NON-LINEAR DYNAMIC ANALYSIS OF PIPE WHIP

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ABSTRACT

The dynamic non-linear behavior of pipe whip of a steam line piping system is studied using the general purpose finite element program MARC. The study showed that plastic deformation of the steam line will occur at strains higher than the maximum permissible material strain of 35%. It also indicates that the magnitude of the blowdown force following a guillotine break may be reduced by the deformation of the pipe cross section.

This study can be used as a guideline for assessing the behavior of other steam lines following a pipe break.

INTRODUCTION

The combined rupture of a pipe containing high energy fluid and its subsequent deflection and rotation under the large blowdown force of the jet is known as pipe whip. In case of circumferential guillotine break, the pipe becomes free to move and the high pressure fluid (steam) will introduce jet force, applied at the free end of the pipe. As a result, the piping system is predicted to undergo very large displacements and rotations which will develop plastic hinges along the pipe causing more breaks to occur at different locations. Since the nature of the steam line pipe whip behavior is not known, this study is intended to analyze a steam line of Gentilly-2 nuclear power station from the postulated break locations outside the reactor building to the boiler nozzle. It will provide the pipe whip loads on the steam line pipe supports. The most severed pipe supports will be known and strengthened if possible. It will also provide sufficient information to judge the needs of adding pipe whip restraints to the steam lines.

The finite element models are based on the layout illustrated in Figure 1. In this layout, the postulated pipe break locations used in the analysis are shown. They are selected to produce failure in the steam line due to bending, twisting and buckling. The blowdown forces are calculated using the procedure provided in the ANSI/ANS-58.2-1989. The high magnitude and dynamic nature of this force require a non-linear dynamic analysis to account for several non-linearities due to extensive yielding and large displacements. For this purpose the non-linear finite element MARC code is selected. The Newmark-Beta method (with $\beta = 1/4$ and $\alpha = 1/2$) is used for the direct time integration. The pre- and post-processing finite element MENTAT code is used for modelling the steam line and previewing the analysis results.

DESCRIPTION OF POSTULATED BREAKS AND LOCATIONS

Figure 1 shows the postulated pipe break locations considered in the study. All of the breaks are guillotine breaks. The analysis assumes that the whipping pipe will not impact other steam lines or concrete walls. The scenario used in Figure 1 will produce the most significant amount of deformation of the whipping pipe. The mechanical properties of the steam line material at the design temperature are given below:

Young's modulus, E = 26380 ksi
Yield strength, σ_y = 34.5 ksi
Ultimate strength, σ_u = 75.0 ksi
Poisson's ratio, γ = 0.29
Mass density, ρ = 0.725×10^{-6} kips·sec²/in⁴ (Metal + Insulation)
Failure strain, ε_u = 35%

Break-1

In Figure 1 the break is located at the first welded end of elbow-1 above the steam header. This scenario would result in a thrust force which would push the pipe upward and cause a twisting moment in the straight run of the steam line. The yield twisting moment M_{ty} for a 26-inch diameter pipe and 1.0-inch wall thickness can be estimated using the following formula:

$$M_{ty} = \tau_y \ (2\pi r^2 t) = 21151 \text{ kips} \cdot \text{in}$$

Where, $\tau_y = \sigma_y / \sqrt{3}$ according to Von Mises yield criterion

The predicted twisting moment exerted on the steam line due to the thrust load is 45216 kips.in

Therefore, it is expected that the thrust force will cause yielding in the material almost immediately after the break.

Break-2

Postulated guillotine Break-2 is located at the second welded end of Elbow-2, as illustrated in Figure 1, it is possible that this break occurs anywhere in the straight length of the pipe between Elbow-2 and pipe support PH-560 (resulting from breaks 1 and 3). The thrust load will accelerate the straight length of the line in the axial direction, and the effects of this motion on the main steam safety valves (MSSVs) in that pipe length will be studied.

Break-3

The postulated guillotine break is located at the second welded end of elbow-1 as shown in Figure 1. Following a pipe break at this location, yielding in the material is predicted to occur due to bending. The yield bending moment, M_b is determined as follows:

$$M_b = \sigma_y \times (\pi r^2 t) = 18317 \text{ kips} \cdot \text{in}$$

In this case too, yielding in the material is expected to occur immediately after the break.

FINITE ELEMENT PIPE WHIP MODELS

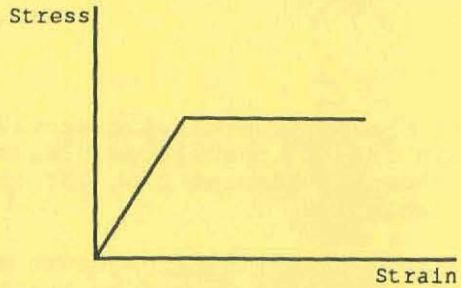
Three finite element models were constructed for this analysis All elements are two-node beam elements (element 14 in MARC). Series of straight segments of beams are used for modelling the elbows. The boiler nozzle node is fixed. All supports are initially assumed to have infinite stiffness (rigid supports).

User subroutine USPRNG is written to permit the introduction of spring constants active only in tension for rod type hangers. It will also assume that other supports have zero spring constant when the pipe whip loads exerted on the supports are twice their design loads.

The jet force is modelled as a follower force which continuously follows the geometry of the pipe. This is accomplished by using the user's subroutine FORCDT.

ANALYSIS MODELS

The main nonlinearities models considered in the analysis are the material and geometric non-linearities, the material non-linearities result from plasticity and strain rate dependency. The material is assumed to be elastic perfect - plastic material (no work hardening) as illustrated below.



Simplified Stress-Strain Curve

The large displacement parameter card is used to include the geometric non-linearties in the analysis. This flags the program to calculate the geometric stiffness matrix and the initial stress stiffness matrix. The Von Mises yield condition is used. It is in good agreement with observed behavior for the ductile materials.

DIRECT INTEGRATION METHOD AND TIME STEPPING SCHEME

The Newmark β method, with $\alpha = 1/2$ and $\beta = 1/4$ (trapezoidal rule), is used in the analysis. This operator is implicit (i.e. matrix solution is required to step the solution forward).

The time interval used is based on the extracted eigenvalues of the Piping System (using the modal shape option). An inspection of the eigenvalues has revealed that the first mode is a bending mode in the Y-Z plane. The period of this mode is 0.85 second. A time step of 0.005 second was used which is much smaller than the suggested time step of 0.06 second (1/15 of the period), it is felt that the behavior will be dominated by higher modes because non-linearity of the material will happen much earlier than the first mode suggests.

DAMPING

Damping is introduced in the direct integration using the same assumption that the system damping matrix is a linear combination of the mass and stiffness matrices of the system:

$$\underline{C} = \alpha\underline{M} + \beta\underline{K}$$

where $\underline{C}, \underline{M} \& \underline{K}$ are the damping, mass and stiffness matrices respectively
$\alpha \& \beta$ are scalar factors

No damping factor is applied to the mass matrix (mass dampers are not introduced and $\alpha = 0$). The β factor is calculated based on the level of damping for steel structure, which is 5% of critical damping. Using the following equation, the β factor is calculated for each model.

$$\beta = \frac{(0.05)(c)}{k}$$

Where c = critical damping = $2\sqrt{km}$

m = generalized mass

k = generalized stiffness

RESULTS

The numerical results of the maximum displacements, velocities, Von Mises stress and plastic strain for all postulated breaks are presented in vector plots and X-Y plots as shown in Figures 2 to 13. The supports peak reaction forces are provided in Table 1.0.

Break-1 Figures 8 and 9 show that yielding occurs simultaneously at integration points 1 and 5 which is caused by the twisting moment generated from the thrust force. For Break-2, the maximum element Von Mises Stress and Strain are shown in Figures 10 and 11. In Figure 11 the calculated Plastic Strain is higher than the permissible material strain. This indicates that a second break is possible due to buckling. Figures 12 and 13 show the maximum element Von Stress and Plastic Strain for Break-3.

CONCLUSIONS

The following conclusions are drawn from the non-linear dynamic models made on the main steam line:

1. The thrust force will cause almost immediate yielding following the postulated breaks. The stresses and strains around the pipe cross section vary from one integration point to another. This means that the deformed cross sectional area of the pipe may lead to a reduction of the thrust load and a guillotine break as a second break is not possible. This conclusion can be studied further by introducing a shell element in the model at the first plastic hinge from the free end of the whipping pipe.

2. The free end of the broken pipe will travel at very high speed, approximately 400 ft/s (270 miles/h), which makes for a very large impact force on the neighboring structures. This motion is followed by considerable displacements that make it possible for the steam line to reach and impact any equipment or concrete walls within a radius of approximately 40 ft. Therefore it is imperative that an auxiliary support mechanism should be added if the surrounding structure and equipment are essential to safety.

REFERENCES

1. MARC ANALYSIS RESEARCH CORPORATION, "General Purpose Finite Element Code", Volumes C and D, Revision K.3-2.

2. MARC ANALYSIS RESEARCH CORPORATION, MENTAT, "A System for Finite Element Pre- and Post-processing", User's Guide Manual, Revision 5.3.0.

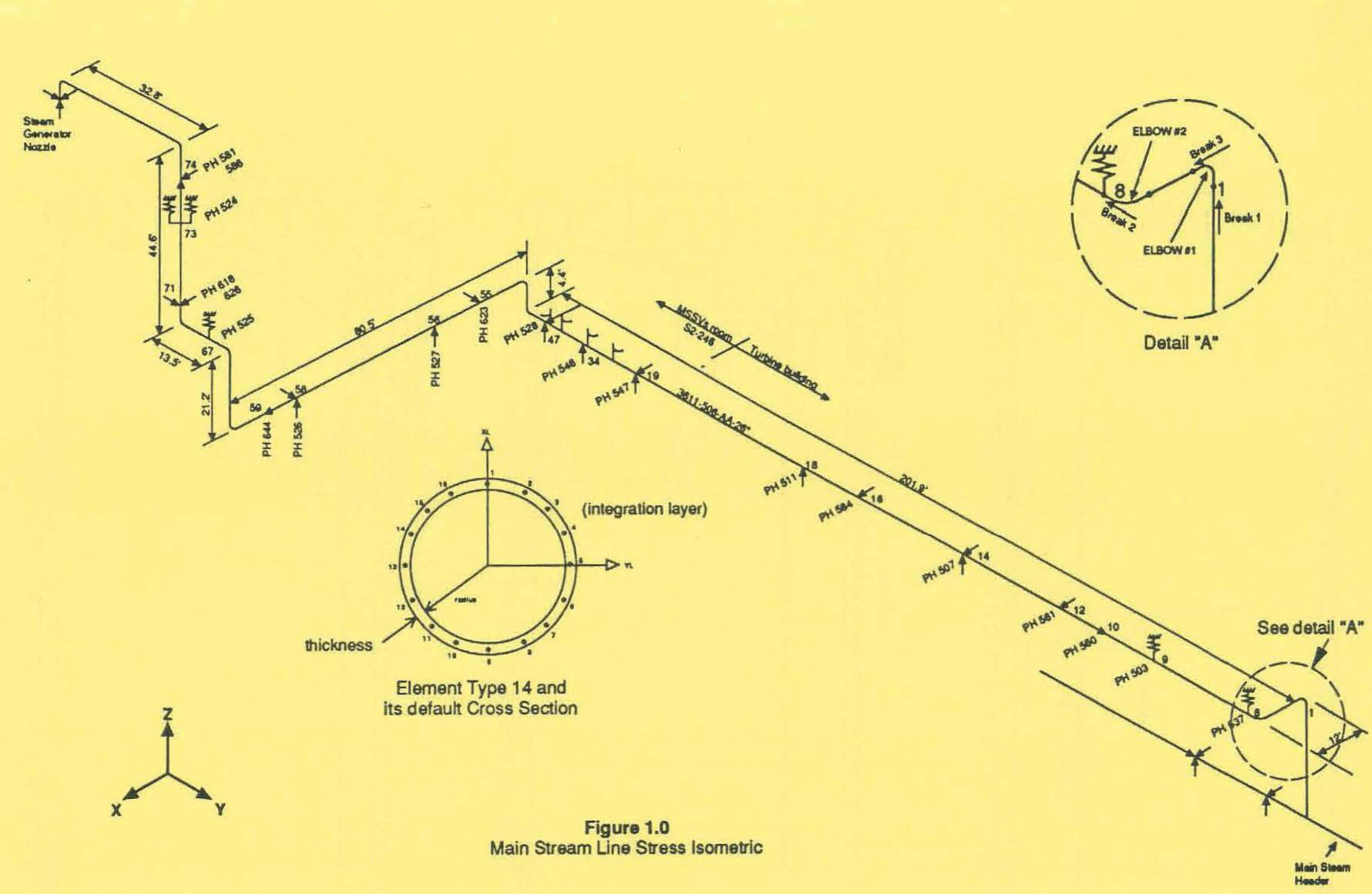
3. AMERICAN SOCITY OF CIVIL ENGINEERS,"Structural Analysis and Design of Nuclear Plant Facilities", Manual of Practice No. 58, 1980.

4. AMERICAN NUCLEAR SOCITY, "Design Basis for Protection of Light Water Nuclear Power Plants Against Effects of Postulated Pipe Rupture", ANSI/ANS-58.2-1989.

TABLE 1-0

MSL PIPE SUPPORTS PEAK REACTIONS (kips)

PH No.	REACTION DIRECTION	BREAK #1		BREAK #2		BREAK #3		REMARKS
		CASE 1	CASE 2	CASE 1	CASE 2	CASE 1	CASE 2	
PH 560	Fy	-115.1	±75.0	±75.0	±75.0	242.7	±75.0	
PH 561	Fx	21.9	17.2	0.0	0.0	±158.1	±75.0	
PH 507	Fx	-6.8	59.9	0.0	0.0	125.2	±75.0	
	Fz	89.0	91.7	0.0	0.0	2.2	-1.4	
PH 584	Fx	9.7	-74.7	0.0	0.0	-25.7	±75.0	
PH 511	Fz	Modelled as a tensile spring only						
PH 547	Fx	-45.3	90.5	-70.3	113.2	7.3	121.0	
	Fz	54.9	58.0	-30.0	-109.7	34.4	31.7	
PH 546	Fz	39.1	63.2	199.2	438.8	-171.8	-189.9	<u>Notes:</u> All pipe whip load directions are in the analysis global axis.
PH 528	Fx	245.7	±75.0	-246.0	-503.1	-38.9	-165.0	Case 1: Without USPRNG subroutine
	Fz	-42.6	-125.7	-332.1	-548.5	114.6	110.8	
PH 423	Fy	25.6	23.7	357.1	±75.0	-209.7	-239.1	Case 2: With USPRNG subroutine. In this case a ±75.0 kips limit is assumed
PH 527	Fz	14.7	89.9	145.3	261.3	41. 7	70.8	
PH 526	Fy	5.7	10.6	-102.0	372.3	26.2	44.8	
	Fz	-5.2	-24.7	60.13	-56.6	-14.9	-27.3	
PH 644	Fx	-218.8	±75.0	±160.6	367.9	70.4	120.8	
PH 618	Fx	0.2	-12.2	32.1	-23.9	-4.3	9.2	
PH 626	Fy	-2.9	-5.1	76.9	-159.5	-4.0	-1.5	
PH 581	Fx	0.2	7.5	0.0	36.7	1.1	4.6	
PH 532	Fz	±0.9	-11.7	0.0	99.0	10.2	15.0	



Element Type 14 and its default Cross Section

Figure 1.0
Main Stream Line Stress Isometric

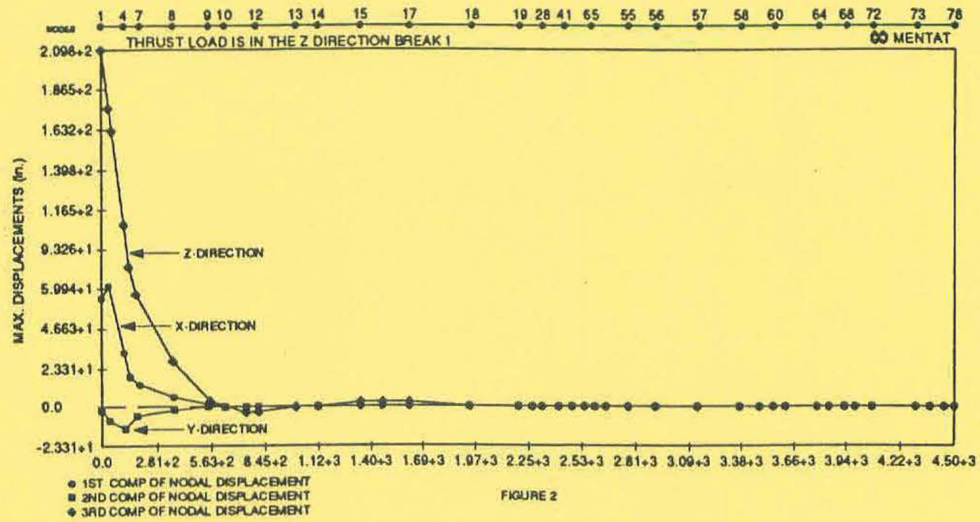


FIGURE 2

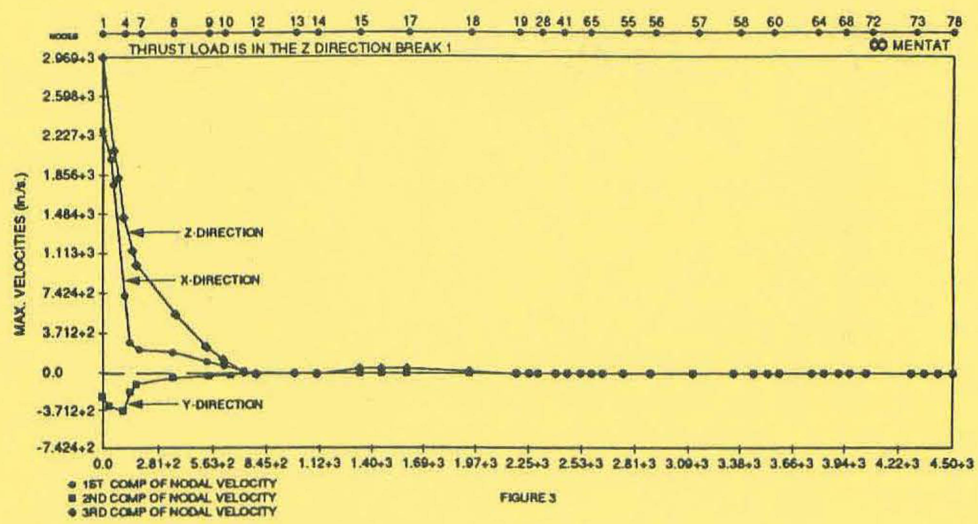


FIGURE 3

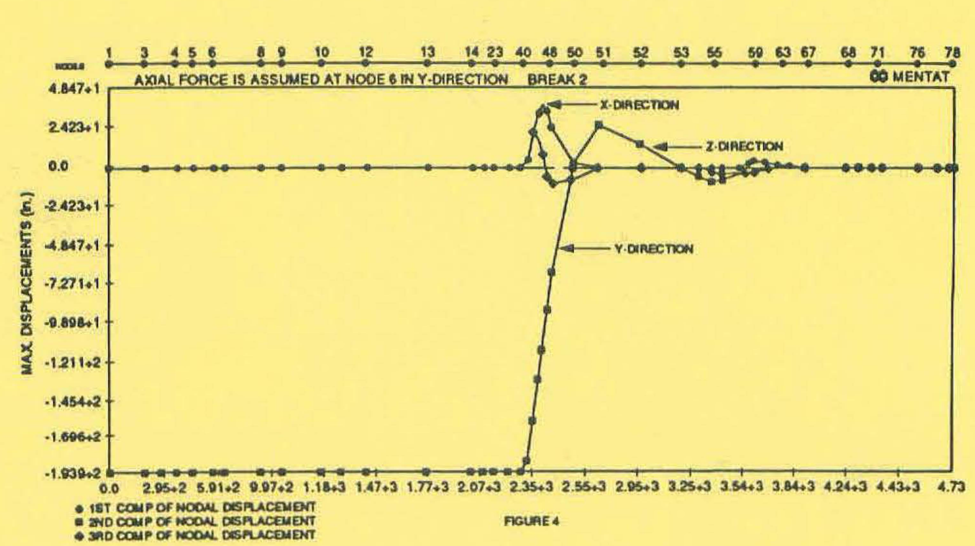


FIGURE 4

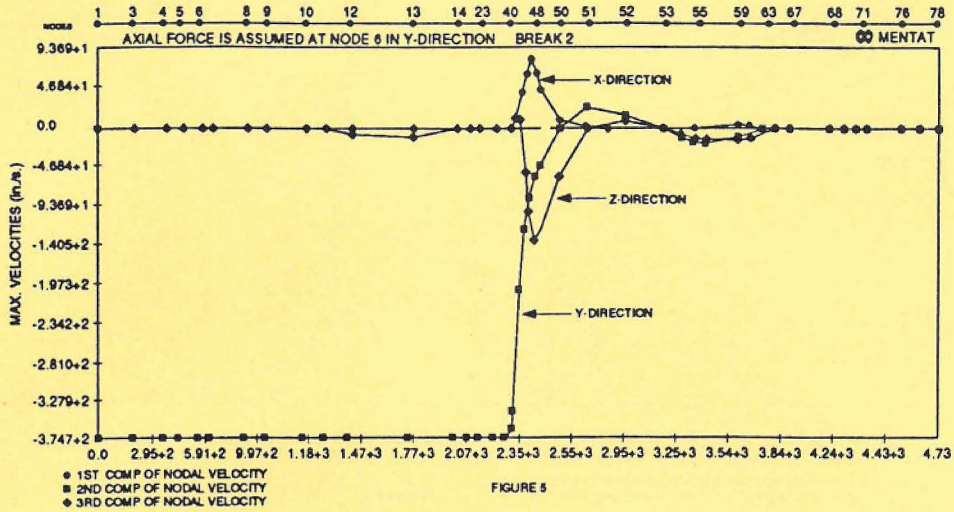


FIGURE 5

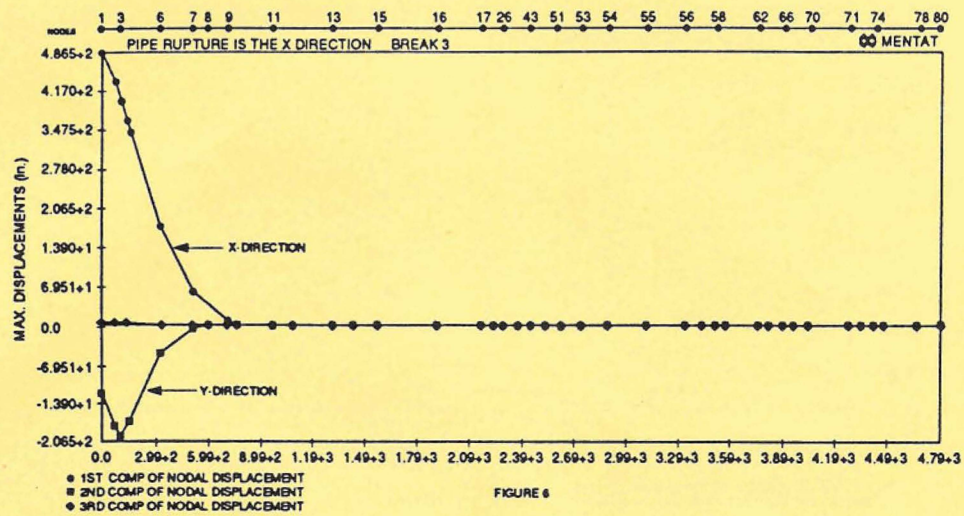


FIGURE 6

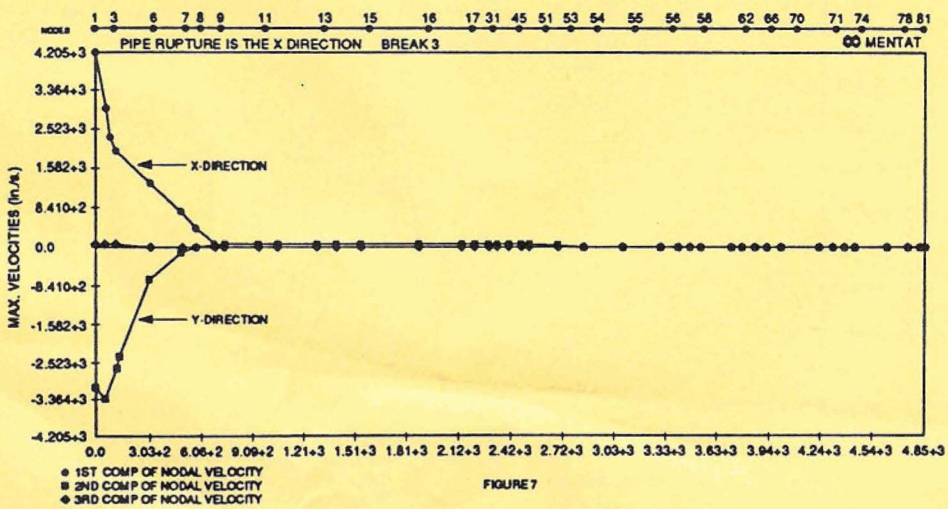


FIGURE 7

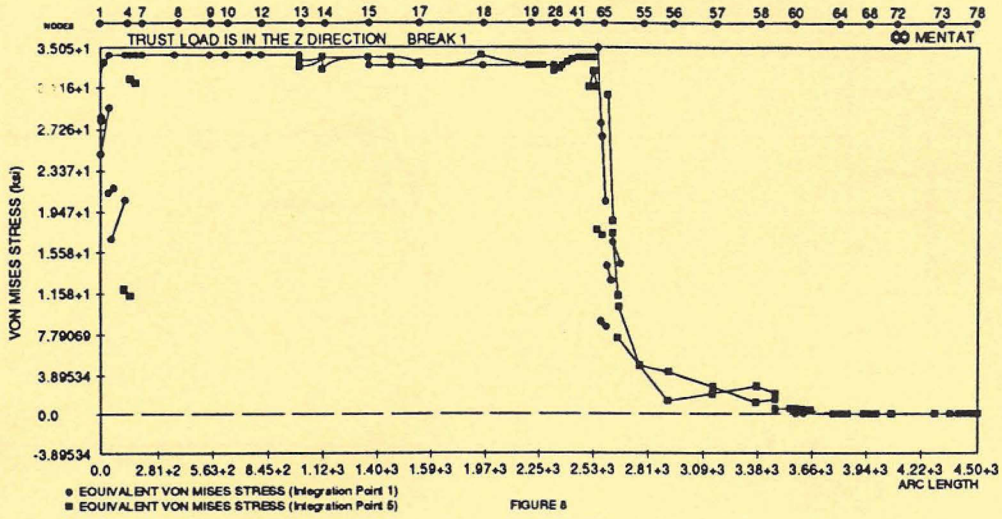


FIGURE 8

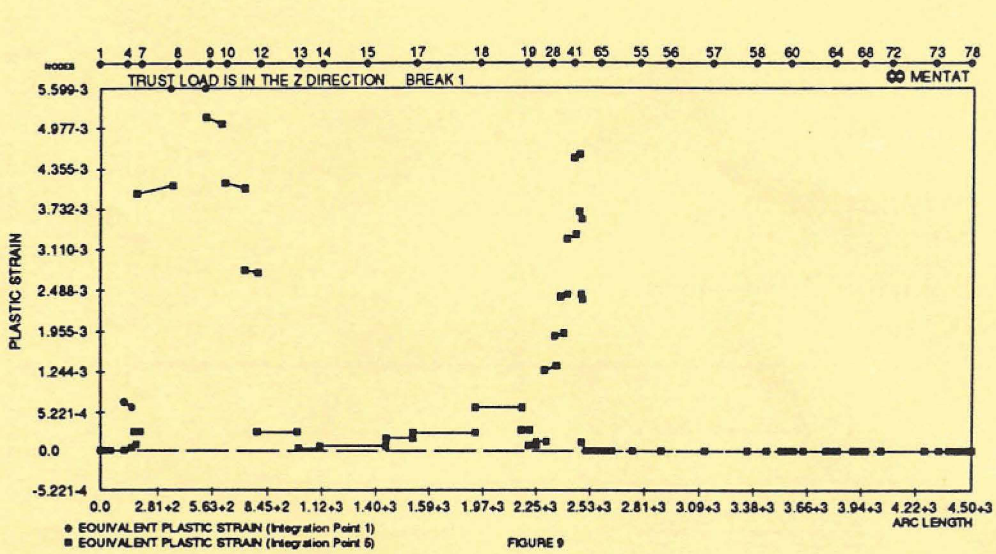


FIGURE 9

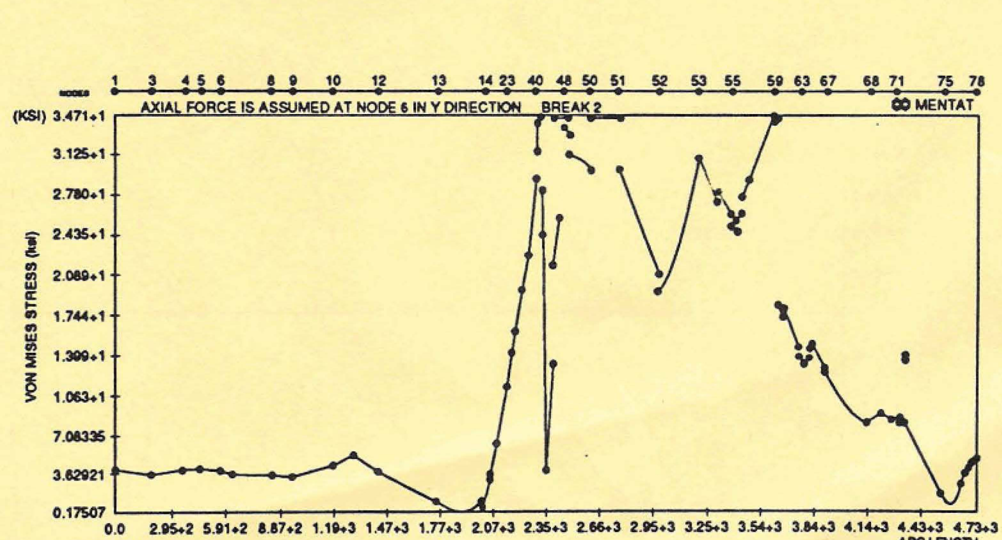


FIGURE 10

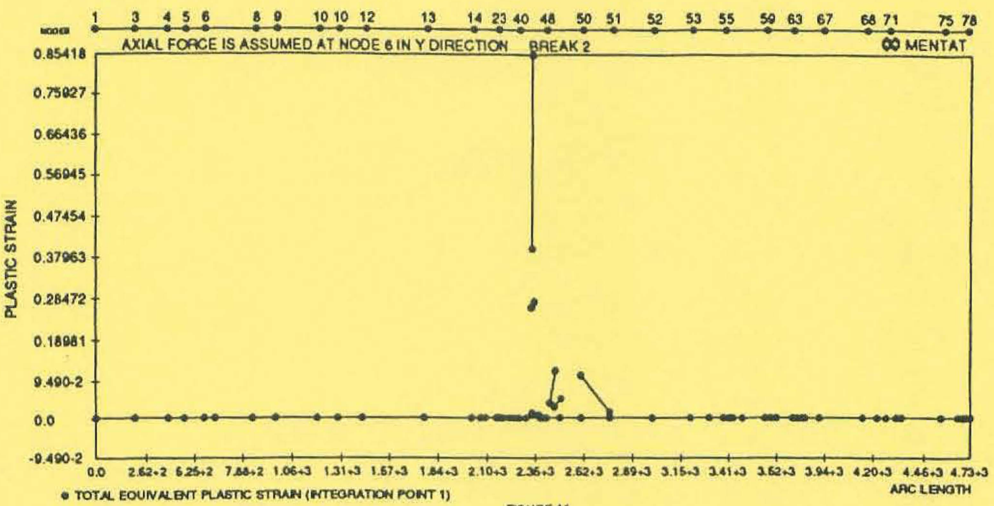


FIGURE 11

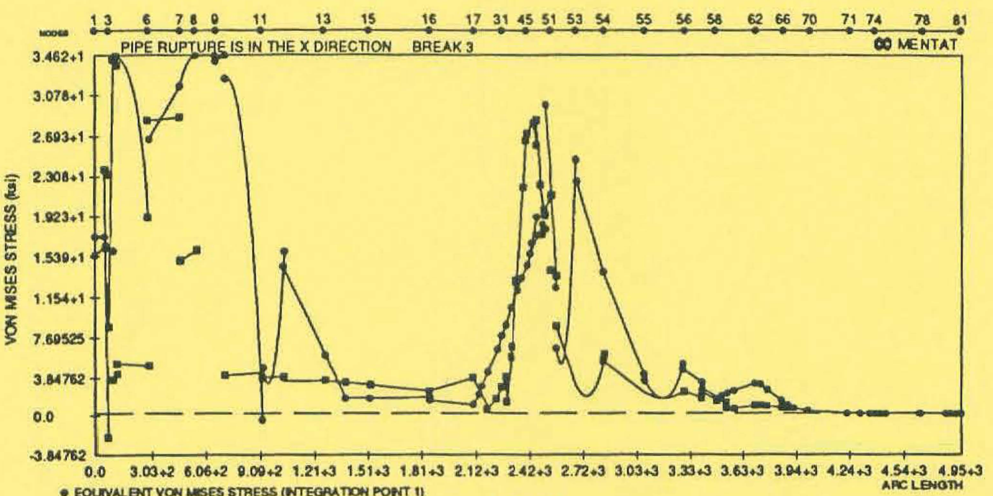


FIGURE 12

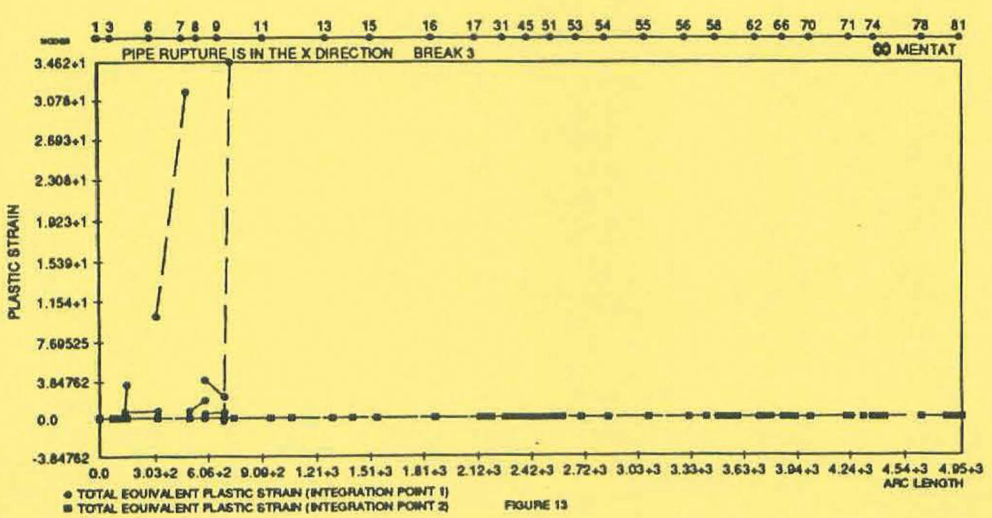


FIGURE 13