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# AN INVESTIGATION OF ELASTIC-PLASTIC SEISMIC ANALYSIS OF PIPING SYSTEMS UNDER HIGH LEVEL OF EARTHQUAKE MOTION

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## ABSTRACT

The current design by rules of the ASME Section III Code for the nuclear power plant piping system is principally based on the elastic design concept. Such design often results in a more rigid piping system, structurally, that may not be so desirable from the viewpoint of long term plant operation. The so called "elastic design" approach has failed to utilize the ductility that steel pipe exhibits, and therefore, the resulting system maintains a great deal of reserve margin in seismic design. This study does not attempt to assess the amount of this reserve margin but provides some findings and discussions with respect to dynamic inelastic analysis results in the piping system design. Using a test correlation analysis it was found that, while the analytical tools that exist are conservative for low strain levels, further studies with loadings at high strain levels are recommended for a more reasonable design.

## 1.0 INTRODUCTION

Most of the seismic design of piping systems in nuclear power plants today are mainly restricted to the elastic analysis. Design measures are commonly taken to ensure that the response of piping systems under even SSE loadings remain largely elastic, and at most, the total strain should be small. Based on such a design approach, the current ASME Code Section III design rules for piping system can be applied. Various investigations from recent tests [1], [2], [3] and [4] demonstrated that, due to its ductility [5], the piping system/component has large reserve margins. These margins cannot be realized if elastic design is maintained.

Laboratory tests of a PWR primary coolant loop system were performed on a seismic vibration table [6]. These tests consisted of a 1/2.5 scale model of a one loop system and several high level time history excitations that induced inelastic response in the system. The tests provided extensive data to be used for the evaluation of elastic and inelastic dynamic analysis techniques. The test correlation analysis was then performed.[7]

The test model was a 1/2.5 scale model containing one loop of a PWR primary coolant system and consists of one steam generator (SG), one reactor coolant pump (RCP), loop piping (hot leg, cold leg and cross-over leg) and component supports. The upper and middle steam generator shell supports of the model were removed and the upper part of the steam generator shell was truncated. The four steam generator lower support columns were replaced by a pin-type support which can rotate in a plane formed by the SG and hot leg. Heavy steel structures were designed to simulate a fixed boundary condition at the RPV end of the hot leg and cold leg pipes. The complete reactor coolant loop system test model is situated in a steel support frame which is designed to be rigid so that the input motion generated from the vibration table is directly transmitted to the reactor coolant loop model. The piping in the test model is stainless steel, 14-15 inches in diameter and 1-1.25 inches thick. Figure 1 shows the details of the hot leg with steam generator pedestal support.

The maximum acceleration time history for the test input motion was designated as the maximum plastic run (MPR). A number of test runs were performed using various ratios of the MPR (i.e., from 0.05 MPR up to 1.0 MPR). The test input motion consisted of four time history segments. The shape of each time history segment was the same. The input time history was synthesized to match the desired input response spectrum with pre-determined ranges of frequency peaks. The duration of each time history segment is approximately 2.7 seconds. In the analysis only one segment of test runs were required. A typical input motion for 1.0 MPR used in the analysis is shown in Figures 2.

## 2.0 SYSTEM ANALYSIS MODEL

The system analysis model was developed using the WECAN [8] computer code. The model consists of three-dimensional elastic or elastic-plastic pipe and elbow elements, straight or curved, used to model the loop piping and to represent the body of equipment components. Support structures were modelled with elastic beam elements. Lumped mass elements with or without an associated mass moment of inertia were used to represent the mass of the system. Spring elements were used for the snubber. Rigid elements connect system components except where the stiffness of the connecting element is known or can be approximated. Since it was designed to study the hot leg piping responses, the hot leg was modeled in a more detailed fashion. The hot leg begins with the reactor vessel outlet nozzle, followed by a safe end, a straight run, a reducing elbow, another safe end, and the steam generator inlet nozzle at the base of the steam generator. Hot leg details are shown in Figure 3.

## 3.0 ANALYSIS METHOD AND APPROACH

The reduced modal analysis technique was used to calculate the natural frequencies and mode shapes for the linear undamped system. The Guyan Reduction Method [8] is applied that yields an equation of motion in terms of only the dynamic degrees of freedom thus providing a reduced eigenvalue problem for frequency study. The direct integration method of dynamic transient analysis was applied in the solution of the seismic time-history analyses. Gravity and pressure preloads were considered also. The theory of plasticity used in small strain elastic-plastic analysis is adopted in WECAN. The procedures are based upon the incremental theory of plasticity using the von Mises yield condition and the associated flow rule, based on the Prandtl-Reuss equations. In all analyses, the combined isotropic and kinematic hardening rule was selected in conjunction with a multilinear stress-strain curve. This study uses the method of successive elastic approximations as the basis for an elastic-plastic analysis. The effect of plastic deformation during a load increment is taken into account by introducing a set of fictitious body forces into the equations.

An initial check of the finite element system model accuracy involved a comparison of natural frequencies with test results. It was reported from test that the first mode was 3.15 Hz and the second mode has 6.64 Hz. The system model produced a first mode frequency of 3.94 Hz, and a second mode frequency of 6.54 Hz. The first mode was characterized as rocking of the steam generator out of the plane of the hot leg and steam generator that is not important to this study. The second mode is rocking of the steam generator in the plane of the hot leg and steam generator that provides important insight to this study.

The integration step size was selected and a study was conducted to determine the number of iterations within the integration step size required to maintain a stable converging solution. In this study, the degree of convergence was closely measured through the whole time history.

## 4.0 ANALYTICAL RESULTS

Two types of test correlation analysis were performed in this study: first, the seismic time history elastic-plastic analysis of the system model for three input levels of earthquake (or 3 time-history input) and second, the static analysis of the elbow component model also for these three input levels (or 3 maximum boundary loads from system analyses).

### 4.1 Modal Analysis Results from Dynamic System Analysis

Table 1 lists the natural frequencies of the first three fundamental modes and their associated physical interpretations. While the hinged condition allows the rocking of the steam generator in plane, the hot leg provided sufficient restraint so that the frequency along the hot leg (6.54 Hz) is higher than frequency along the cross-over leg (3.94 Hz). Table 1 also shows the comparison of modes between the analysis and test data. The analytical model is considered to be adequate for the subsequent dynamic transient analysis since the dominating mode along the direction of the input motion is only 2% different from the test frequency. For the out-of-plane motion, which has no seismic input, the analysis frequency is 20% different from the test data. This difference is considered acceptable because of no input motion along that direction.

### 4.2 Time History Displacement and Acceleration

Time-history displacements and accelerations were generated from the elastic-plastic time history analysis of the system model for the 2.7 second duration and for the 5 analysis cases. In the analysis, the time-history displacement and acceleration plots at the top of the SG and the top of the RCP were made for MPRs of 0.1, 0.4, and 1.0. For the 0.1 MPR case, three values of system damping, 0.5%, 1.0% and 5.0% were considered in the analysis.

### 4.3 The Overall Peak Responses

Table 2 illustrates the overall peak responses for both test and analysis results for 0.1, 0.4 and 1.0 MPR. The displacement and acceleration results provide better comparisons, in general, for the SG than for the RCP. This is mainly due to the predominate low frequency motion of the system is exhibited in the response of the SG rather than for the RCP and also our modelling emphasize was given primarily to the SG and the hot leg. It is found surprisingly that the analysis loads in the SG support compare poorly with the test data for all three load components. For both the 0.4 MPR and 1.0 MPR inputs, the major forces in the hot leg direction from the analyses reached about two-fifths of the same forces measured in the tests.

Table 3 lists the peak strain comparisons for the three MPRs considered and at four locations. All data compare well for the axial strain. For the hoop strain the system analysis has consistently shown ratcheting in the hoop direction that was not observed in the test. Such ratcheting resulted in a cumulative permanent strain in the hoop direction even after the seismic shock had coasted down. From a structural failure viewpoint this discrepancy in the hoop strain between the test and the analysis leads the authors to believe that design analysis or testing in the inelastic region requires more work in the future to be considered adequate [9].

## 5.0 SUMMARY, CONCLUSION AND OBSERVATION

The actual PWR reactor coolant loop system is a very complex one. This complex system was simplified for the test and the analysis by altering the standard design of the structural system so that the seismic input motion, the support structural behavior, and the system dynamic responses were predominated by the horizontal motion in a vertical plane, which contains the steam generator and hot leg. This simplification, coupled with a short duration of input motion (2.7 sec), allowed the analyst to perform the dynamic time-history elastic-plastic system analysis at reasonable computer costs. Due to the desire of calculating a more accurate strain in the hot leg elbow, the static elastic-plastic analysis of the hot leg elbow with 3-D isoparametric solid element was also performed. The comparison of analytical results with those from the test provided following observations with respect to the available in-elastic analysis methods used in dealing with high level earthquake motions:

(A) Dynamic elastic responses are influenced mainly by the combination of the following structural characteristics: (i) frequency, (ii) mode-shape, and (iii) modal participation factor. The measured frequencies compared well with analysis.
(B) A good comparison of displacement, acceleration and strain values between test and analysis at low levels of strain suggests that the current industry analysis methods and tools are adequate. Further study with loading at a higher level of strain, particularly with a good deal of plasticity, is recommended.
(C) Through-wall strain variation is important for the ovalization effect at a cross-section. Furthermore, the plane-sections-remain-plane assumption in a system model may be inadequate at high levels of strain.
(D) Seismic ratcheting phenomia was not observed from the test but is an important aspect of the piping response. In the future study, this phenomia should be included in both test study and correlation analysis.

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Table 1
Comparison of Frequency and Mode Shapes Between Analysis and Test

| Mode Description | Frequency from Test | Frequency from WECAN Analysis |
|---|---|---|
| 1. S. G. Rocking about Y-Axis | 3.15 Hz | 3.94 Hz |
| 2. S. G. Rocking about X-Axis | 6.64 Hz | 6.54 Hz |
| 3. S. G. Twisting about Z-Axis | No test data available | 23.15 Hz |

Table 2
Comparison of Peak Response of Displacement, Accelerations, Loads

| | | 0.1 MPR | | 0.4 MPR | | 1.0 MPR | |
|---|---|---|---|---|---|---|---|
| Location | Dis./Acc./Lds. | Test | Analysis | Test | Analysis | Test | Analysis |
| Top of SG | Ux (cm) | 0.95 | 1.029 | 3.88 | 3.124 | 7.64 | 5.842 |
| | Uy (cm) | 0.14 | 0.091 | 0.92 | 0.318 | 3.04 | 0.635 |
| | Ax (gal) | 1630 | 1588 | 5470 | 4572 | 7280 | 7366 |
| | Ay (gal) | 212 | 114 | 510 | 396 | 600 | 648 |
| Top of RCP | Ux (cm) | 0.021 | 0.041 | 0.076 | 0.102 | 0.104 | 0.173 |
| | Uy (cm) | 0.011 | 0.010 | 0.04 | 0.028 | 0.05 | 0.046 |
| | Ax (gal) | 395 | 101 | 1610 | 605 | 3800 | 1803 |
| | Ay (gal) | 75 | 91 | 825 | 254 | 1230 | 660 |
| SG Pin Support | Fx (ton) | 7.0* | 31.1 | 254 | 95.5 | 402 | 295 |
| | Fz (ton) | 9.0* | 78.0 | 90 | 130.4 | 152 | 140.6 |
| | Mx (ton-m) | 0.16* | 1.9 | 3.68 | 6.0 | 6.14 | 12.0 |
| RCP Snubbers | 83x (ton) | 2.66 | 4.04 | 13.5 | 10.0 | 23.7 | 18.6 |
| | 84x (ton) | 1.15 | 2.99 | 6.6 | 6.03 | 11.6 | 8.64 |

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* Unreliable Measurement

Table 3
Comparison of Peak Response of Strains (%)

| | | 0.1 MPR | | 0.4 MPR | | 1.0 MPR | |
|---|---|---|---|---|---|---|---|
| Location | Strain | Test | Analysis | Test | Analysis | Test | Analysis |
| Hot Leg at RV-end$^+$ | Axial | 0.078 | 0.078 | 0.39 | 0.460 | 1.18 | 1.170 |
| | Hoop | 0.006 | 0.054 | 0.026 | 0.710 | 0.08 | 2.0 |
| Hot Leg at Tapered Joint | Axial | 0.153 | 0.150 | 0.78 | 0.85 | 2.28 | 2.63 |
| | Hoop | 0.038 | 0.003 | 0.19 | 0.039 | 0.34 | 0.22 |
| Hot Leg at Elbow* | Axial | 0.10 | 0.11 | 0.39 | 0.70 | 0.78 | 2.13 |
| | Hoop | 0.59 | 0.025 | .22 | 0.236 | 0.37 | 0.385 |
| Crossover Leg at SG-end$^+$ | Axial | 0.02 | 0.027 | 0.08 | 0.067 | 0.14 | 0.097 |
| | Hoop | 0.01 | 0.07 | 0.035 | 0.129 | 0.06 | 0.180 |

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$^+$ System Analysis Data

* Component Analysis Data

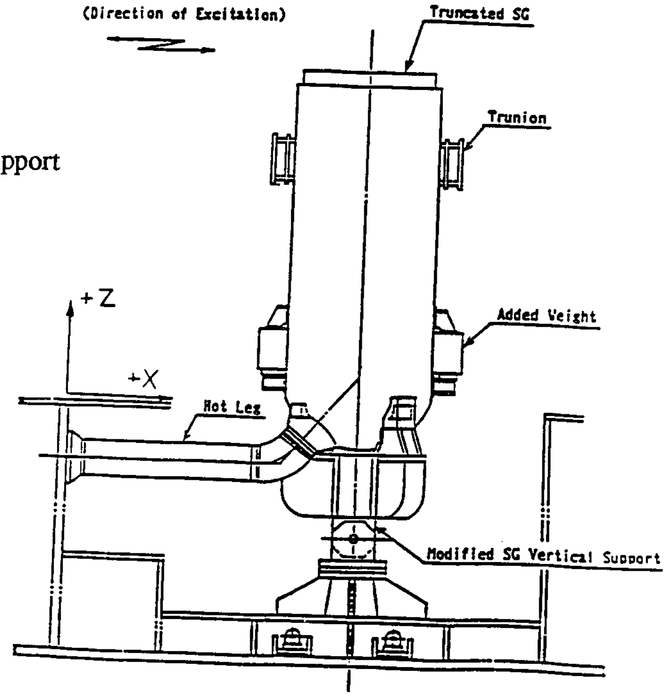

Figure 1. SG, Hot Leg and SG Support

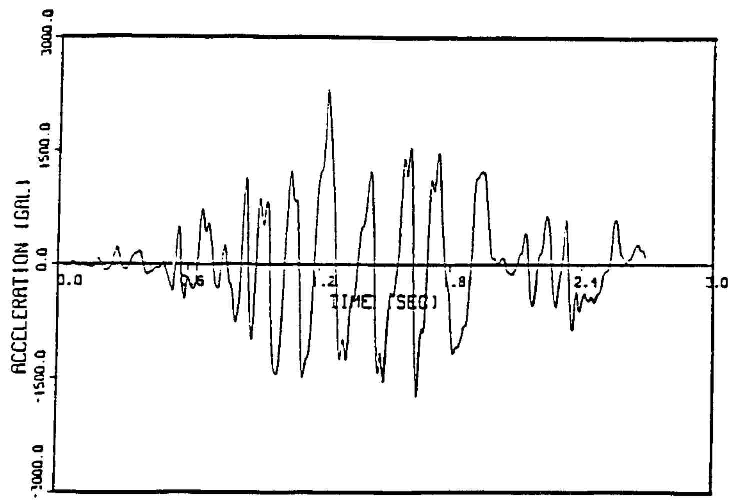

Figure 2. Recorded Horizontal Table Motion at 1.0 MPR Test (A-Segment)

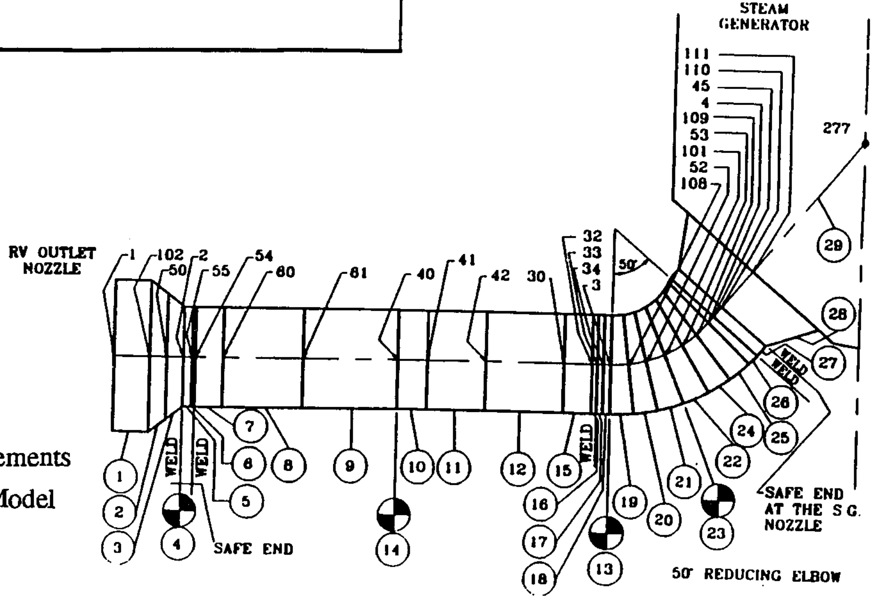

Figure 3. Hot Leg Elements in System Model