Nonlinear Dynamic Analysis of High Energy Line Pipe Whip

L.C. Hsu, A.Y. Kuo
NUTECH Engineers, 6835 Via del Oro, San Jose, California 95119, U.S.A.
H.T. Tang
Electric Power Research Institute, P.O. Box 10412, Palo Alto, California 94303, U.S.A.

Summary

To facilitate potential cost savings in pipe whip protection design, TVA conducted a 1" high pressure line break test to investigate the pipe whip behavior. The test results are available to EPRI as a data base for a generic study on nonlinear dynamic behavior of piping systems and pipe whip phenomena.

This paper describes a nonlinear dynamic analysis of the TVA high energy line tests using ABAQUS-EPGEN code. The analysis considers the effects of large deformation and high strain rate on resisting moment and energy absorption capability of the analyzed piping system. The numerical results of impact forces, impact velocities, and reaction forces at pipe supports are compared to the TVA test data. The pipe whip impact time and forces have also been calculated per the current NRC guidelines and compared.

The calculated pipe support reaction forces prior to impact have been found to be in good agreement with the TVA test data except for some peak values at the very beginning of the pipe break. These peaks are believed to be due to stress wave propagation which cannot be addressed by the ABAQUS code. Both the effects of elbow crushing and strain rate have been approximately simulated. The results are found to be important on pipe whip impact evaluation.

1.0 INTRODUCTION

It is well recognized in the nuclear industry that the current methodology on pipe whip restraint design is overly conservative and not cost effective. This conservatism neglects to account for high strain rate and geometrical nonlinearity effects associated with large deformation during the pipe whip impact. The over conservatively designed massive restraint structures often create problems in plant accessibility and maintainability in addition to higher plant construction cost.

To facilitate potential cost savings in pipe whip protection design, TVA conducted a 1" high energy line break test using live steam. The test results were made available to EPRI as a data base for studying nonlinear dynamic behavior of piping systems and pipe whip phenomena[1].

This paper simulates the pipe whip test system using ABAQUS-EPGEN code to predict the dynamic behavior as observed in the TVA tests. The analysis considered the effects of high strain rate on the resisting moment and energy absorption capabilities of the analyzed piping system. The numerical result of reaction forces and strains are compared to the TVA test data. The adequacy of using the ABAQUS-EPGEN code in evaluating nonlinear pipe whip problems is assessed.

2.0 TVA PIPE BREAK TEST PROGRAM

The TVA pipe break testing program involved pressurizing 1-inch diameter schedule 40 pipe. The pipe had an "L" shape so that the "stick" portion of the "L" would provide mass for producing dynamic loads on an impact pad. The pipe was pressurized to approximately 1000 lb/in^2 by a steam extraction line. Strain gauges and accelerometers were placed at several selected locations on the pipe and pipe supports. A sketch of the test set-up is shown in Figure 1.

Two variables, support location and impact angle, were used in nineteen tests. The front support location was varied from 3 inches to a maximum of 54 inches from the thrust line of the jet. The impact platform was positioned so that the pipe could swing on an angle of 30 to 45 degrees before impacting the platform.

In the present analyses, three TVA pipe break test cases were selected. The reactions of the front support load cell in the TVA Test Case Number 10 was used as the pipe break thrust loads. The time history is plotted in Figure 2. The Test Cases 16 and 17 representing various front pipe support distances and impact angles were selected in the present analyses and tabulated in Table I.

3.0 ABAQUS-EPGEN ANALYSIS MODEL

Pipe whip is a highly nonlinear problem due to the simultaneous existence of geometry, material, and boundary nonlinearities. The geometry nonlinearity arises from large deformation of the structure. The material nonlinearity is a result of plasticity and strain rate dependency. The boundary nonlinearity comes from two sources: the contact between pipe and platform and the change of external load whose direction follows the deformed configuration. A general purpose finite element program, ABAQUS-EPGEN[2], is used for the current analysis. A brief description of the theoretical formulation of the finite element model is given as follows.

3.1 Element Type and Boundary Conditions

Figure 3 shows the finite element model constructed for the present pipe whip analyses. In this model Elements 13 and 19 are two-node truss elements which take axial loads only. Elements 22 through 25 are unidirectional gap elements that take compressive force when the gap clearance becomes zero. All other elements in Figure 3 are two-node beam elements. The boundary nodes 20, 113, 118, and 214 through 217 are fixed.

3.2 Material Model

The pipe material in the TVA 1" pipe whip test is known to be black iron. The static stress-strain curve of this material is shown in Figure 4. For a one-dimensional problem, the yield condition can be written as

$$\sigma \leq \sigma_o(\bar{\varepsilon}^{p\ell} , |\dot{\varepsilon}|) \qquad (1)$$

where σ designates stress,

$\bar{\varepsilon}^{p\ell} = d\varepsilon^p$ is the equivalent plastic strain,

$\dot{\varepsilon}$ is the rate of total strain, and

σ_o is the static yield stress.

The incremental stress and strain relation may be expressed as:

$$d\sigma = E\, d\varepsilon$$

for elastic response, and

$$d\sigma = \frac{H}{(1+H/E)}\, d\varepsilon + \frac{R}{(1+H/E)}\, d\dot{\varepsilon} \qquad (2)$$

during the plastic loading

where $H = \dfrac{\partial\sigma_o}{\partial\bar{\varepsilon}^{p\ell}}$ and $R = \dfrac{\partial\sigma_o}{\partial\dot{\varepsilon}}$

To account for the strain rate effect the following equation is adopted,

$$\dot{\varepsilon}^{p\ell} = D(\frac{\sigma}{\sigma_o} - 1)^p \quad (3)$$

where p and D are material constants.

To the authors' knowledge there is no experimental strain rate effect data available for black iron. The present investigation assumes the same SA-106 carbon steel D and p values [3], 240 and 3.9 respectively, for black iron, although the static yield strength of black iron (26.26 ksi) is considerably lower than that of SA-106 (43.2 ksi).

3.3 Time Integration and Automatic Time Stepping Schemes

An implicit, stable time integration method, modified Newmark's method [4], is used in this paper for solving the dynamic responses of structure. An automatic time stepping scheme option has been used in the present analyses. Within each time step, ABAQUS code will iterate until the maximum residual force and moment are less than an allowable residual force (PTØL) and residual moment (MTØL) specified by users. To further control errors between end points of each time step ABAQUS code will calculate the residual forces and moments at the middle point of each time step. If these values are greater than the specified limit (HAFTØL) the program will automatically adjust the time increment to meet its error band requirement.

The present analyses selected the automatic time step option with the following allowable magnitude for residual force, moment, and half-step forces:

PTØL = 10 lbs
MTØL = $10L_1$ in-lb
and HAFTØL = 10^5 lbs

where L_1 designates the horizontal distance from the vertical pipe to the front support.

3.4 External Loads

The applied loads at Node 1 of the pipe whip model (Figure 3) are given by the reaction loads at the front support of the TVA Test Number 10 as shown in Figure 2. The direction of the axial force follows the severed pipe i.e., the external load is a function of structural deformation.

3.5 Elbow Crushing Stiffness

To assess the effect of the elbow deformation on pipe whip energy absorption capability, a linear spring was simulated for the elbow stiffness. The compressive linear springs are placed between the impact platform and the ends of the gap elements (shown in Figure 3). As a first order upper bound approximation neglecting large plastic deformation, linear elastic stiffness of a ring ovalyzing mode with a 1" pipe cross-section is assumed.

4.0 PIPE WHIP ANALYSIS PER ANSI-58.2 STANDARD

The current U.S. Nuclear Regulatory Commission (NRC) guidelines on pipe whip analysis (ANSI-58.2) assume a perfect elastic-plastic material and a plastic hinge at the pipe support[5]. The calculated impact time, velocities, and impact forces based on these conservative assumptions are compared with the TVA test results.

5.0 RESULTS AND DISCUSSIONS

The ABAQUS code analyzed reaction forces at the front and rear support. These reaction forces are compared with the corresponding data recorded by the TVA tests. These comparisons are shown in Figures 5 and 6 for Test Case 16, and Figures 7 and 8 for Test Case 17.

It may be observed from these figures that the calculated time histories of the reaction forces at the pipe supports have missed some peaks at the very beginning. These peaks are believed to be due to stress wave propagated immediately after the rupture of the pipe and the ABAQUS code does not address the problems associated with stress wave propagation. However, as shown in these figures the reaction time histories after 10 milli-seconds agree reasonably well with the TVA test results.

The impact times, impact velocities and maximum impact forces for the TVA pipe whip cases tested and analyzed are tabulated in Table 2. It can be shown from this table that the maximum pipe whip impact forces calculated by the current NRC guides are more than five times that of the TVA test results. The same table shows that the ABAQUS code will also significantly over predict the pipe whip impact force if the elbow deformation is neglected. When the elbow deformation is considered, even in a very approximate manner, much less discrepancy is observed between the calculated impact forces and the test results. This impact load reduction is believed to be due to the increase of impact contact time. It is felt that to predict the pipe impact force accurately, the elbow stiffness should be determined on the basis of an equivalent shell model.

A comparison of the impact time in Table 2 shows that the ABAQUS code predicted values agree reasonably well with the test results. As expected, a longer impact time is predicted for the cases considering the strain rate effect.

The automatic time step option of the ABAQUS-EPGEN code has been found to be very convenient for nonlinear dynamic analysis; however, the parameters of PTØL, MTØL, and HAFTØL should be properly selected to balance the computational time with the accuracy desired. This selection requires considerable experience and engineering judgment.

REFERENCES

/ 1 / "Testing Pipe Support Reaction Due to Steam Blowdown Loads From a 1-inch Schedule 40 Pipe", TVA Report No. 82-28, (Sept. 1982).

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/ 3 / Peterson, D., Schwarbe, J.E., and Fertis, D.G., "Strain Rate Effects in SA-106 Carbon Steel Pipe", J. of Pressure Vessel Technology, ASME Vol. 104, pp. 31-35, (1982).

/ 4 / Hilbert, H.M., Hughes, T.J.R., and Taylor, R.L., "Improved Numerical Dissipation of Time Integration Algorithms in Structural Dynamics", Earthquake Engineering and Structural Dynamics, Vol. 5, pp. 283-292, (1977).

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TABLE 1

ANALYSIS MATRIX

TVA Test Case No.	Front Pipe Support Distance (in)	Second Pipe Support Distance (in)	Pipe Pressure (psi)	Approx. Impact Angle	Remarks
10	As close as possible	76	980	No Impact	The load time history of the front support load cell will be used as pipe break thrust loads.
16	54	76	980	30	Identifies pipe strain time history which is available near the front support position.
17	30	76	980	45	

TABLE 2

COMPARISON OF IMPACT TIME, VELOCITIES, AND FORCES

CASE ANALYZED		IMPACT TIME (ms)	IMPACT VELOCITY (in/sec)	MAX. IMPACT FORCE (lbs)
16	TVA Test	70.0	Not Available	8,500 (4)
	ANSI - 58.2 Standard (1)	48.9	1156.87	70,375
	ABAQUS Code w/o strain rate effect (2)	68.8	596.13	50,000
	ABAQUS Code with strain rate effect (2)	71.0	561.60	79,440
	ABAQUS Code with strain rate effect (3)	71.8	561.60	17,050
17	TVA Test	120.0	Not Available	7,900
	ANSI - 58.2 Standard (1)	58.0	813.14	44,754
	ABAQUS Code w/o strain rate effect (2)	92.9	313.04	33,960
	ABAQUS Code with strain rate effect (2)	102.0	280.51	29,330
	ABAQUS Code with strain rate effect (3)	102.0	280.51	11,180

Remarks:
(1) Based on average velocity equal to half of impact velocity, perfect impact, and 1 ms contact duration.
(2) Without considering the elbow deformation
(3) Use an approximate constant pipe crushing stiffness of 47,463 in/lb.
(4) Measurement is questionable due to possible malfunctioning of the load cell under the impact pad [1]

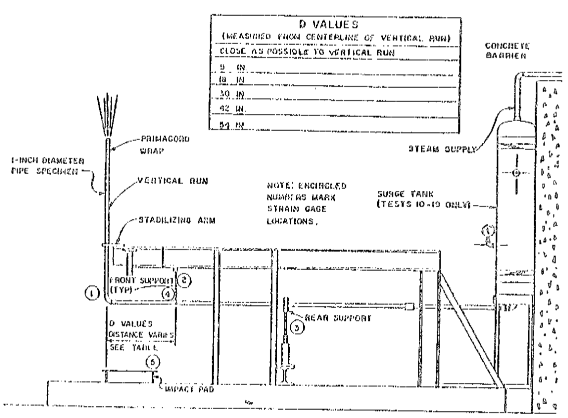

FIGURE 1 TVA PIPE WHIP TEST SET UP

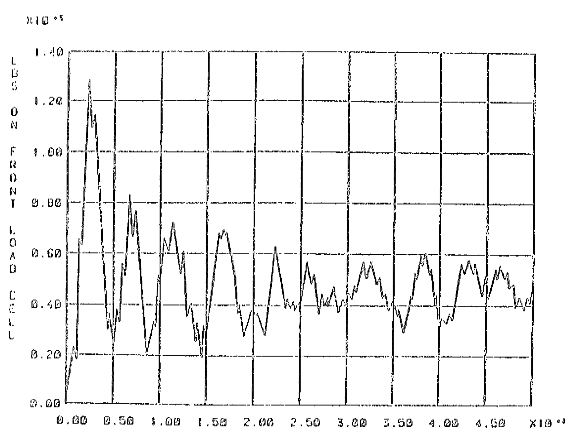

FIGURE 2 INPUT PIPE THRUST LOAD TIME HISTORY FOR PIPE WHIP ANALYSES

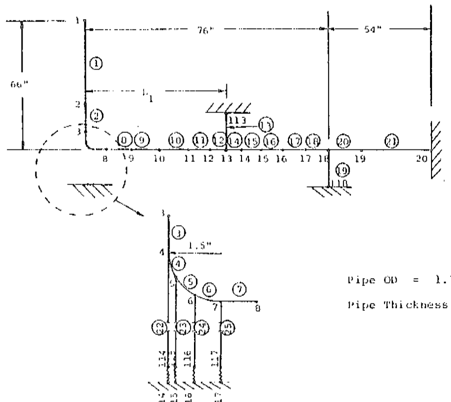

FIGURE 3 ABAQUS PIPE WHIP MODEL

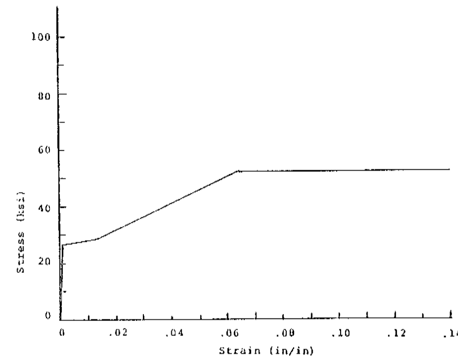

FIGURE 4 STRESS-STRAIN CURVE OF BLACK IRON AT 500°F

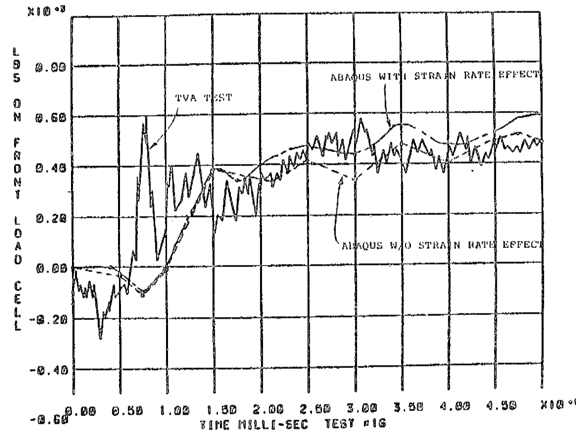

FIGURE 5 REACTION FORCE AT FRONT SUPPORT OF TVA TEST CASE 16 - TEST VERSUS ANALYSIS DATA

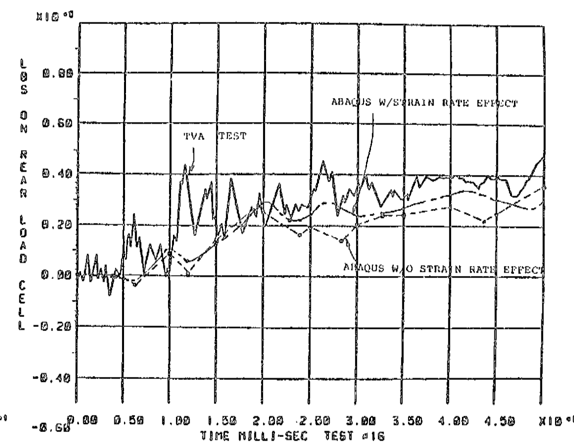

FIGURE 6 REACTION FORCE AT REAR SUPPORT OF TVA TEST CASE 16 - TEST VERSUS ANALYSIS DATA

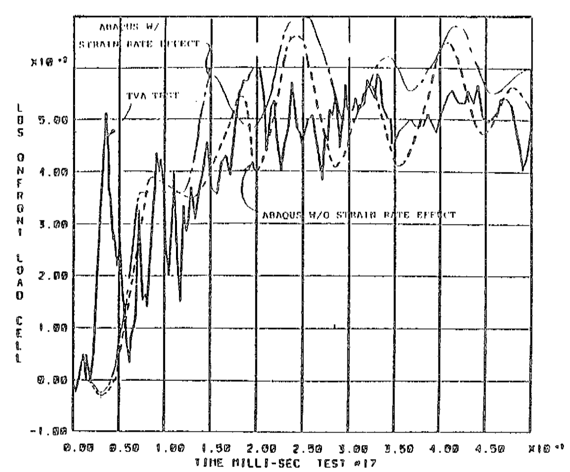

FIGURE 7 REACTION FORCE AT FRONT SUPPORT OF TVA TEST CASE 17 - TEST VERSUS ANALYSIS DATA

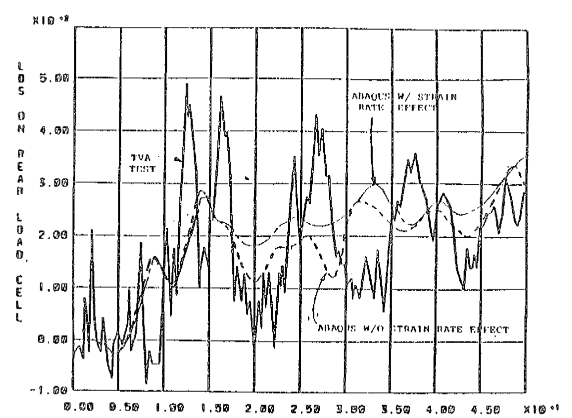

FIGURE 8 REACTION FORCE AT REAR SUPPORT OF TVA TEST CASE 17 - TEST VERSUS ANALYSIS DATA