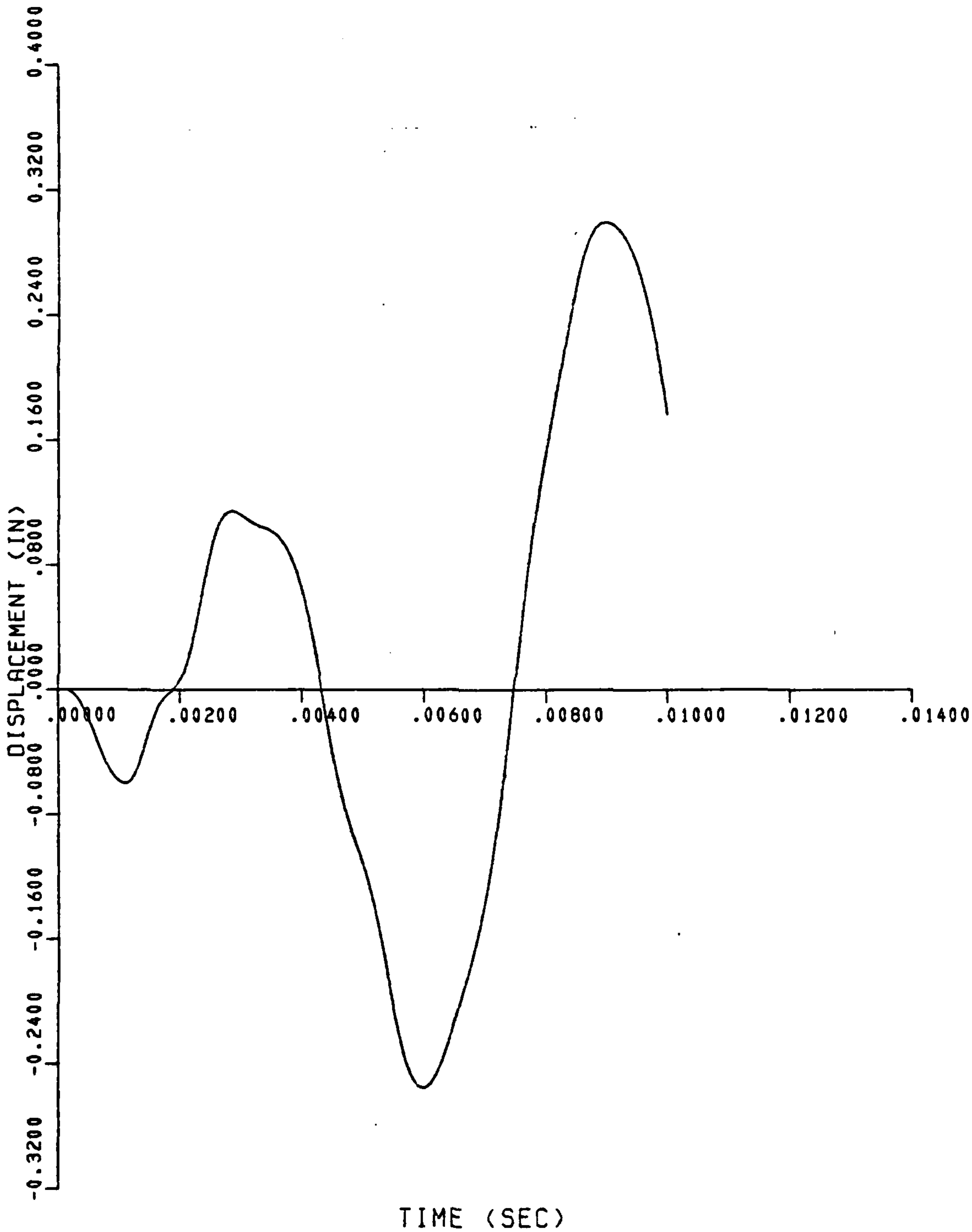

FIGURE 12. DISPLACEMENT-TIME HISTORY AT 180^0

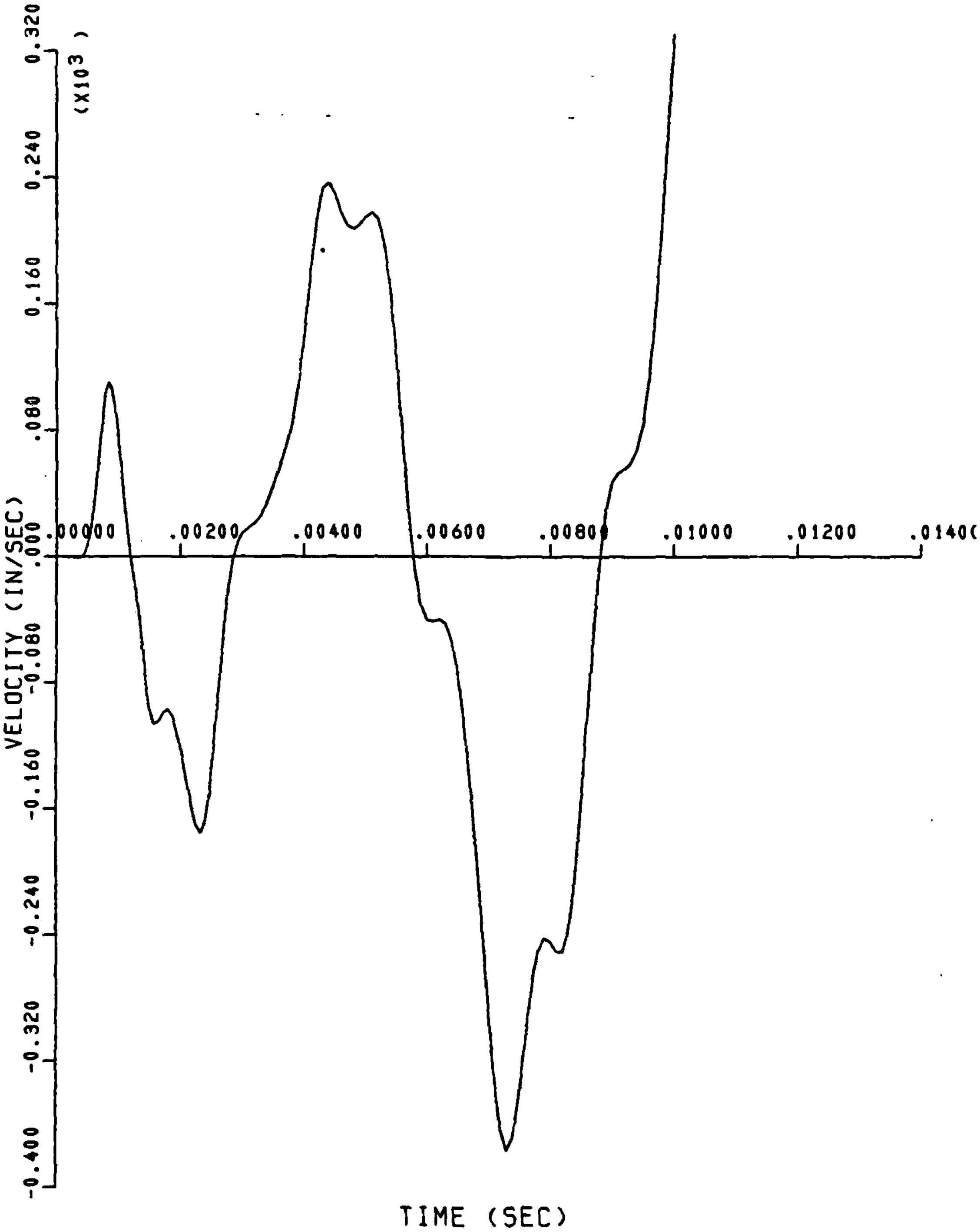

FIGURE 13. VELOCITY-TIME HISTORY AT 0^0

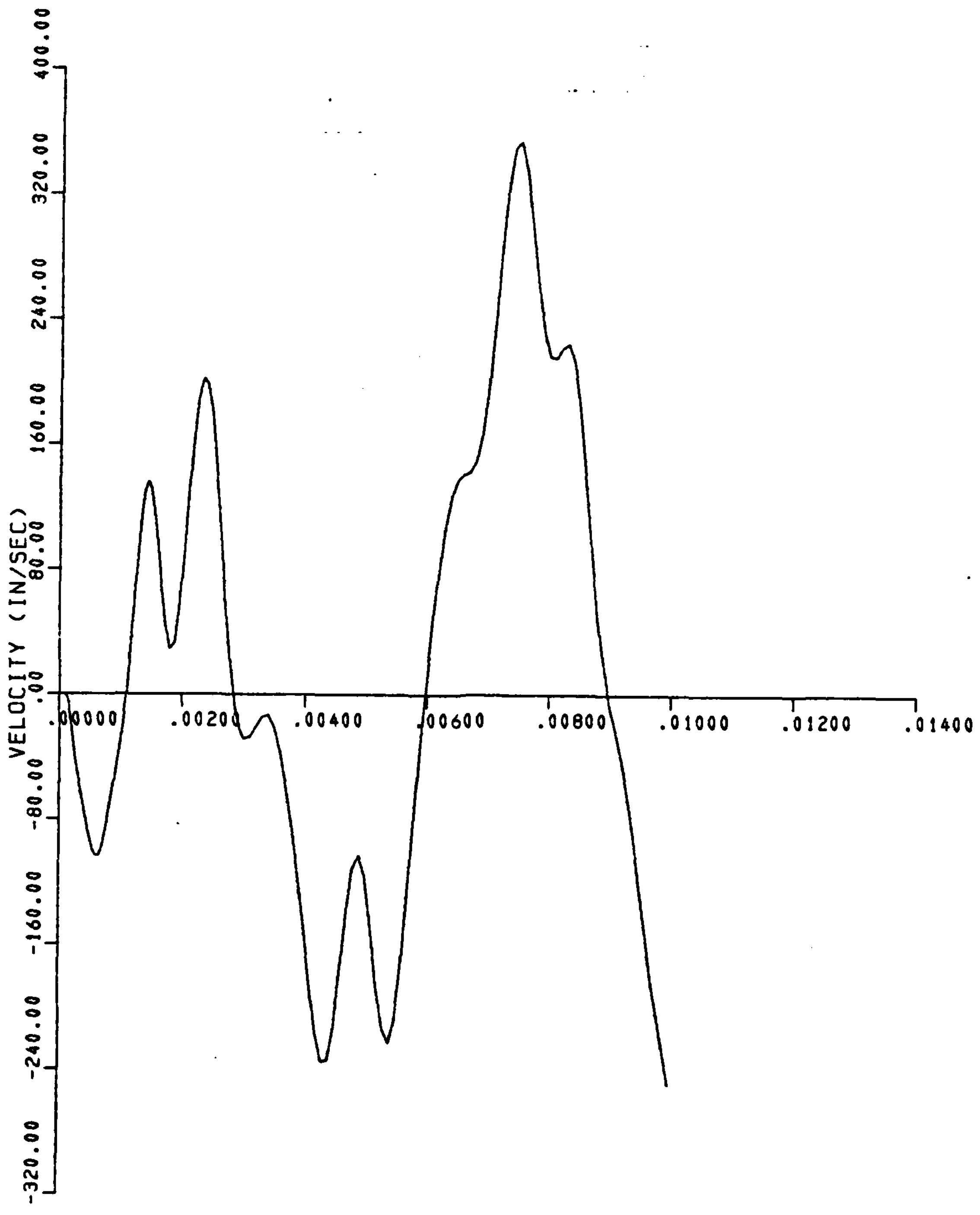

FIGURE 14. VELOCITY-TIME HISTORY AT 180^0

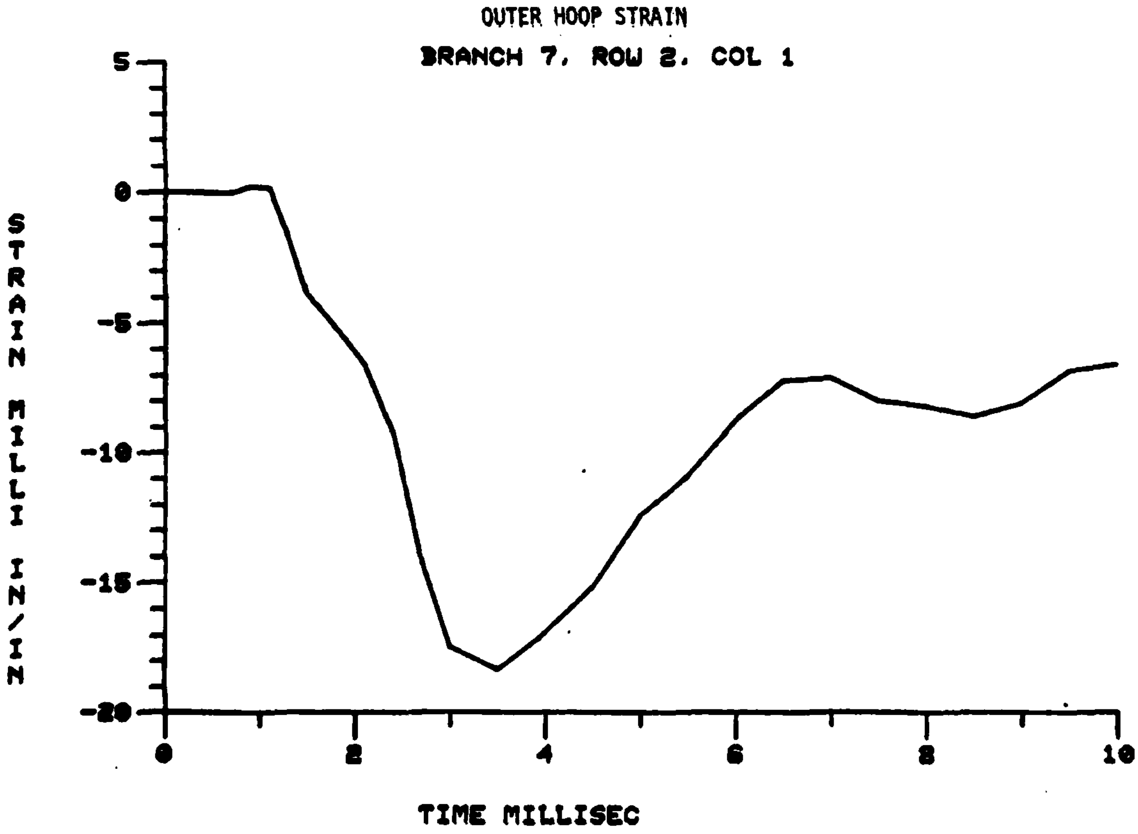

FIGURE 15. STRAIN-TIME HISTORY
BRANCH 7 - ROW 2, COLUMN 1

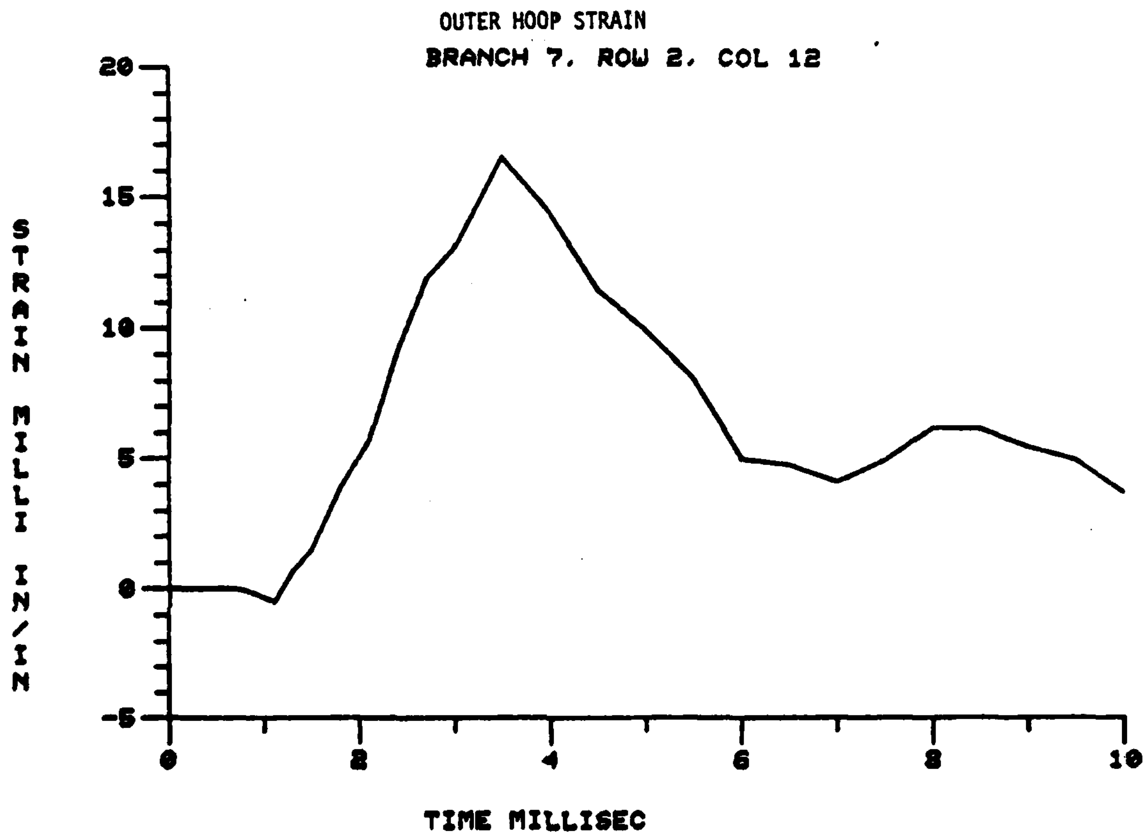

FIGURE 16. STRAIN-TIME HISTORY

BRANCH 7 - ROW 2, COLUMN 12

TABLE 1 ELEMENT YIELD OCCURRENCE TABLE

Branch	Row	Column	Times (msec) where yielding* occurrs
1	3	7	5.5, 8.5
1	3	8	5.5, 8.5, 9.5
2	1	1	5.5, 6.0, 8.0, 8.5
2	1	2	6.0, 8.0, 8.5
2	1	5	3.0, 8.5
2	1	6	0.9, 3.0, 8.5
7	1	1	2.4, 2.7, 3.0, 3.5, 6.5
7	1	2	1.8, 2.1, 2.4, 3.0, 9.5
7	1	11	2.4, 2.7, 3.0, 6.5, 7.0
7	1	12	2.4, 2.7, 3.0, 3.5, 10.0
7	2	1	1.1, 1.5, 2.1, 2.4, 2.7, 3.0, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 9.5
7	2	2	1.5, 2.1, 2.4, 2.7, 3.0, 6.0, 6.5, 8.0, 9.5, 10.0
7	2	3	1.8, 2.4, 2.7, 3.0, 6.0, 6.5
7	2	9	3.0, 3.5
7	2	10	2.1, 2.4, 2.7, 3.0, 3.5, 5.5, 6.0, 6.5, 7.0, 10.0
7	2	11	1.8, 2.1, 2.4, 2.7, 3.5, 5.0, 5.5, 6.0, 6.5, 7.0
7	2	12	1.8, 2.1, 2.4, 2.7, 3.0, 3.5, 5.0, 5.5, 6.0, 7.0, 10.0

*Yielding is based on Von Mises criterion.

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