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CORRELATION OF ANALYSIS WITH HIGH LEVEL VIBRATION TEST RESULTS FOR PRIMARY COOLANT PIPING

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ABSTRACT

Dynamic tests on a modified 1/2.5-scale model of pressurized water reactor (PWR) primary coolant piping were performed using a large shaking table at Tadotsu, Japan. The High Level Vibration Test (HLVT) program was part of a cooperative study between the United States (Nuclear Regulatory Commission/Brookhaven National Laboratory, NRC/BNL) and Japan (Ministry of International Trade and Industry/Nuclear Power Engineering Center). During the test program, the excitation level of each test run was gradually increased up to the limit of the shaking table and significant plastic strains, as well as cracking, were induced in the piping. To fully utilize the test results, NRC/BNL sponsored a project to develop corresponding analytical predictions for the nonlinear dynamic response of the piping for selected test runs. The analyses were performed using both simplified and detailed approaches. The simplified approaches utilize a linear solution and an approximate formulation for nonlinear dynamic effects such as the use of a deamplification factor. The detailed analyses were performed using available nonlinear finite element computer codes, including the MARC, ABAQUS, ADINA and WECAN codes. A comparison of various analysis techniques with the test results shows a higher prediction error in the detailed plastic strain values than in the overall response values. A summary of the correlation analyses was presented before by BNL (Hofmayer, et al., 1991). This paper presents a detailed description of the various analysis results and additional comparisons with test results.

INTRODUCTION

A correlation study between prediction analyses and test results is presented for a modified 1/2.5-scale model of one loop of a PWR primary coolant piping system tested under earthquake-like high-level excitations. The testing was performed using a large shaking table (15 m X 15 m) at Tadotsu, Japan, as a part of the cooperative study between the U.S. and Japan (Kawakami, et al., 1989; Hofmayer, et al., 1989). The input excitation level was the parameter varied during the experiment. The dynamic behavior of the test model during eighteen runs at various excitation levels was recorded through a 300-channel data acquisition system (Park, et al., 1991). During the maximum excitation runs, a peak strain of 2.3% was recorded on the outer surface of the hot leg pipe. Both bulging and crack initiation were also detected.

Analyses were performed after the test, in which measured input motions were provided and analysts were asked to predict measured responses. Nonlinear finite element models were developed using commercially available computer codes such as MARC and ABAQUS (Park, et al., 1991). Several organizations participated in the analysis study, and contributed independent post-test predictions (Wesley, 1990; Hahn, et al., 1990; Kamil, 1990; Liu, et al., 1990). Since the piping experienced significant plastic responses, it was possible to compare analysis results with the highly inelastic behavior under earthquake-like loading conditions. A correlation of the test and analysis results for the above studies is presented in this paper. The Electric Power Research Institute (EPRI), one of the sponsors of the testing, also conducted a post-test prediction program. Those results were described in the 1991 ASME Pressure Vessel and Piping Conference (Jaquay, et al., 1991).

HIGH LEVEL VIBRATION TEST PROGRAM

The test model is a modified 1/2.5-scale model of one loop of a PWR primary coolant system enclosed in a rigid support structure as shown in Figures 1 and 2. The model consists of a steam generator (SG), a reactor coolant pump (RCP), and three sections of the primary piping system, i.e., the hot leg, the cold leg, and the crossover leg. Several modifications were made to the original SG model in order to impose plastic bending action on the hot leg pipe; including, (i) the upper and middle supports were removed; (ii) the top portion of the shell was removed; and (iii) the lower support columns were replaced by a pin-connection. Figure 3 shows the hot leg pipe. The straight portion of the pipe has an outer diameter of 13.9 inches and is 1.14 inches thick. The hot leg elbow has an outer diameter of 15 inches and is 1.5 inches thick. The pipe was heavily instrumented with a number of strain gauges to capture the ovalization deformation due to bending actions. The internal pressure was maintained at 2,230 psi during the tests.

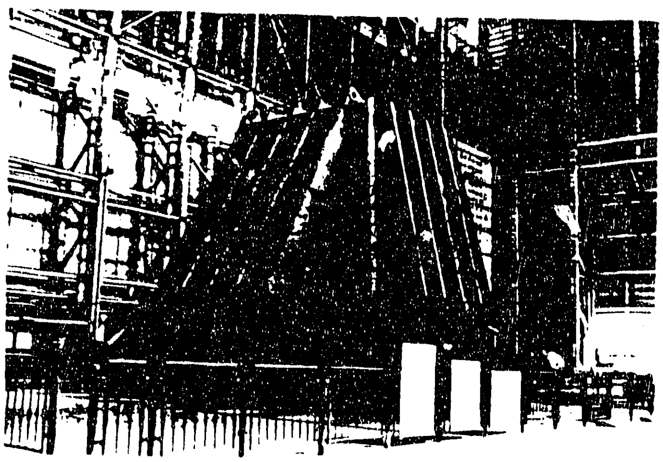

Figure 1 Test Model on Shaking Table

MASTER

DISCLAIMER

Figure 4 shows the accelerogram and response spectra of the input table motion (target motion). The actually recorded maximum peak acceleration was increased from the target value of 1.93 g to 2.48 g. However, the response spectrum was reproduced fairly well. Only the segment-A of Figure 4 was used for the time history analysis described below. Table 1 lists all the major test runs. In the table, the MPR level indicates the intended excitation level as an approximate ratio of the maximum excitation level. For some test runs only segment-A of the accelerogram shown in Figure 4 was used.

Figure 5 shows the transfer functions of the SG in the X (excitation direction) and Y-directions obtained during a low-level random motion test. The measured vibration frequencies were 6.38 Hz and 3.15 Hz in the X- and Y-directions, respectively. The damping value at a low excitation level was estimated to be 0.9% for the X-direction motion. During the test, the lower support structures for the SG were reinforced to reduce a strain concentration found in the support joints. As a result, the vibration frequency in the X-direction was increased from 6.38 Hz to 6.64 Hz.

Figure 6 illustrates the damage observed in the hot leg pipe after the test. Also shown are the material test results performed before and after the dynamic test. For all the three sections of pipes, SCS14A stainless steel was used which has a nominal yield stress of 30 ksi and is almost equivalent to ASME SA-351-CF8M. The crack initiation was detected after the second application of the maximum amplitude excitation run at the tapered transition location between the straight hot leg portion and the hot leg elbow. The final crack depth was 94% of the wall thickness as shown in Figure 7.

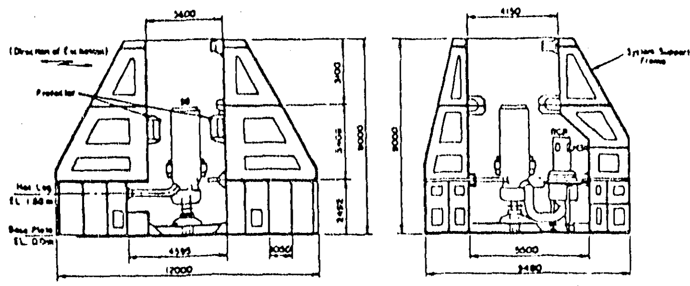

Figure 2 Test Model

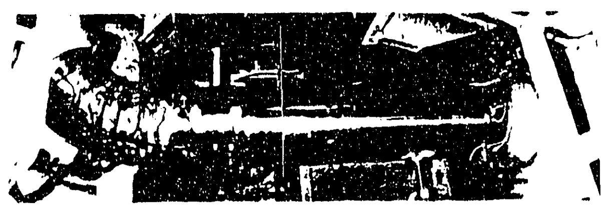

Figure 3 Hot Leg Pipe

Table 1 Major Test Runs

MPR Level	Number of Runs	Peak Acceleration, g	
		(Target)	(Achieved)
0.075	1	0.14	0.15
0.1	2	0.18	0.19
0.2	1	0.36	0.40
0.3	1	0.54	0.72
0.35	1	0.63	0.76
0.4	3	0.72-0.77	0.83-1.12
0.6	1	1.08	1.28
0.75	1	1.45	1.82
0.8	1	1.52	1.89
1.0	6	1.81-1.93	2.40-2.48

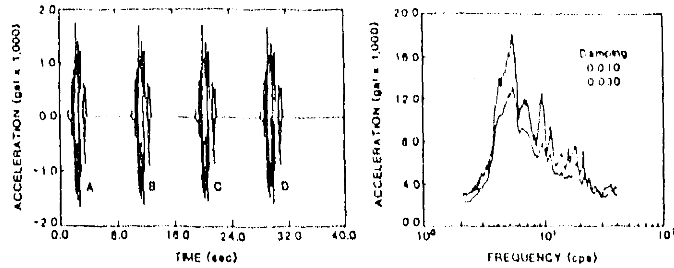

Figure 4 Input Table Motion

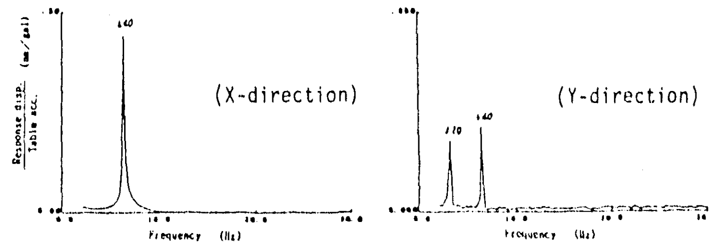

Figure 5 Transfer Functions of SG

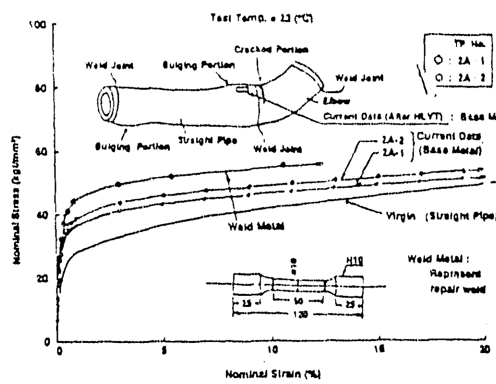

Figure 6 Damage in Hot Leg Pipe and Material Test Results

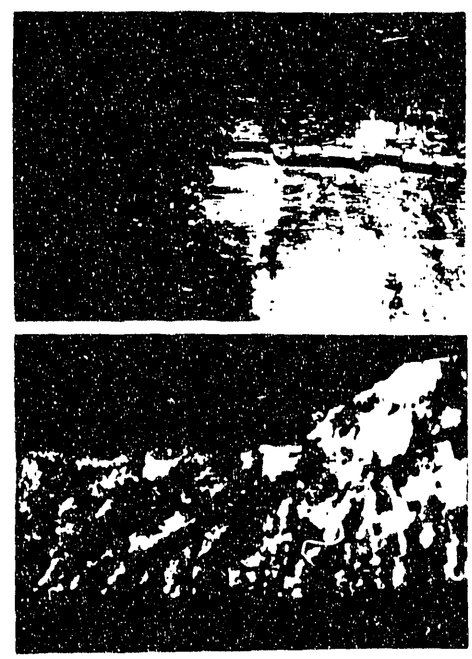

Figure 7 Crack in Hot Leg Pipe

ANALYSIS MODEL DEVELOPMENT

Various nonlinear finite element models were developed using the MARC and ABAQUS computer codes. Figures 8 and 9 illustrate two different modeling schemes. For the ABAQUS elbow model in Figure 8, elbow elements were used to model both straight pipes and pipe bends. In the ABAQUS code, the ovalization deformation of a pipe cross-section is approximated by Fourier series, called the "ovalization modes". Twelve circumferential integration nodes and three ovalization modes were used in the analysis. The SG, RCP and their support structures were modelled using linear beam elements. For the MARC plate model shown in Figure 9, only the critical portion of the hot leg pipe, in which the plastic action was considered to be significant, was modelled in detail using flat plate elements. The RCP, the cold leg and the crossover leg, which were expected to remain essentially elastic, were eliminated using the substructuring technique.

Table 2 lists the various MARC and ABAQUS analysis models. The ABAQUS beam model was developed to obtain the piping responses without considering the shell-type deformation. For this model, all the pipes were modeled using straight and curved beam elements. The ABAQUS shell model is similar to the MARC plate model in Figure 9; however, 8-node thick shell elements were used to model the critical portion of the hot leg pipe. This model was used only for a static analysis to obtain the strain distribution of the pipe. The MARC elbow model, which was extensively used in the pre-test prediction analysis, is very similar to the foregoing ABAQUS elbow model. In the MARC code, a pipe bend is modeled by axisymmetric shell elements whereas a straight pipe segment is modeled by "pipe elements", which are identical to beam elements.

In modeling the material nonlinearity, coupon test results of virgin material were used together with the kinematic hardening assumption. Each of the analysis runs, i.e., at .1 MPR, 0.4 MPR and 1.0 MPR levels, was performed as an "isolated run" since the plasticity models in the foregoing codes are history-independent. However, the effects of previous runs were considered indirectly based on the material test results performed after the testing. The post-test tensile tests of coupons taken from the bulged part of the hot leg pipe showed an increase in the yield stress (see Figure 6). To study the effects of the observed material change, additional analyses were performed for the ABAQUS elbow and beam models assuming yield stress values about 30% higher than the virgin material.

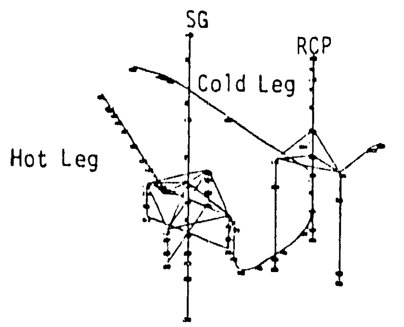

Figure 8
ABAQUS Elbow Model

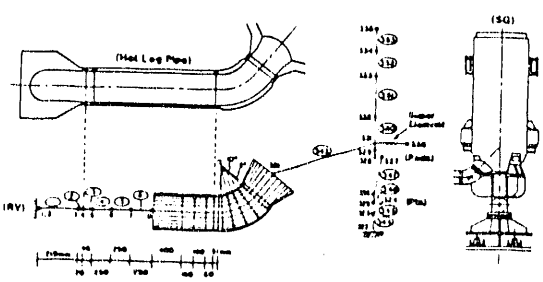

Figure 9 MARC Plate Model

Table 2 Analysis Models

Analysis Models	Straight Pipes		Pipebends	
	Elements	Ovalization	Elements	Ovalization
ABAQUS Elbow Model	"ELBOW31"	YES	"ELBOW32"	YES
ABAQUS Beam Model	Beam, "B31"	NO	Beam, "B32"	NO
ABAQUS Shell Model	Shell, "S8R"	YES	Shell, "S8R"	YES
MARC Elbow Model	Pipe	NO	Elbow	YES
MARC Plate Model	Flat Plate	YES	Flat Plate	YES

PREDICTION OF OVERALL DYNAMIC BEHAVIOR

Table 3 lists the measured and calculated vibration frequencies. The calculated frequency in the excitation direction ranges from 6.46 Hz to 6.81 Hz compared with the measured value of 6.64 Hz (after the reinforcement). Figure 10 compares the time histories of the relative displacement, Ux, at the top of the SG at the maximum excitation level. Both the time history shape and the peak value agree with the test results fairly well.

In Figures 11 through 13, the relationships of the peak input velocity versus the peak responses of the SG are shown, in which analysis values are indicated by a range. At the 0.1 MPR level (i.e., 10% of the maximum excitation level), the ABAQUS elbow model gives the best prediction. However, at the 1.0 MPR level (i.e., 100% of the maximum excitation level), the MARC analyses have slightly better results than the ABAQUS analyses.

In spite of the above agreement in the responses in the X-direction, all the analyses underestimate the responses of the SG in the Y-direction, as well as the shear force at the pin-connection in both directions. After the reinforcement of the SG support, the shear force at the pin connection increased considerably. However, the analyses, which are more representative of the test

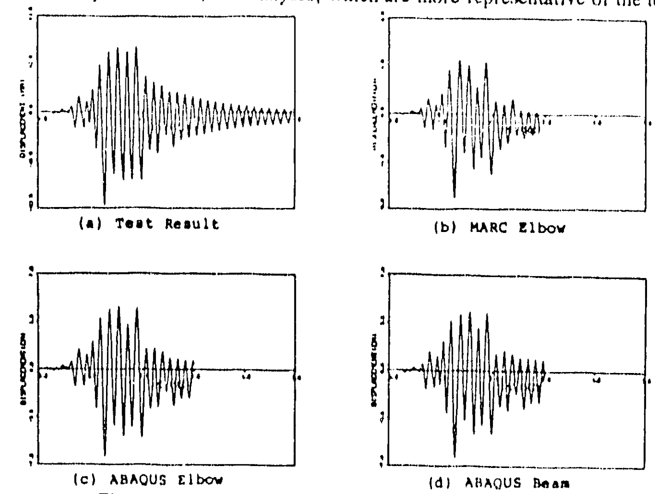

Figure 10 Relative Displacement of SG at 1.0 MPR

Table 3 Comparison of Vibration Frequencies

	X-Direction	Y-Direction
Test		
Before Reinforcement (B.R.)	6.38 Hz	3.15 Hz
After Reinforcement (A.R.)	6.64 Hz	3.15 Hz
MARC Elbow Model (B.R.)	6.35 Hz	3.81 Hz
MARC Elbow Model (A.R.)	6.46 Hz	3.61 Hz
MARC Plate Model	6.81 Hz	2.23 Hz
ABAQUS Elbow Model	6.59 Hz	3.76 Hz
ABAQUS Beam Model	6.68 Hz	3.80 Hz
ABAQUS Shell Model	6.55 Hz	2.71 Hz

specimen conditions after the reinforcement, follow the lower shear force values obtained before the reinforcement. As indicated in Fig. 13, analyses tend to underestimate the shear force by as much as 50%. A similar comparison regarding the under-prediction of support forces was reported in the HDR test program (Kot, et al., 1992).

Figure 14 compares the hysteresis behavior in terms of the top SG relative displacement and the shear force at a cross-section of the SG right above the hot leg connection (different displacement scales are used for measured and calculated hysteresis loops in Figure 14). This comparison indicates that the ABAQUS analyses captured the overall nonlinear behavior of the hot leg-SG system fairly well. The equivalent hysteretic damping value, estimated from the recorded hysteresis loops, was found to be about 15% at the 1.0 MPR level.

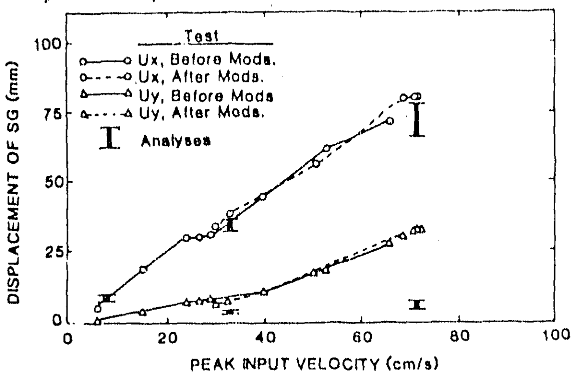

Figure 11 Peak Relative Displacement of SG

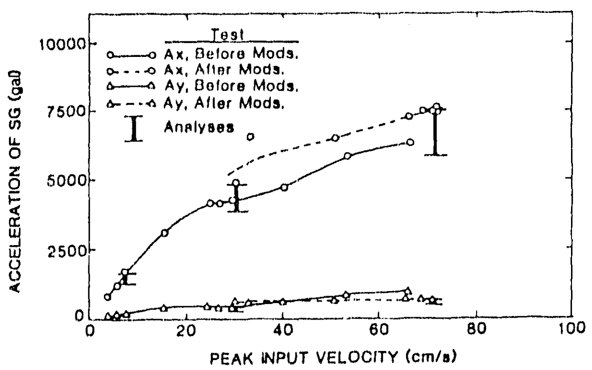

Figure 12 Peak Acceleration of SG

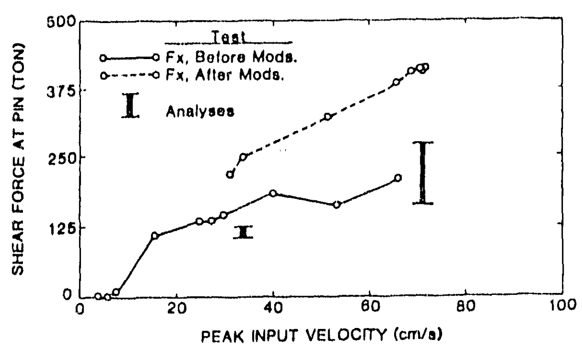

Figure 13 Peak Shear Force at SG-Pin Connection

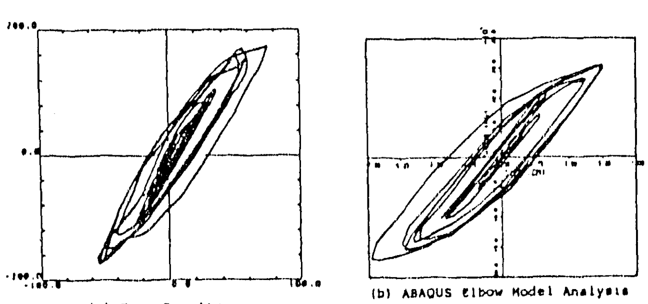

Figure 14 Shear Force-Displacement Relationship of SG

PREDICTION OF PIPING BEHAVIOR

Figure 15 shows the strain distribution in the hot leg pipe near the SG joint calculated from a static analysis using the ABAQUS shell model. A significant strain concentration is observed at the top of the hot leg pipe near the tapered transition joint with the hot leg elbow, which is the exact location where the crack initiated.

The distribution of the peak axial strain along the hot leg pipe is shown at 0.1 MPR and 1.0 MPR level in Figures 16 and 17. Again, a sharp strain concentration is found at the tapered transition location from the measured strain distributions. At the 0.1 MPR level, all the analyses underestimate the axial strain at this location. The estimated yield strain is about 0.1% whereas the measured peak axial strain at the tapered transition location is 0.15%. For the ABAQUS elbow model, a purely elastic analysis gives a lower value at this location, i.e., by assuming linear properties, the peak value is reduced from 0.124% to 0.11%. At the 1.0 MPR level, however, most of the analyses tend to overestimate the peak strain value as indicated in Figure 17. This is due to the "ratchetting phenomenon" observed in the analyses at higher excitation levels. This ratchetting becomes more prominent in the hoop strain than in the axial strain.

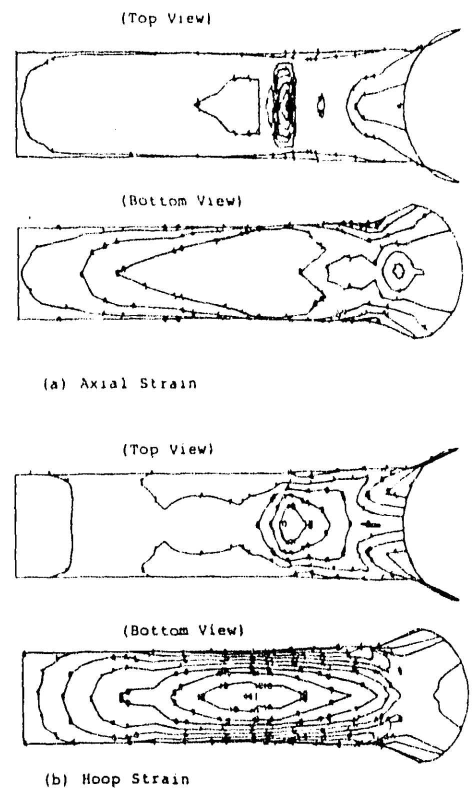

Figure 15 Strain Distribution of Hot Leg Pipe

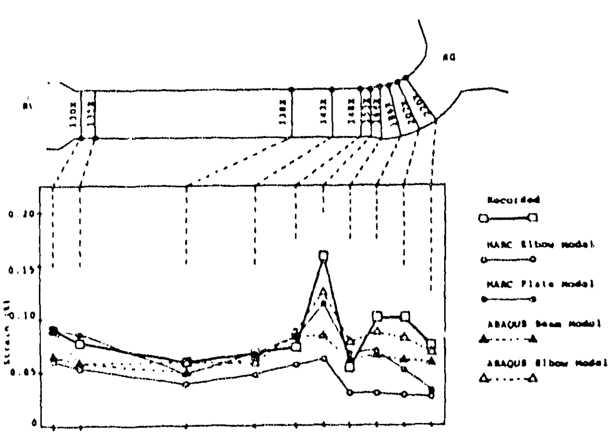

Figure 16 Axial Strain Distribution at 0.1 MPR

Figure 18 shows the time histories of the hoop strain at the top of the hot leg elbow during the 1.0 MPR run. A significant ratchetting is observed in both the MARC and ABAQUS analyses, whereas the test result shows no sign of ratchetting. In the ABAQUS elbow model, it was found that the assumed yield stress values have a significant impact on this phenomenon. A comparison between Figures 18c and 18d indicates that the use of a higher yield stress tends to reduce the ratchetting phenomenon. It seems the ABAQUS beam model, in which the shell-type deformation is not considered, predicts the piping behavior better than the elbow models for the thick-walled hot leg pipe.

POST-TEST PREDICTION PROGRAM

To further utilize the foregoing test results, USNRC/BNL sponsored a post-test prediction program. The participants of the program were asked to perform either a detailed nonlinear finite element analysis or a simplified analysis, such as by using a modified response spectrum approach, to predict the test results. The principal investigators and the affiliate organizations are as follows:

(For simplified approach)

- D.A. Wesley, ABB Impell Corporation (currently with EQE International)
- H. Kamil, Structural Analysis Technology, Inc. (SAT)

(For detailed approach)

- W.F. Hahn, ABB Impell Corporation
- T.H. Liu, Westinghouse Electric Corporation

The simplified analysis performed by Wesley (Wesley, 1990), is based on a linear modal analysis solution and the concept of the deamplification factor for approximating the effects of the inelastic responses. To determine the deamplification factor, which is a function of the estimated ductility factor, both Spectral Averaging and Riddell-Newmark methods were used. After the determination of the system ductility factor, which is based on the estimation of

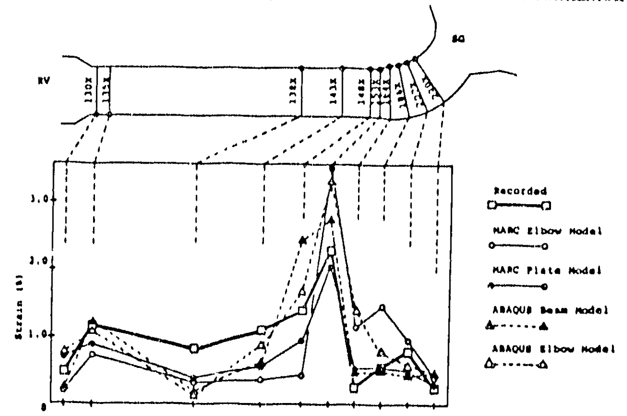

Figure 17 Axial Strain Distribution at 1.0 MPR

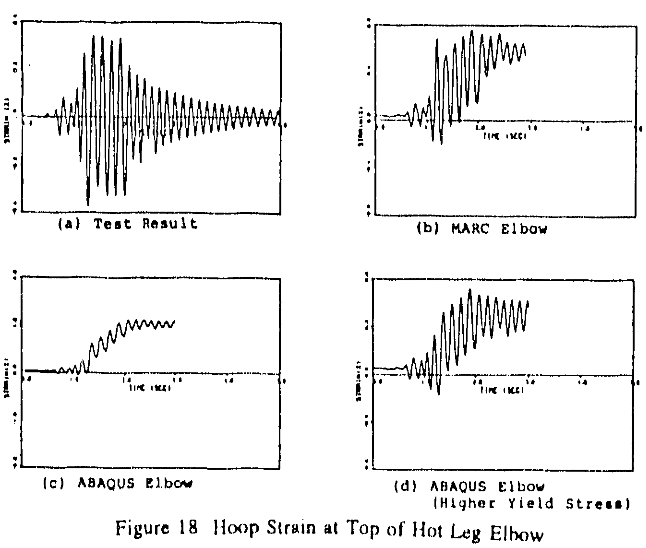

Figure 18 Hoop Strain at Top of Hot Leg Elbow

the peak strain value in piping, no iterations were performed to improve the initial estimate of the ductility (and therefore the peak strain value).

SAT applied a similar approach (Kamil, 1990). The inelastic responses were estimated using the modal analysis solution of a "softer system". The stiffness matrix was determined iteratively from the secant component stiffnesses. To obtain a convergent solution, eight interations were necessary at the 1.0 MPR level.

For the detailed analysis, Westinghouse used the WECAN Code (Liu, et al., 1990) and ABB Impell used the ADINA Code (Hahn, et al., 1990). The development of a detailed finite element model by both the participants was very similar to the foregoing MARC and ABAQUS elbow models. Both used standard elbow elements to model the hot leg pipe. In addition, Westinghouse developed a detailed static analysis model of the hot leg elbow using isoparametric solid elements to improve the prediction of strains around the hot leg elbow.

Figures 19 through 21 show the predicted peak responses for the SG, where the results of the foregoing ABAQUS elbow model are also included. Again the analysis values are indicated by a range. Compared to foregoing Figures 11 through 13, a very similar correlation between the analyses and test results is observed, except a larger scatter is found in Figures 19 through 21. In predicting the overall responses of the hot leg-SG system, there seems to be no significant differences between the simplified and detailed analyses.

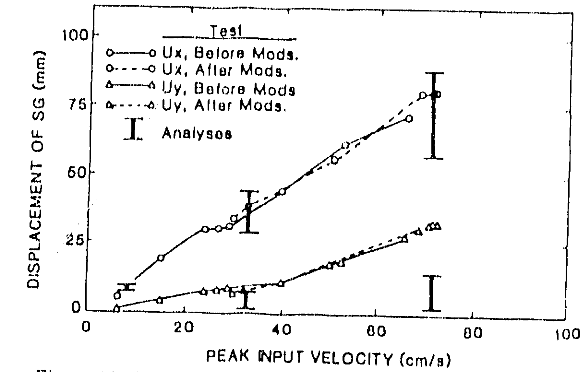

Figure 19 Comparison of Peak Relative Displacement of SG

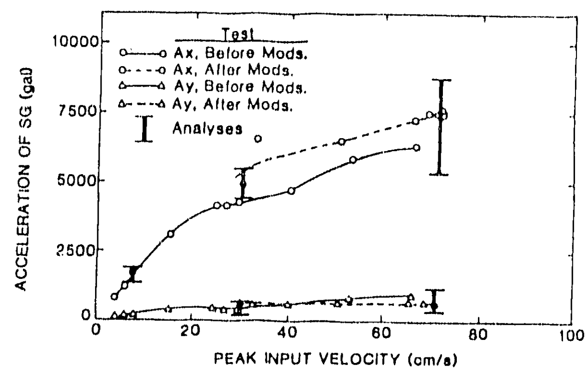

Figure 20 Comparison of Peak Accleration of SG

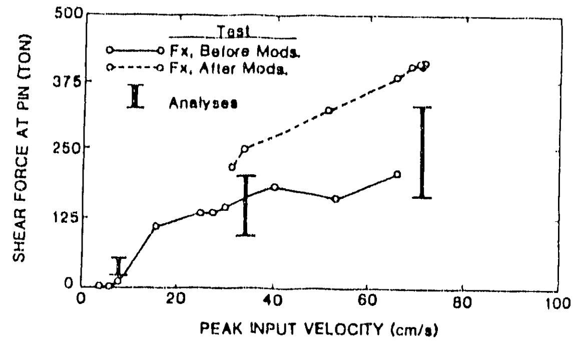

Figure 21 Comparison of Peak Shear Force at SG-Pin Connection

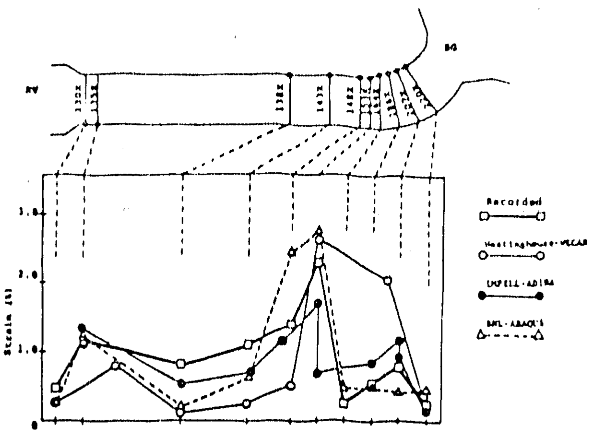

Figure 22 Comparison of Axial Strain Distribution at 1.0 MPR

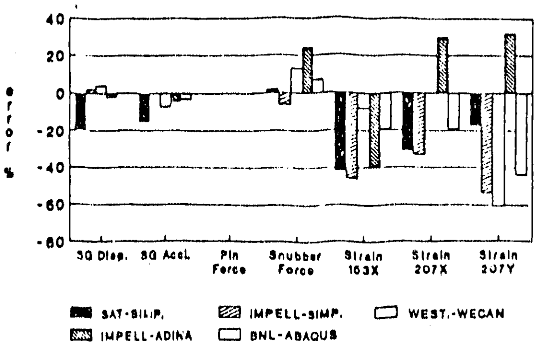

Figure 23 Comparison of Erros at 0.1 MPR

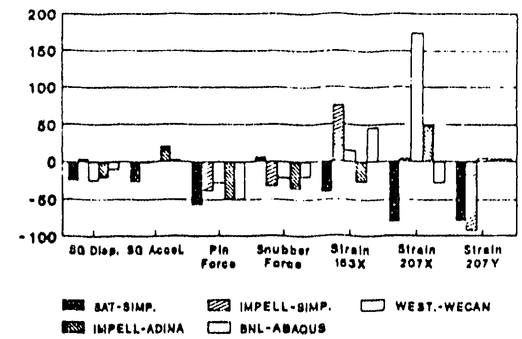

Figure 24 Comparison of Errors at 1.0 MPR

Figure 22 compares the peak axial strain distributions predicted by the detailed analysis, i.e., by Westinghouse, ABB Impell and BNL (ABAQUS elbow model). The analysis results using elbow models by both Westinghouse and ABB Impell indicate a significant ratchetting behavior in the hoop strain, which is very similar to Figure 18. The Westinghouse analysis modified this erroneous prediction by using the static analysis model for the hot leg elbow. The comparison in Figure 22 indicates a similar strain distribution pattern among the three different analyses. However, a significant variation is observed regarding the predicted strain values.

The overall correlation between the foregoing analysis predictions and the test results are summarized in Figures 23 and 24 in terms of the prediction error as a percent value of the test results, and a positive value indicates overprediction of the results. In the figures, the strain "153X" indicates the axial strain at the tapered transition location, and "207X" and "207Y" indicate the axial and hoop strains at the top of the hot leg elbow. At the 0.1 MPR level, a larger error is found in the prediction of the strain values than the prediction of overall responses. Most of the analyses tend to underestimate the strains at this excitation level. At the 1.0 MPR level, this error tends to magnify as the plasticity increases.

SUMMARY AND CONCLUSIONS

A correlation study between the high-level vibration tests of a modified PWR primary piping system and various prediction analyses was presented. Analyses were performed using both available nonlinear finite element codes and simplified analysis techniques. The overall nonlinear behavior of the hot leg-SG system was predicted reasonably well by both the detailed and simplified analyses. Strains were not as well predicted. A larger analysis error was observed in the prediction of the strains at higher excitation levels. Particularly, the analyses using standard elbow elements predicted a significant ratchetting phenomenon in the hot leg pipe, which was not present in the measured test results. Based on the detailed finite element analysis results, it was found that the material properties and plasticity modeling had a major impact on the predicted piping responses. Some analysis models underpredicted strains at low excitations and overpredicted at high excitations.

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