QUAD CITIES UNIT 1 FUNCTIONALITY STUDY OF PIPING SYSTEMS IN RESPONSE TO THE SSE EVENT

Prepared for:

COMMONWEALTH EDISON COMPANY

Prepared by:

EDS Nuclear Inc.

December 1980

EDS Report No. 01-0590-1135
Revision 0

EDS NUCLEAR INC.

REPORT APPROVAL COVER SHEET

Client: Commonwealth Edison Company

Project: 79-14 Bulletin Response   Job Number: 0590-013

Report Title: Functionality Study of Piping Systems in Response to the SSE Event

Report Number: 01-0590-1135   Rev. 0

The work described in this report was performed in accordance with the EDS Nuclear Quality Assurance Program. The signatures below verify the accuracy of this Report and its compliance with applicable quality assurance requirements.

Prepared By: John Eidinger   Date: December 5 1980

Reviewed By: Hai Tung Yung   Date: December 23, 1980

Approved By: [signature]   Date: December 24, 1980

REVISION RECORD

Rev. No.	Prepared	Reviewed	Approval	Approval Date	Revision

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1.0 INTRODUCTION

In response to NRC bulletin 79-14, Commonwealth Edison Company (CECo) is required to show the operability under seismic excitation of seismic class piping systems in Quad Cities Units 1 and 2, and Dresden Units 2 and 3 Nuclear Power Stations, for those systems shown to exceed FSAR limitations. EDS Nuclear (EDS), at the request of CECo, is performing analysis and design of piping systems to meet the requirements of this bulletin.

In the course of this work, EDS has found that several existing piping systems in these Units exceed FSAR stress limits. The solution to these overstress situations is to provide new supports on the affected systems and to qualify the upgraded piping system to the code of record.

The intent of this report is to study the stress levels, due to SSE excitation, of several piping systems before the addition of new required supports. Various analysis techniques, including both elastic and inelastic methods, are used to show that piping systems previously shown to be significantly overstressed can in fact be shown to remain functional during and after the SSE event.

A total of seven piping systems in the Quad 1 plant have been shown, to date, to exceed the operability stress limit due to the OBE event. Of these systems, six describe "class-break" problems. The last is the Recirculation System (RRCI). The studies in this report address a "class-break" piping system, the RHR system, and include both elastic and nonlinear analyses. The results are extended to the RRCI and the other class-break piping systems.

Elastic analyses of the RHR system were performed using the response spectra technique. Results from these analyses indicate that original high stress levels of 102,000 psi (based upon hand calculations) are very conservative. Detailed elastic analysis results gives SSE level stresses of 40,000 psi, which is only moderately above the ASME code allowable stress level of 2.4 S_h or 36,000 psi.

As a bounding case, a portion of the RHR system was subsequently analyzed assuming that a seismic support exists in the non-seismic portion of the piping. The analysis confirms that, as expected, the presence of this support reduces the stress levels in the RHR seismic piping to below code stress limits.

To show pipe functionality even if elastic analysis predicts stresses in excess of code limits for SSE motions, nonlinear dynamic analyses of the RHR piping were performed. Results show that a reduction of moments in pipe elbows of 30 percent or more can be expected when explicit nonlinear analyses are performed in lieu of elastic analyses. In addition, pipe elbow moments are under ASME Section III Appendix F collapse levels, while resulting ovality results in less than 1 percent flow restriction.

Several conclusions are made in this study concerning the functionality of as-built piping systems in response to an SSE event. The following main points are noted:

- Stresses in the RHR piping, as predicted by elastic response spectra analysis, are slightly over code allowables.

- Nonlinear analysis techniques show a large decrease in internal pipe moments for systems shown by elastic analysis to be stressed beyond yield; associated yielding causes less than 1 percent flow restriction at pipe elbows, the most overstressed portions of the analyzed system.

Based upon these conclusions, it is judged that the piping systems identified in this report would remain functional during an SSE event.

2.0 SELECTION OF PIPING SYSTEM FOR DETAILED EVALUATION

To date, EDS has performed analysis of existing as-built piping configurations in the Quad 1, 2 and Dresden 2, 3 Nuclear Power Plants in accordance with project specific instructions[1]. These instructions state that a piping system meets operability requirements if the combined stress from OBE plus gravity plus pressure does not exceed one-half the ultimate strength of the piping material. Operability criteria require that only seismic class piping need be evaluated. The seismic class piping must remain functional during and after the SSE event in order to bring the plant to a safe shutdown condition.

In the course of the analysis work, two types of piping systems have been identified: "closed-loop" systems and "class-break" systems. A closed loop system is comprised of seismic class piping from pipe anchor to pipe anchor. A class-break system is comprised of seismic class piping beginning at one pipe anchor, followed by an amount of non-seismic class piping; the class "break" occurs at the end of the second of two safety valves in the seismic portion of the piping.

To perform the analysis of all piping systems in a timely manner, and to conform to code of record requirements, several assumptions were made in the original analyses. In general, closed loop systems were analyzed using finite element response spectra method with the SUPERPIPE code. Class-break systems, owing to their extreme length, were analyzed using simplified conservative hand calculations.

When compared to the CECo operability criteria, seven piping systems were identified to be overstressed. These systems are noted in Table 2.1. Of these, the RRCI (Recirculation) system is a closed loop system, while the remaining six are class-break systems.

In the as-built configuration, the RRCI system was analyzed using the response spectra technique. Stresses were found to be slightly over operability stress criteria. The six class-break systems were analyzed by hand calculations, and all systems were shown to have stresses greatly in excess of the operability stress limit. Hence, it was decided that a more representative piping system on which to perform further analyses would be one of the class-break systems.

Of the six class-break piping systems, the RHR system was chosen for analysis for several reasons:

- Hand calculation predicted stresses of 102,000 psi, which was significantly over the operability allowable of 30,000 psi.
- The RHR system has unsupported (non-seismic) piping in excess of 200 foot spans.
- Complete fabrication isometrics were available for the RHR system.
- One detailed model of the RHR system could include three different branches of seismic class piping.

The specific Quad 1 plant identifier for the portion of the RHR system discussed in this report is 1-1067-3". The EDS specific identifier used for this portion of the RHR system, as used in other EDS analysis packages, is Q1-RHRS-03B.

Sections 3.0, 4.0 and 5.0 discuss the analyses performed on the RHR system. The RHR system was modeled both in a flexible configuration ("as-engineered") and in a stiff configuration (by adding a fictitious support in non-seismic piping close to the class-break). The stiff configuration of the RHR system has dynamic characteristics similar to those of the RRCI system; the stiff configuration is then used to perform nonlinear analyses.

Section 6.0 discusses the conclusions of these analyses, and shows that the piping systems remain functional during the SSE event.

3.0 ELASTIC ANALYSIS

Based upon stress levels, availability of information, and configuration, the RHR system described in Section 2.0 was chosen as the representative piping system for further study by elastic and non-linear methods. Previous simplified operability calculations assumed a cantilever model with an equivalent static seismic loading of 1.5 times the peak acceleration of the appropriate response spectrum. This simplified analysis technique was used as it is both conservative and easy to apply. The combined stress for OBE, gravity load and pressure, including appropriate stress intensification factors, was found to be 102,000 psi. This exceeded the original operability allowable of 1/2 S_{ult} (30,000 psi) for this load combination.

In response to this apparent severe overstress condition, further elastic and nonlinear analyses of the RHR system were performed to:

- confirm conservatism in the simplified operability calculations
- determine behavior of "class-break" piping
- determine actual piping stresses
- confirm functionality of piping system after initial yield.

This Section describes the elastic analyses performed. The following Sections 4.0 and 5.0 describe the nonlinear analyses performed.

The elastic analyses were performed with EDS computer program SUPERPIPE. The analyses considered two bounding models of the RHR system. First, a flexible model was developed, which included all 3" and 4" lines connected to line 1-1067-3". In this model, much of the piping is seismically unsupported, with one span of 215 feet. In addition, a total of three branch runs of this model include seismic class piping. These are runs 1, 2 and 4. Second, a stiff model considered all piping included in the standard "class-break" walkdown. The second model assumes an anchor at the non-seismic end of the walkdown piping. These two models are shown in Figures 3.1 and 3.2.

The elastic analyses performed with SUPERPIPE include response spectrum analyses with simultaneous excitation in the vertical and in two perpendicular horizontal directions. OBE and gravity load case analyses were performed on the flexible system, and SSE stresses were extrapolated from the OBE stresses. OBE and SSE load case analyses were performed on the stiff system. Pressure stress was calculated by hand. Seismic, gravity and pressure stresses were combined and compared to code stress allowables. ASME Code Subsection NC stress intensification and flexibility factors were incorporated in the analyses.

3.1 SUPERPIPE Math Model

Two mathematical models were developed to define the system geometry used for elastic analyses. Model 1, illustrated in Figure 3.1, defines the flexible system and consists of 3" and 4" lines anchored at large piping. Model 2, illustrated in Figure 3.2, defines the stiff system and consists of line 1-1067-3" anchored at large piping and the branch point with line 1-1065-4".

Certain assumptions were made in developing the math models. The non-seismic piping was modeled using "as-engineered" configurations, since walkdown information was not available in these areas. Individual rod hanger locations were not always uniquely indicated on the fabrication drawings; these hangers were equally spaced on the math models. Rod hangers were allowed to participate in the restraint of piping under seismic loading, although a few indicated uplifting loads during the excitation. Detailed review of the pipe system behavior showed that the exclusion of these few uplifting hangers would not significantly affect pipe stresses.

The mathematical models developed were not exact, detailed reproductions of the existing system, nor were they replete with conservative assumptions. Rather, since this study investigates actual piping behavior, the models represent the pipe system such that analysis results are accurate predictions of the expected behavior of the piping system.

Frequency analyses of the two RHR models showed that the first model has several modes with frequencies below 1 Hz. The stiffer RHR model has higher first mode frequencies, with first mode of 2.36 Hz, and other significant modes occurring near the peak of the input response spectrum. The frequencies of these models are given in Tables 3.1 and 3.2, while the input spectrum is shown in Figure 5.1.

3.2 Stress Results

Results of the elastic analyses are reported in Tables 3.3a through 3.3e. Tables 3.3a through 3.3d cover the seismic piping in the flexible system. Table 3.3e covers the seismic piping of the stiff system.

Seismic analysis of the flexible system was performed using the response spectra technique. The horizontal spectrum for 0.5 percent damping was developed by Keitn, Feibush Associates, Engineers for the Quad 1 Reactor Building at an elevation of 595 feet[2]. A 2 percent damping spectrum[3] used for SSE analyses was developed from a time history motion compatible with the 0.5 percent OBE spectrum, as discussed in Section 5.1, and is shown in Figure 5.8. The vertical spectrum used was a constant 0.08g for all frequencies, in accordance with the Quad 1 FSAR[4].

Seismic loading of the flexible system consisted of two perpendicular horizontal excitations and a vertical excitation applied simultaneously. Three directional stresses are added by the SRSS method, with closely spaced modes combined by absolute sum, as per USNRC Regulatory Guide 1.92. Gravity stress computation was also performed on the flexible system. A constant pressure stress of 700 psi, calculated for RHRS line 1-1067-3", was used for all seismic piping. This stress corresponds to the piping pressure of 210 psig.

Preliminary stress combinations of OBE, gravity, and pressure stress for all seismic areas in the flexible system are tabulated in Tables 3.3a through 3.3c. The resulting stress was derived by adding the three stresses (seismic, gravity and pressure) at each point, and conservatively ignores the direct vector addition of the individual moments and torques. For these stresses, there were nine locations where stresses exceeded the stress criterion of 1.2 S_h (or 18,000 psi). However, all stresses were below the 1/2 S_{ult} (or 30,000 psi) allowable used in the original operability assessment. Exact combination of moments to derive stresses showed that 6 of the 9 points still exceeded the 1.2 S_h B31.1 OBE allowable with a maximum stress of 26,800 psi. SSE level stresses for these 6 points are tabulated along with the OBE stresses in Table 3.3d.

The conservative assumptions in the original operability analysis yielded an OBE level stress of 102,000 psi. In the elastic dynamic analysis of the flexible system, the maximum OBE level stress in the seismic piping was 26,800 psi. Modeling assumptions in the SUPERPIPE analysis were not overly conservative; further detailed elastic analyses would not significantly reduce this stress intensity. However, the simultaneous seismic excitation in three directions was more conservative than the combination of one horizontal and one vertical directional excitation in the original analysis.

The model of the stiff RHR system was computer analyzed for seismic excitation only. The gravity analysis for the flexible system, and a pressure stress of 700 psi, were used to calculate total stresses. OBE and SSE stresses were computed using response spectra at 0.5 and 2.0 percent damping respectively, with these spectra developed by the procedures discussed in Section 5.1. The OBE and SSE stresses listed in Table 3.3e are well below code stress criteria.

3.3 Elastic Analysis Discussion

RHRS line 1-1067-3" was chosen as representative of those piping systems previously shown to exceed operability stress limits. SUPERPIPE response spectra analyses showed that stress levels significantly decreased compared to hand calculation values when detailed dynamic analyses of the RHR system were performed. Inspection of the properties of the RHR piping system reveals that similar stress decreases would occur for all class-break piping systems identified in Section 2.0 of this report. The basis for this statement is as follows:

- All class-break problems were originally analyzed by static hand calculation methods.

- All original class-break operability stresses were calculated using equivalent static lateral load, at 1.5 times peak spectral acceleration. Actual equivalent static lateral accelerations on flexible systems are much lower than 1.5 times peak spectral acceleration. The piping systems are flexible, with first mode periods at low values of spectral acceleration.

For the RHR piping system analyzed, a stress reduction of 74 percent was observed (102,000 psi to 26,800 psi). For the other class break piping systems identified in Section 2.0, similiar reductions in original operability stress levels are expected. In lieu of performing complete dynamic analyses of these systems, a simplified approach is taken to estimate the stress reductions:

- Identify spectral acceleration level used in original operability calculation

- Identify likely first mode spectral accelerations of flexible system

- Reduce original stress level by ratio of above acceleration values.

The results of this analysis are shown in Table 3.4.

As much of the nonseismic portions of the RHR and the other class-break piping systems have not been walked down, there exists the possibility that these systems are in fact not "flexible" - in effect some seismic supports may exist near the class break. To study this possibility, the stiff model of the RHR system was also analyzed, assuming an anchor at the point where the standard "class-break" walkdown ended. Results from this case show much reduced stress levels in the piping, below code allowables.

It is thus concluded that the six class-break systems originally identified to be highly overstressed by hand calculation in fact have stresses close to code allowables. Further nonlinear analyses discussed in the next sections confirm that at SSE levels, a system shown to be overstressed by elastic methods can be shown to remain functional.

4.0 PIPE ELBOW CAPACITY

The piping model used to perform nonlinear analyses with Computer Program ANSYS was composed of elastic and plastic straight pipe elements and plastic elbow elements. To maintain functionality, the critical elbow components of the piping system must not distort excessively during the SSE event. This Section 4.0 discusses the modeling assumptions used in the ANSYS analysis, and the verification of the ANSYS theoretical elbow behavior versus experimental test results.

In finite element analysis, certain geometric and material property relationships are idealized. In the ANSYS analyses, only a bilinear stress-strain relationship can be used for the non-proportional loading encountered in seismic analysis. This bilinear stress-strain relationship is adjusted so that the behavior of the plastic elbow element closely matches the experimental results.

The experimental results used to verify the ANSYS plastic elbow element were presented in the report ORNL/NUREG-24 by Greenstreet[5]. In this report, load-deflection curves for various elbows were developed. Selected curves were reproduced analytically using ANSYS (Figure 4.1). Young's modulus and the yield strength of the elbow were modified, and the bilinear stress-strain curve developed to obtain the desired load-deflection relationship. The ANSYS results were also compared with the limit load analysis, which assumes an elastic-perfectly plastic material behavior. The yield stress (0.2 percent offset stress) is as specified in the code. The collapse load is defined as the load at which the distortion is twice the value at the calculated departure from linearity (ASME Appendix F-1321.1 (d)).

Once the appropriate parameters were determined, they were applied to the analysis of a 3" Schedule 40 long radius elbow used in the analysis of the RHR piping system. The results of the analysis are represented in Figure 4.2.

4.1 Experimental Data

The study of ORNL/NUREG-24 experimentally determined the load-deflection response for sixteen 6 inch (nominal) commercial carbon steel elbows and four 6 inch stainless steel elbows. Each specimen was loaded to produce predominately plastic response. The influences of bend radius, wall thickness and material properties were studied.

Specimen PE-8 was chosen for the correlation analysis of the ANSYS elbow element. Specimen PE-8 is a 6-inch Schedule 80 long radius elbow of ASTM A-106 Grade B steel. The specimen was incrementally loaded with an in-plane point load, from 5,000-12,000 lbs. such that compression stresses were produced on the intrados. The material properties for the elbow were also given in the report. These were used in the correlation study discussed in the next section. Tests on this and other test specimans showed no significant flow restriction at elbow strains of 1 percent and greater. At peak strains of 1 percent, elbows carry moments on the order of those predicted using Equation 9 of ASME subsection NC, at level D stress levels.

4.2 ANSYS Analytical Correlation

Elastic straight pipe elements and plastic elbow elements were used to model Specimen PE-8 for analysis by ANSYS. The 90^o long radius elbow was discretized into four elements. The bilinear stress-strain curve was developed using the material properties reported in ORNL/NUREG-24. The elastic portion of the curve was determined from the modulus of elasticity and the 37.8 ksi yield stress[5]. The plastic portion of the curve was determined from the yield strength, yield strain (0.2% offset strain), ultimate strength[5], and the corresponding maximum strain of similar steel[6]. In ANSYS analyses, two options are available to model the flexibility factor of an elbow. These are the ASME flexibility factor and the Karman flexibility factor. The Karman flexibility factor was chosen for the analyses.

The first ANSYS analysis showed a much higher yield load than the yield load obtained experimentally. The ANSYS yield load was 11,000 lbs. compared to 7,000 lbs. from the experiment. Also, the ANSYS analysis predicts a higher flexibility factor in the elastic range.

A limit load analysis was done to refine the bilinear stress-strain curve. In this analysis, the ASME

Subsection NC stress intensification factor i was used to calculate the yield and collapse loads[7]. These loads were found to be 8,000 lbs. and 11,000 lbs. respectively. Using the results of the first analysis, the maximum stress of 27.5 ksi (73% of 37.8 ksi) at a load of 8,000 lbs. was used as the yield stress for the refined bilinear stress-strain curve. The slope of the plastic portion of the new curve was taken to be the same as that of the first curve. The PE-8 elbow was then re-analyzed with the refined stress-strain curve. The correlation of the second ANSYS analysis with the experimental results is presented in Figure 4.1. As can be seen, with the modified stress-strain curve, the ANSYS elbow element closely models true experimental test results, in a slightly conservative manner.

The results of the correlation study were applied to a 3" Schedule 40 long radius elbow. The model was made dimensionally proportional to the 6" model to reduce the elastic deflection of the straight pipes. The bilinear stress-strain curve was obtained by increasing Young's modulus by 25% to match the flexibility factor in the elastic range and reducing the yield strength to 73% of code values as prescribed by the above discussed correlation study. The results of the ANSYS analysis match those of the limit load analysis and are presented in Figure 4.2. In addition, the analysis was done using both 2 and 4 element discretization with identical results. Hence, further analysis was performed using two-element elbows.

5.0 NONLINEAR ANALYSIS

To show that a piping system remains functional during an SSE event, the ASME Subsection NC code allows the use of a stress level of 2.4 S_h. For both carbon and stainless steels, this level of stress is beyond nominal yield stress values. To satisfy functionality requirements, and to demonstrate the conservatism of elastic analysis methods at this level of stress, nonlinear analyses were performed on the RHR piping system. Certain conclusions drawn from the response of the RHR piping can be applied to other piping systems, demonstrating their functionality.

5.1 Time History Motions

To perform a dynamic nonlinear analysis of the RHR piping system, it was necessary to input to the direct integration analysis a full time history seismic motion. The required response spectra for the RHR piping system is the KFAE[2] spectrum at elevation 595 feet in the Quad 1 plant. Hence, it was necessary to develop a suitable input motion which would envelope the KFAE spectrum.

The KFAE spectrum is shown in Figure 5.1. The spectrum is a duplicate of that used for plant design, from a period of 0.0 to 2.0 seconds. No data was supplied in the original spectrum for periods past 2.0 seconds. As some of the RHR piping modes are past 2.0 seconds. the spectrum was extended to 5.0 seconds by using USNRC Regulatory Guide 1.60 values at 0.5 percent damping.

Two time history motions were developed to envelope this spectrum and subsequently used as the two horizontal excitations in the ANSYS analysis. To assure statistical independence of these motions, two different acceleration time histories were used as a basis for developing the final required motions; these were the El Centro N-S 1940 and San Fernando (Pacoima Dam) E-W 1971 motions.

Significant modifications to both the El Centro and Pacoima Dam motions were required in order for the motions to match the desired broadened spectra. This was done by adjusting the Fourier series components of each motion, within the approprate frequency bands, so that the augmented El Centro and Pacoima Dam motions would give the desired response spectrum. This procedure required an iterative process: first, the input motion is resolved into a response spectrum, using computer code RESPEC; then the spectral energy of the input spectrum is modified to match the required spectrum, using computer code FREAK; this two step process is iterated until the final motion gives a spectrum closely enveloping the required spectrum.

The resulting time history motions are shown in Figures 5.2 through 5.5. The spectra of these motions are shown in Figures 5.6 and 5.7, and as can be seen, closely envelope the required spectrum. The motions are of 16 second duration, which was shown to be long enough to capture peak responses of the piping systems.

Once the motions were developed to match the required spectrum at 0.5 percent damping, the 1.0 and 2.0 percent spectra were easily calculated. As can be seen in Figure 5.8, the 2.0 percent spectrum is approximately 80% of the 0.5 percent spectrum over the frequency bandwidth of interest.

In the nonlinear ANSYS analysis, the augmented El Centro motion is input in the N-S (x) direction, and the augmented Pacoima Dam motion is input in the E-W (z) direction.

As the elastic analyses of the stiff RHR system showed low stresses, well below yield, the input motions to the nonlinear analyses are increased by a factor 11.1 to ensure that significant yielding would occur. This factor corresponds to the maximum stress of 60,000 psi in the elastic analysis of the stiff system.

5.2 ANSYS Math Model

The ANSYS math model used to perform detailed nonlinear dynamic analysis is shown in Figure 5.9. This model configuration corresponds exactly to the stiff model of the RHR system, previously discussed in Section 3.1.

The ANSYS model used more dynamic degrees of freedom than the SUPERPIPE model in order to accurately capture the nonlinear behavior of the system. The model consists of elastic straight pipe elements (STIF9), plastic straight pipe elements (STIF20), and plastic elbow elements (STIF60). All elbows used plastic elements, while straight pipe used plastic elements where yielding was expected.

Two elements were used to model 90 degree elbows. The accuracy of this assumption was confirmed by running a sensitivity study, comparing results from elbows modeled with two or four elements, as described in Section 4.0.

The stress-strain law used for straight pipe elements is based upon minimum code material strengths, at temperature, for A-106 Grade B, and are given in Table 5.1. The material law for elbow pipe elements was modified so that the elbow behavior matched experimental results, as described in Section 4.0.

Damping for the SSE seismic event was incorporated using ALPHA-BETA damping, (using the current stiffness matrix), set to 2 percent, ranging from 0.2 to 33 Hz.

Seismic analyses were performed using motions in the N-S and E-W directions by the direct integration method. Pressure, gravity and vertical earthquake stresses were not included. Pressure stresses cause actual increase in pipe elbow capacity (see discussion, Section 6.0) and hence are conservatively neglected. Gravity and vertical earthquake stresses are small (about 5000 psi) and would not significantly influence the piping system response behavior. Thermal stresses are neglected at ASME level D limits.

5.3 PWHIP Math Model

Due to the excessive computation costs associated with performing a dynamic analysis with the ANSYS model for a full 16 second earthquake motion, a similar nonlinear PWHIP model was developed. (The time step integration using ANSYS was 0.001 seconds versus 0.020 seconds for PWHIP.) The full 16 second time history analysis performed using PWHIP gave key results such as peak moments and displacements, and number of cycles where yield moment was reached; the ANSYS analysis extends past the time where critical moment was reached (at 3.28 seconds), and gives detailed results concerning moments and strains at elbow elements.

The PWHIP math model is shown in Figure 5.10. The straight pipe shown has identical properties to the straight pipe ANSYS element; the length of the system is adjusted so as to give matching first mode (elastic) frequencies between the detailed ANSYS and simplified PWHIP systems. Table 5.2 compares the lower mode frequencies between the two models.

Dynamic analyses using both models showed extreme similarity in response: first yield for both PWHIP and ANSYS models occurs at 3.22 seconds; response characteristics up to the time of yield are very similar; unloading after first yield occurs at 3.28 seconds for both systems. Figure 5.14 shows the comparison of time-varying moments on the yielding pipe elements. It is thus concluded that the simple PWHIP model can be used as an adequate predictor of the RHR system's overall behavior for the entire earthquake motion.

5.4 Response Results

Basic response of the piping system is shown in Figures 5.11 through 5.14. As can be seen in Figure 5.12, nonlinear analyses predict that peak pipe moments will occur between 3 and 5 seconds into the event. A total of seven excursions past yield are expected. After 5 seconds, the system will continue to vibrate, although no further plastic excursions occur.

In comparison, by not allowing the system to yield, substantially higher pipe moments occur in the system, as shown in Figure 5.12.

A comparison of peak pipe moments as determined by both elastic and nonlinear analysis methods is given in Table 5.3. Results show that straight pipe moment reduces by 34 percent and elbow pipe moment reduces by 27 percent.

A similar reduction of moment is expected to occur for other piping systems not analyzed in this study for the following reasons:

- Pipe yielding increases the energy absorption of the system, hence reducing response.
- Pipe yielding alters the system's dynamic characteristics, typically moving its response "frequencies" away from the peak input energy pulses causing the yielding.
- Pipe yielding causes redistribution of moments in a indeterminantly supported system, thus limiting moments in highly stressed portions, while increasing moments in lower stressed portions.

The critical elements in the RHR piping system are the elbows. As elbows yield, they start to undergo large shape deformations: if extensively yielded,the resulting ovality may cause a reduction in the pipe cross sectional area.

The detailed ANSYS model shows that the peak moment on the most highly loaded elbow was 42,580 lb-inch. This moment is below the collapse load as calculated per ASME Appendix F-1321.1(d) method. Further, the peak strain in the elbow associated with this moment was just slightly over 1 percent. Experimental tests on elbows by Greenstreet and others[5,8,9,10] have shown that elbows are well capable of yielding to strains in excess of 1 percent, without any significant flow restriction due to ovality changes.

6.0 DISCUSSION

The intent of this evaluation was to study the functionality of piping systems in response to the SSE event. The analyses performed have utilized the RHR piping system in Quad Cities Unit 1. By the use of detailed elastic and nonlinear analyses, this system has been shown to remain functional during the SSE event. This section of the report discusses the applicability of these results to other piping systems in Quad Cities Units 1 and 2 and Dresden Units 2 and 3.

As discussed in Section 3.3, the use of detailed elastic analyses significantly reduces the peak stresses in the RHR system, as compared to values initially predicted by hand calculations. This is primarily due to the flexibility of this class-break system, which puts its first mode frequency at a point on the response spectrum of very low spectral acceleration. Review of the remaining five class-break systems shows that they are also flexible, and that they too can be analyzed using the low spectral accelerations of a flexible system. This has been done, in a simple manner, and results shown in Table 3.4. While these results are not exact (they are still based on simple hand calculations of the class-break systems), they do show that seismic stresses are in the range of allowable levels.

To provide verification that class-break systems are not affected by the amplified portion of the response spectrum, an upper bound stiffness analysis of the RHR system was performed, by adding a fictitious support. Resulting stresses were confirmed to be at low levels, below code allowables.

Of further concern is the Recirculation system, which has previously been analyzed by response spectrum methods, and still shown to exceed a code allowable of 2.4 S_h. To justify that this system would remain functional during the SSE event, as well as to determine a more reasonable functionality limit, nonlinear analyses have been performed on a piping system of similar dynamic characteristics; results show that internal pipe moments, as calculated by nonlinear methods, are 27% lower than those calculated by linear methods, while at the same time peak strains in elbow elements are limited to 1 percent, with no significant flow restriction. Of significance is the result that elbows, predicted to have 60,000 psi stress by elastic analysis, are below lowest bound collapse load and are shown functional by nonlinear analysis.

Table 6.1 summarizes SSE stresses as predicted by either hand calculation or response spectra analysis techniques. Hand calculation values have been adjusted to reflect SSE motion, (by use of multiplier of 1.6; Figure 5.8 suggests that a 2 percent SSE spectrum is approximately 80 percent of a 0.5 percent OBE spectrum. Hence, as SSE is twice the OBE zero period acceleration, use 1.6 = 2 times 0.8). As can be seen in this Table, all elastically calculated stresses are below 60,000 psi. This indicates that all the piping systems would remain functional during the SSE event.

Further, the following important conservatisms were not considered:

- The code value of S_h is very conservative. A more realistic value of S_h is at least 20 percent larger.
- Experimental test results have shown that elbows can strain in excess of 1 percent without loss of functionality.

The justification of an allowable stress level of 20 percent larger than 2.4 S_h is that:

- In situ material yield strengths are 10 percent over code minimum.[11,12]
- Strain rate effects increase nominal yield strengths by 10 percent.[13,14]

Other conservatisms not included in the analysis include:

- Doubling gravity and pressure stress.
- Actual component thickness.
- Conservative modeling assumptions.
- Collapse loads of pressurized elbows are significantly higher (on the order of 50 percent) than non-pressurized elbows, as verified by experimental results.[5,9,10]

It is therefore concluded that all piping systems identified in Table 2.1 as being over original operability criteria would in fact remain functional during the SSE event.

7.0 CONCLUSION

A total of seven piping systems were identified by previous calculation to exceed operability limits. This report has studied one of these systems in depth, using both elastic and nonlinear methods. Results from these analyses show the following:

- The analyzed RHR class-break system has elastic stresses slightly in excess of code allowables, but remains functional during the SSE event when nonlinear effects are accounted.
- The remaining class-break systems all have approximately-calculated stresses near code allowables, and remain functional during the SSE event when nonlinear effects are accounted.
- The RRCI system has elastic stresses slightly in excess of code allowables, but remains functional during the SSE event when nonlinear effects are accounted.

As an outcome of this study, it is recommended that the simplified hand calculations used to analyze class-break systems on Quad 1 be modified to remove large conservatisms.

Based upon these conclusions, it is judged that the piping systems identified in this report would remain functional during an SSE event.

8.0 REFERENCES

1. EDS Project Specific Instructions, Numbers 5.0, 6.0, 10.0 Job 0590-003.

2. Keith, Feibush Associates, Engineers letter of September 29, 1970, transmitting Quad 1 Response Spectra.

3. USNRC Regulatory Guide 1.60, Revision 1, December 1973.

4. Commonwealth Edison Company Quad-Cities Station Units 1 and 2 Safety Analysis Report and Section 12, Question 12.3, Amendment 13.

5. Greenstreet, W. L., "Experimental Study of Plastic Responses of Pipe Elbows," ORNL/NUREG-24, February 1978.

6. Mashgiz, ed., Enziklopediceskii Spravocinik "Masinostroenie," Vol. 3 & 4, 1974.

7. EDS Nuclear "AED Technical Procedures - Structural Analysis," May 1, 1979.

8. Evaluation of the Functional Capability of ASME Section III Class 1, 2 and 3 Piping Components Mark I Containment Program Task 3.1.5.4, Sargent & Lundy Engineers Report SL-3670, September 21, 1978.

9. Gross, Nicol, "Experiments on Short-Radius Pipe Bends," Proceedings Institution of Mechanical Engineers, (B), Vol. 1B, 1952-1953, p. 465.

10. Ellyin, Fernand, "An Experimental Study of Elasto-Plastic Response of Branch-Pipe Tee Connections Subjected to Internal Pressure, External Couples and Combined Loadings," Welding Research Council Bulletin 230, September, 1977.

11. Calambos, T.V. and Ravindra, M. K., "Properties of Steel for Use in LRFD," ASCE JSD, September 1978.

12. Final Report on Bar Tests for the Committee of Concrete Reinforcing Bar Producers, AISI, Wiff, Janneg, Elstner and Associates, April 30, 1970.

13. "Determination of Break Locations and Dynamic Effects Associated with the Postulated Rupture of Piping," Section 3.6.2, Standard Review Plan, USNRC.

14. Code Requirements for Nuclear Safety-Related Concrete Structures, ACI 349-76, Appendix C.

15. EDS calculations 0590-013-456

A-001 Rev. 0: Operability Assessment
N-001 Rev. 0: Time History Development
N-002 Rev. 0: SUPERPIPE Model
N-003 Rev. 0: Inelastic Elbow Verification
N-004 Rev. 0: ANSYS Model
N-005 Rev. 0: PWHIP Model
N-006 Rev. 0: Assessment of Q1-RBCW-02B
N-007 Rev. 0: PWHIP Analysis Results
N-008 Rev. 0: ANSYS Analysis Results

IDENTIFIED PIPING SYSTEMS

EDS Problem No.	Original Method of Analysis
Q1-RRCI-01C	Computer/Elastic Response Spectrum
Q1-RHRS-03B	Hand Calculation/Equivalent Static Method
Q1-RHRS-02B	Hand Calculation/Equivalent Static Method
Q1-RHRS-09B	Hand Calculation/Equivalent Static Method
Q1-CCCD-02B	Hand Calculation/Equivalent Static Method
Q1-RBCW-01B	Hand Calculation/Equivalent Static Method
Q1-RBCW-02B	Hand Calculation/Equivalent Static Method

Abbreviations:

RRCI - Reactor Recirculation
RHRS - Residual Heat Removal
CCCD - Clean and Contaminated Drain
RBCW - Reactor Building Cooling Water

Table 2.1

RHR FLEXIBLE SYSTEM FREQUENCIES

Mode No.	Frequency (cps)	Period (sec)
1	.205	4.8762
2	.266	3.7534
3	.465	2.1489
4	.820	1.2196
5	1.033	.9678
6	1.294	.7728
7	1.471	.6797
8	1.668	.5996
9	2.037	.4909
10	2.158	.4634
11	2.311	.4327
12	2.527	.3957
13	2.610	.3832
14	2.625	.3810
15	2.677	.3735
16	2.783	.3593
17	3.070	.3257
18	3.618	.2764
19	4.150	.2410
20	4.413	.2266
.	.	.
.	.	.
.	.	.
.	.	.
45	10.642	.0940

Table 3.1

RHR STIFF SYSTEM FREQUENCIES

Mode No.	Frequency (cps)	Period (sec)
1	2.365	.4228
2	5.510	.1815
3	8.086	.1237
4	9.022	.1108
5	9.269	.1079
6	16.342	.0612
7	18.263	.0548
8	23.539	.0425
9	25.741	.0388
10	27.515	.0363

Table 3.2

PRELIMINARY CALCULATION OF STRESSES IN RHR SEISMIC PIPING

Run 1   1-1067-3"   Flexible System

Control Point	OBE Stress, psi	Gravity Stress, psi	Preliminary Stress, psi
100	5422	1019	7141
C01A, Elbow	5974	219	6893
C01B, Elbow	9066	246	10012
102	4224	202	5126
104	5173	2154	8027
C1XA, Elbow	11839	2443	14982
C1XB, Elbow	11648	1280	13628
106	7885	597	9182
C02A, Elbow	16460	2991	20151
C02B, Elbow	16809	2877	20386
108	8075	876	9651

Formula:

Preliminary Stress = OBE + gravity + pressure

$$\text{Pressure} = \frac{Pd^2}{D^2-d^2} = \frac{(210)(3.068)^2}{(3.5)^2-(3.068)^2} = 697 \text{ psi} \cong 700 \text{ psi at all points}$$

B31.1 Code Criteria = 1.2 S_h = 18000 psi

Material A-106 Grade B

Reference:

OBE - Computer run N-002-002

Gravity - Computer run N-002-003

Table 3.3a

PRELIMINARY CALCULATION OF STRESSES IN RHR SEISMIC PIPING

Run 2 1-1065-3". Flexible System

Control Point	OBE Stress, psi	Gravity Stress, psi	Preliminary Stress, psi
200	4088	2086	6874
C05A, Elbow	7061	3694	11455
C05B, Elbow	7158	3351	11209
C5XA, Elbow	7031	2537	10268
C5XB, Elbow	6970	2516	10186
201	4552	1440	6692
202	6311	1457	8468
C06A, Elbow	14646	3417	18763
C06B, Elbow	15677	3270	19647
204	8595	857	10152
206	9370	665	10735

Formula:

Preliminary Stress = OBE + gravity + pressure

Pressure Stress = 700 psi at all points

B31.1 Code Criteria = 1.2 S_h = 18000 psi

Material A-106 Grade B

Reference:

OBE - Computer run N-002-002

Gravity - Computer run N-002-003

Table 3.3b

PRELIMINARY CALCULATION OF STRESSES IN RHR SEISMIC PIPING

Run 4 1-1066-3" Flexible System

Control Point	OBE Stress, psi	Gravity Stress, psi	Preliminary Stress, psi
C38A, Elbow	15440	3062	19202
C38B, Elbow	15561	3315	19576
C39A, Elbow	15455	3345	19500
C39B, Elbow	12935	3503	17138
406	4478	2164	7342
C40A, Elbow	20320	4265	25285
C40B, Elbow	22227	4275	27202
C41A, Elbow	10446	5362	16508
C41B, Elbow	9328	5876	15904
408	4864	3310	8874

Formula:

Preliminary Stress = OBE + gravity + pressure

Pressure Stress = 700 psi at all points

B31.1 Code Criteria = 1.2 S_h = 18000 psi

Material A-106 Grade B

Reference:

OBE - Computer run N-002-002

Gravity - Computer run N-002-003

Table 3.3c

STRESSES IN RHR SEISMIC PIPING FLEXIBLE SYSTEM

Control Point	Preliminary OBE Stress, psi	OBE Stress, psi	SSE Stress, psi
C02A, Elbow	20151	18217	27007
C02B, Elbow	20386	20162	30233
C06A, Elbow	18763	18322	27070
C06B, Elbow	19647	14923	
C38A, Elbow	19202	18499	27672
C38B, Elbow	19576	12741	
C39A, Elbow	19500	12618	
C40A, Elbow	25285	24558	36383
C40B, Elbow	27202	26801	40067

Formulas:

Preliminary OBE Stress: = OBE + gravity + pressure

OBE Stress: $= \frac{1}{Z}\left[(i)^2(M_{yy,OBE} + M_{yy,gravity})^2 + (i)^2(M_{zz,OBE} + M_{zz,gravity})^2 + (M_{t,OBE} + M_{t,gravity})^2\right]^{1/2} + \text{(pressure)}$

SSE Stress: $= \frac{1}{Z}\left[(i)^2(M_{yy,SSE} + M_{yy,gravity})^2 + (i)^2 (M_{zz,SSE} + M_{zz,gravity})^2 + (M_{t,OBE} + M_{t,gravity})^2\right]^{1/2}$

$+ \text{(pressure)}$

(pressure) = 700 psi at all points

Code Criteria: OBE Stress - 1.2 S_h = 18000 psi

SSE Stress - 2.4 S_h = 36000 psi

Reference:

OBE - Computer run N-002-002

Gravity - Computer run N-002-003

STRESSES IN RHR SEISMIC PIPING
STIFF SYSTEM

Control Point	OBE Case Stress, Psi	SSE Case Stress, Psi
100	5507	7406
C01A, Elbow	2987	3932
C01B, Elbow	5316	7223
102	2954	3868
104	3939	4614
C1XA, Elbow	5791	7473
C1XB, Elbow	5773	7782
106	6937	9866
C02A, Elbow	5241	6162
C02B, Elbow	6183	7326
108	2676	3309

Formulas:

$$\text{Stress} = \frac{1}{Z}\left[(i)^2(M_{yy,seismic} + M_{yy,gravity})^2 + (i)^2(M_{zz,seismic} + M_{zz,gravity})^2 + (M_{t,seismic} + M_{t,gravity})^2\right]^{1/2} + (\text{pressure})$$

Pressure = 700 psi at all points

Code Criteria: OBE Stress - 1.2 S_h = 18000 psi

SSE Stress - 2.4 S_h = 36000 psi

Reference:

OBE - Computer runs N-002-003
N-002-004

SSE - Computer runs N-002-003
N-002-005

Table 3.3e

System	Original Stress/OBE	Modified Stress/OBE(2)
RRCI-01C	25,000	25,000
RHRS-03B(1)	102,155	26,800
RHRS-02B(1)	58,580	33,666
RHRS-09B(1)	124,358	14,544
CCCD-02B(1)	203,394	24,704
RBCW-01B(1)	Similar to RBCW-02B	
RBCW-02B(1)	301,000	30,000

Notes:

1. Original stress calculated using 1.5 peak spectral acceleration
2. Modified stress calculated using first mode spectral acceleration

Table 3.4

MATERIAL STRESS-STRAIN LAW

Low Carbon Steel, A106 Grade B

E = 27,700,000 psi (at 200°F)

Poisson's Ratio = 0.30 (elastic)
varies to 0.50 at full plasticity

S_y = 31,900 psi

E_T = (.01)E = 280,000 psi (at 200°F)

Table 5.1

DETAILED ANSYS AND SIMPLE PWHIP SYSTEM FREQUENCIES

Mode	Detailed ANSYS Model[1]	Simple PWHIP Model[2]
1	2.36 Hz	2.36 Hz
2	5.51 Hz	6.55 Hz
3	9.27 Hz	12.80 Hz

References

1. Computer Run N-002-002
2. Calculation N-005

Table 5.2

PIPE MOMENTS COMPARISON

	Elastic Analysis	Nonlinear Analysis	Percent Reductions
Straight Pipe	111.9 k-in[1] (64.9 ksi)	71.6 k-in[2]	36
Elbow Pipe	53.8 k-in[3] (60.0 ksi)	42.6 k-in[4]	21

Reference Computer Runs

1. N-007-003
2. N-007-002
3. N-002-005
4. N-008-005

Table 5.3

SUMMARY STRESSES

System		Elastic SSE Stress psi (3)
RRCI-01C	Note 1	43,000
RHRS-03B	Note 1	40,087
RHRS-02B	Note 2	53,865
RHRS-09B	Note 2	23,270
CCCD-02B	Note 2	39,526
RBCW-01B	Note 2	similar to RBCW-02B
RBCW-02B	Note 2	50,694

Notes

1. By response spectra analysis
2. By static hand calculation using first mode spectral acceleration
3. SSE stress developed for hand calculation systems is 1.6 times OBE stress

Table 6.1

Flexible RHR piping system

SUPERPIPE Math Model

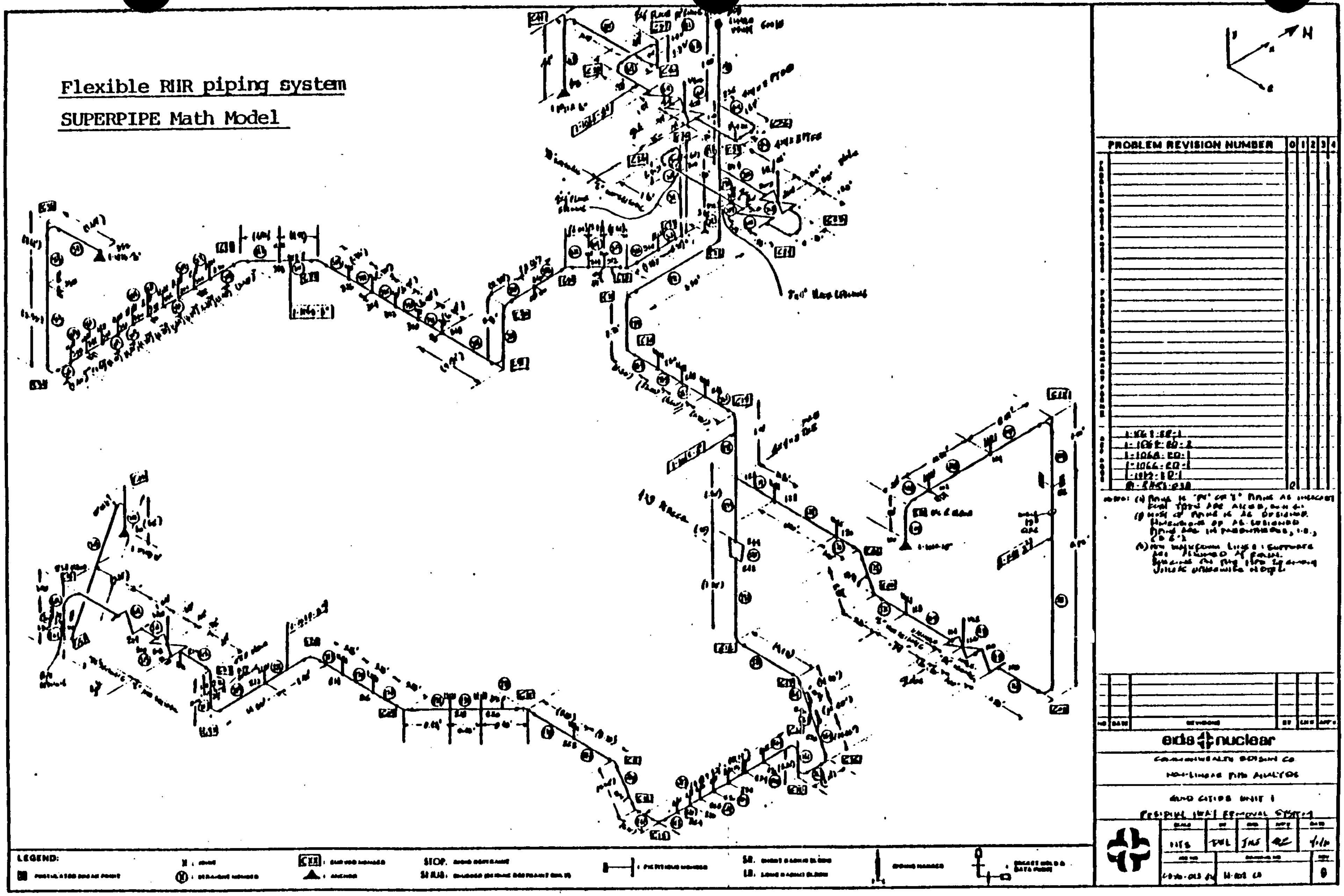


Figure 3.1

Stiff RHR piping system

SUPERPIPE Math Model

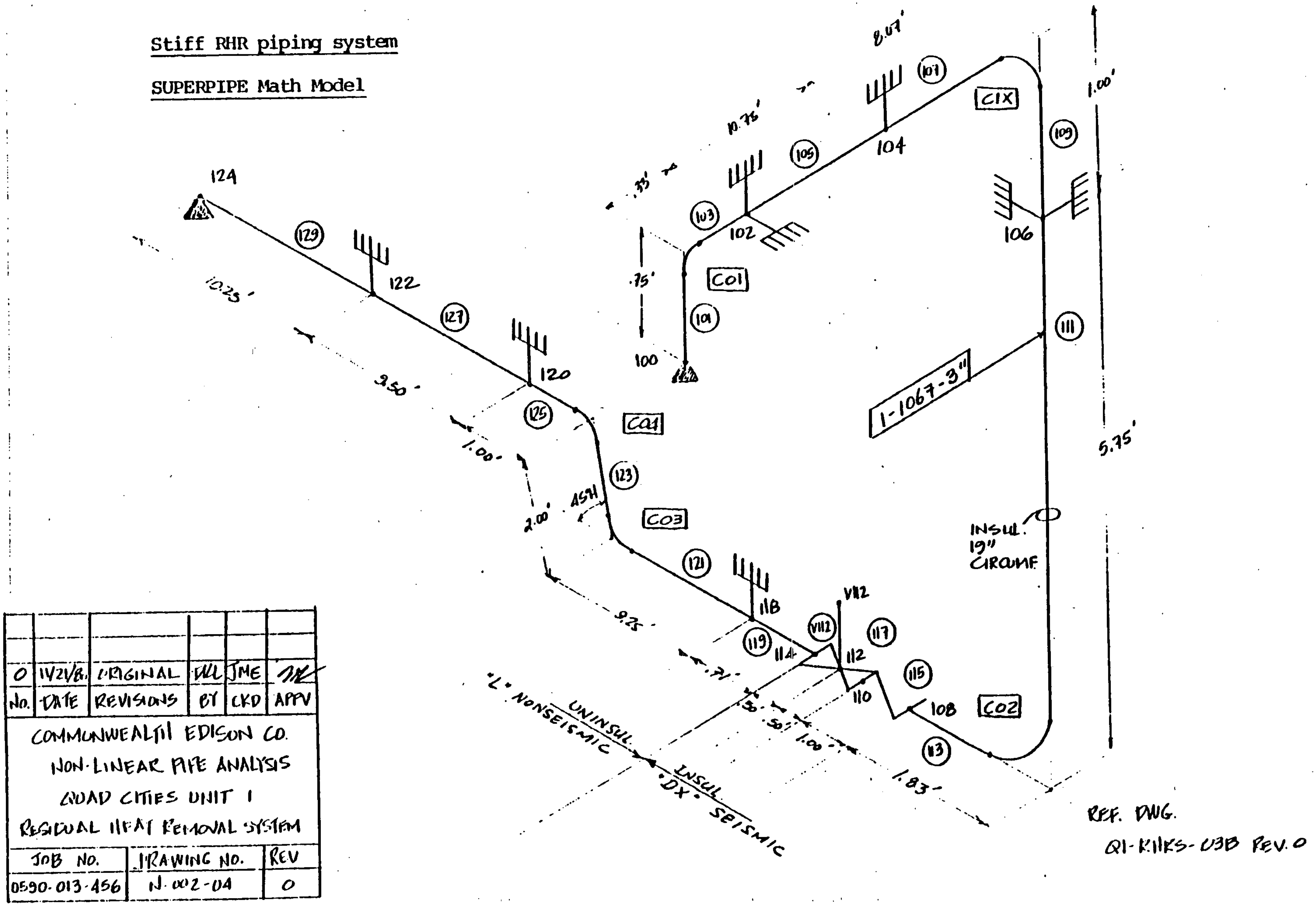


Figure 3.2

ANSYS Correlation Study with a 6" Elbow

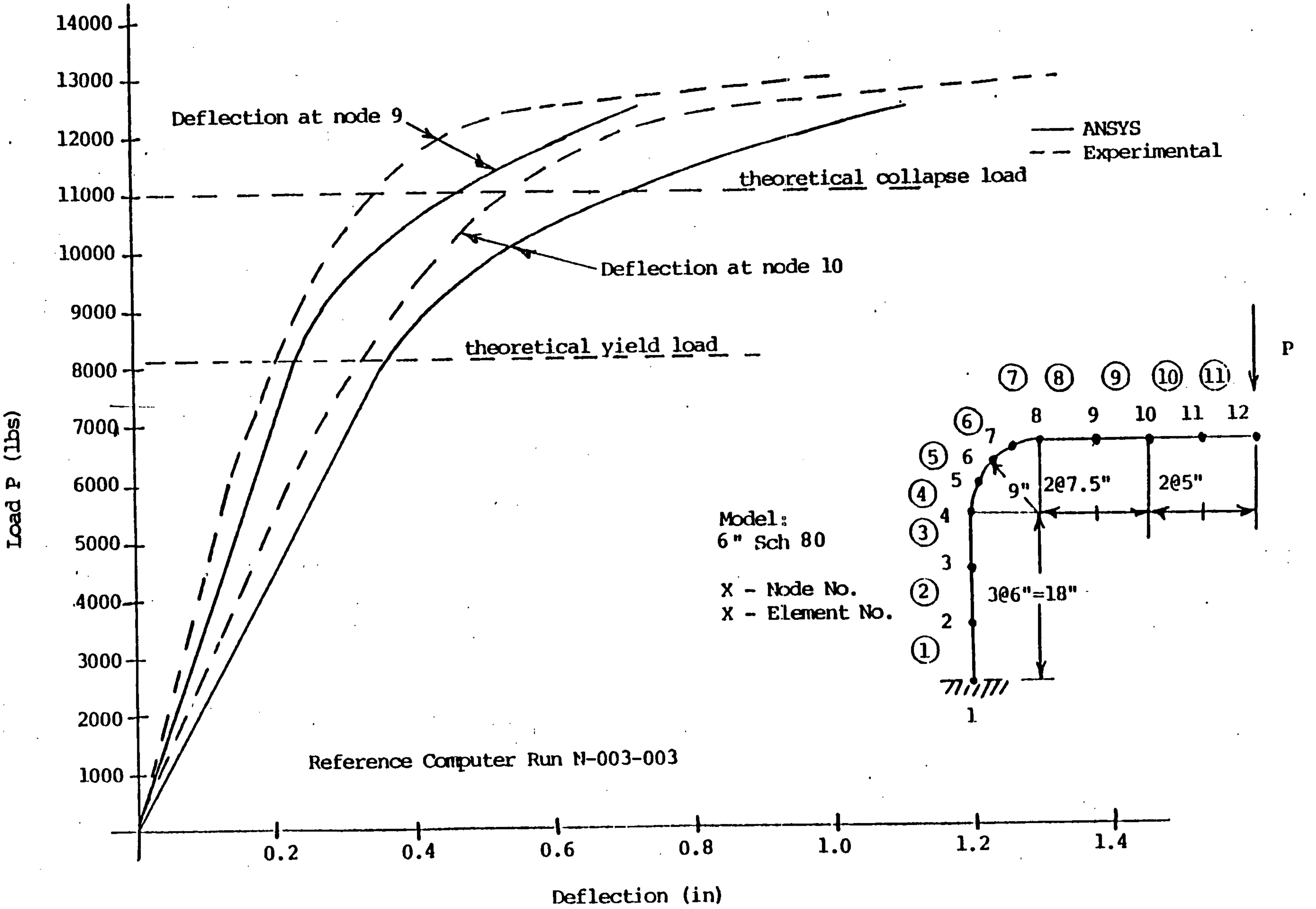


Figure 4.1

Moment-Deflection Curve for a 3" Schedule 40 Long Radius Elbow

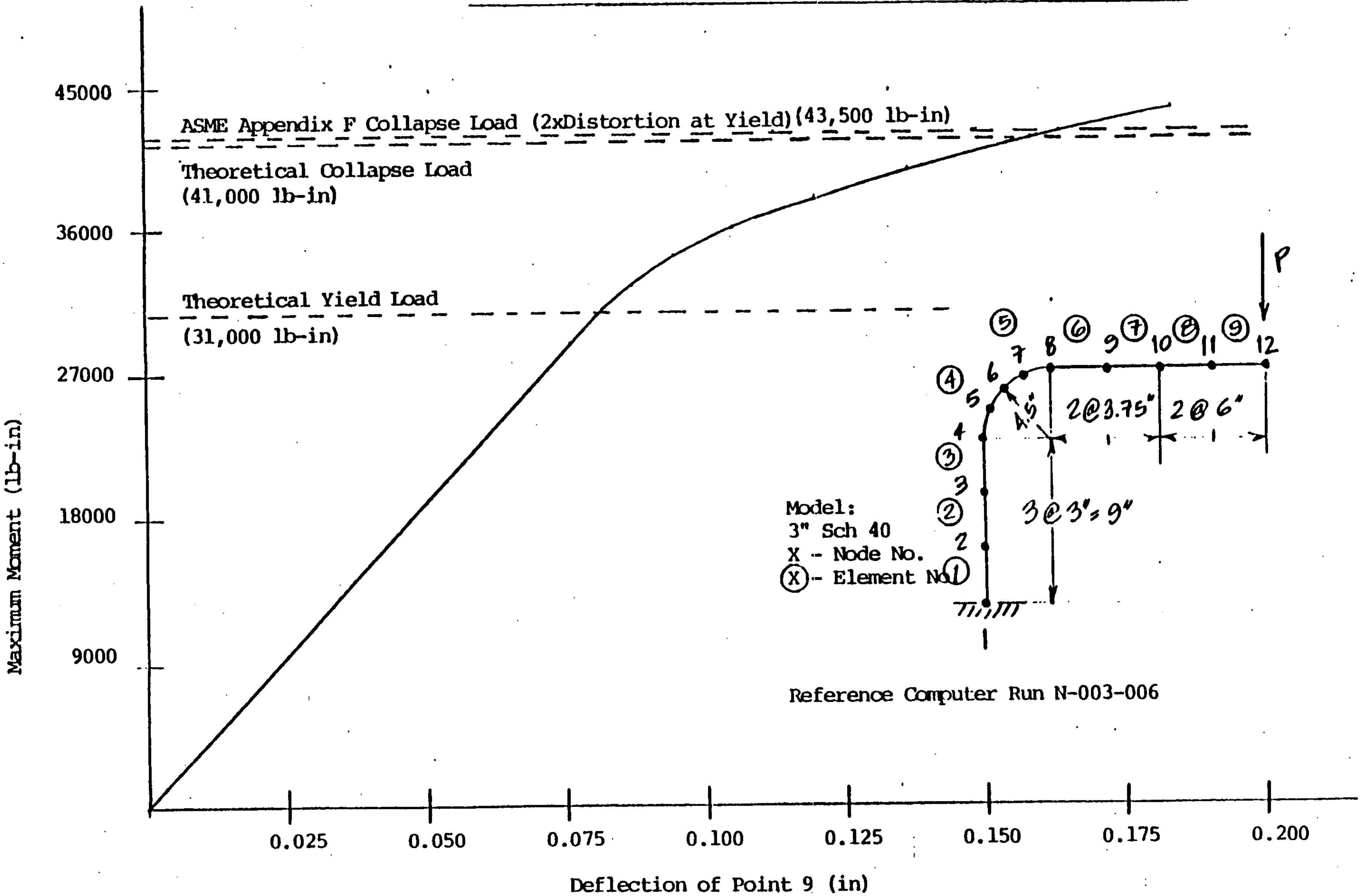


Figure 4.2

Required Input Spectrum for RHR System

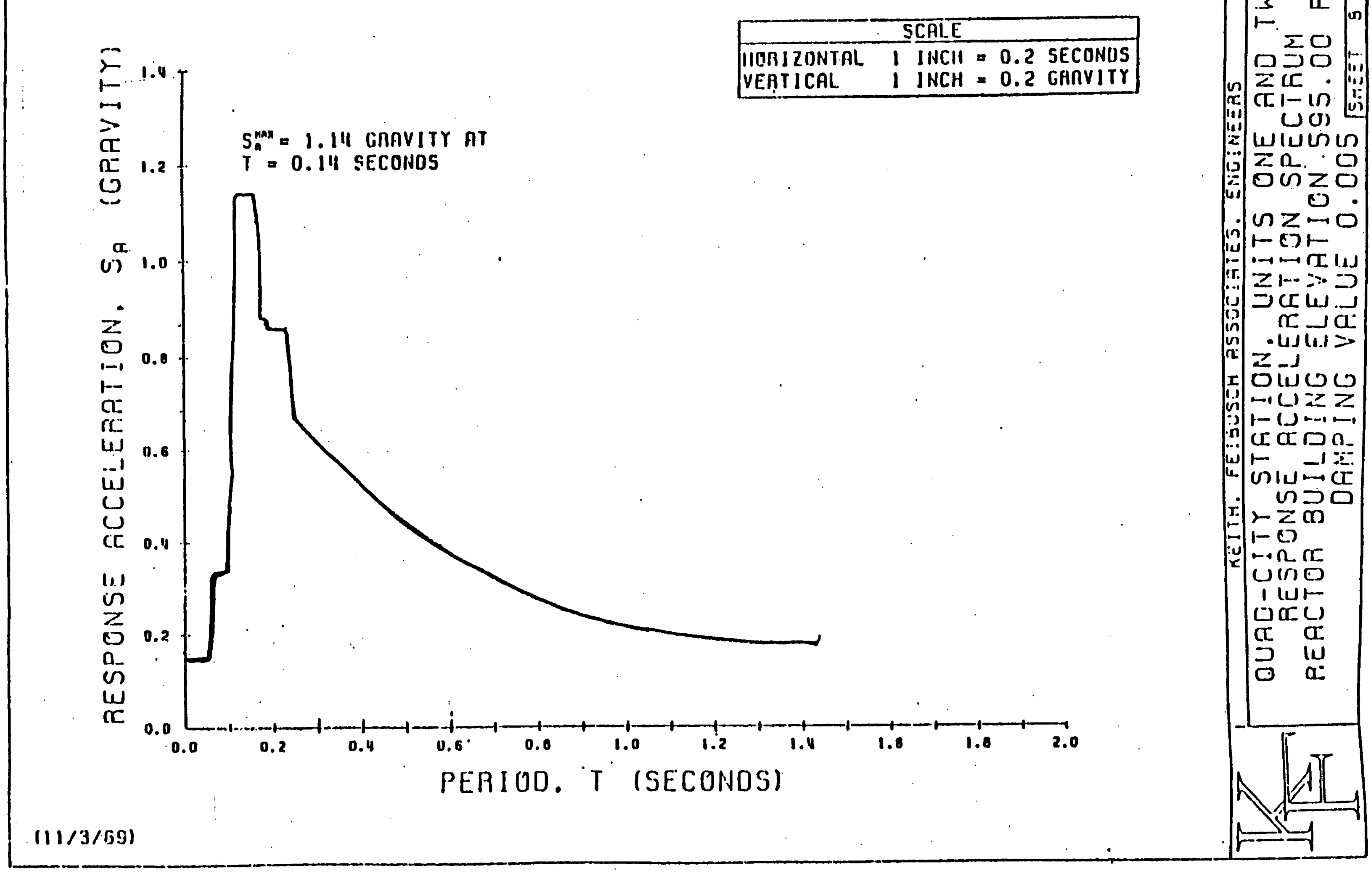


Figure 5.1

Acceleration Time History Based on El Centro Record

(Note: This time history is increased 11.1 times for nonlinear analyses.)

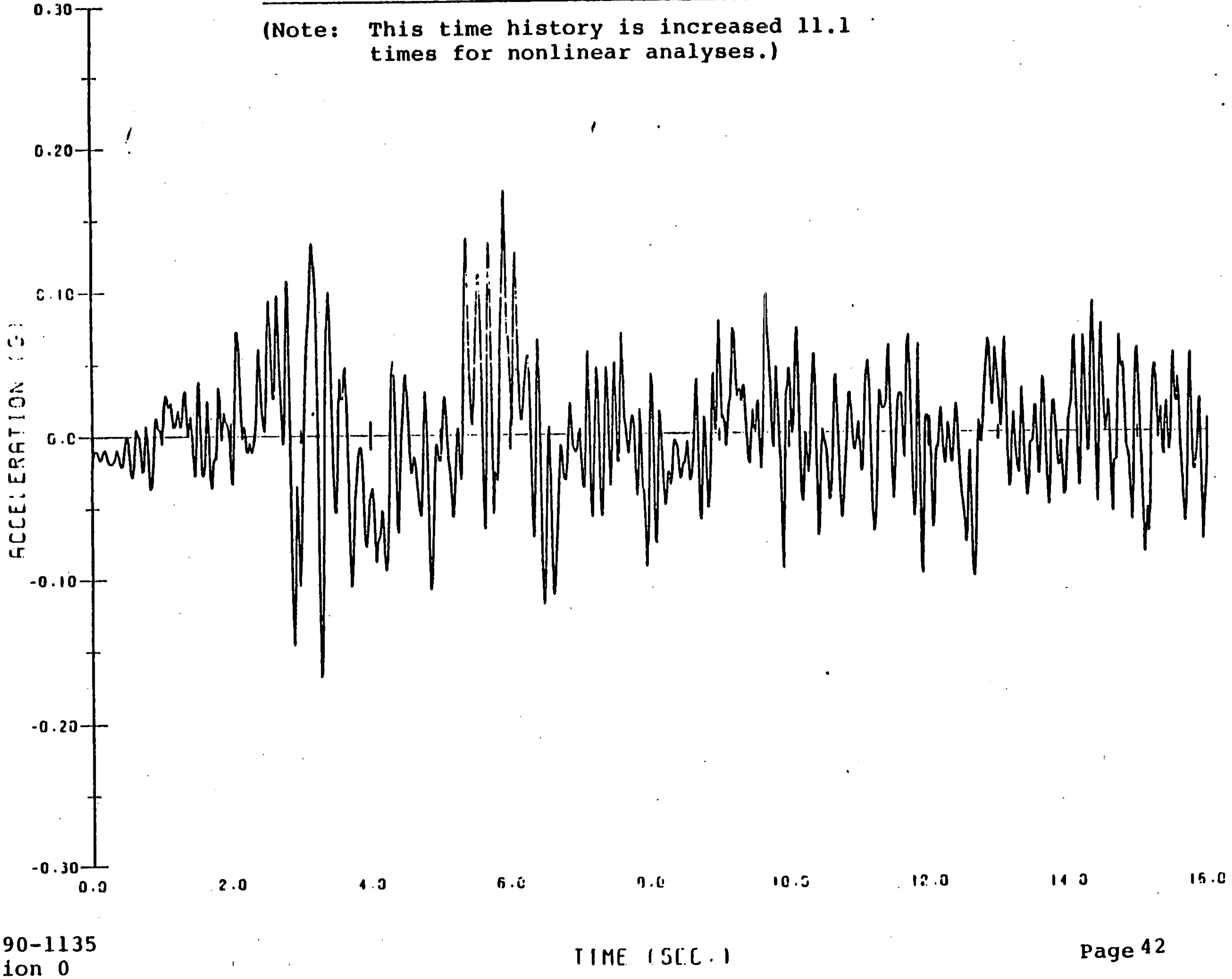


Figure 5.2

Displacement Time History Based on El Centro Record

(Note: This time history is increased 11.1 times for nonlinear analyses.)

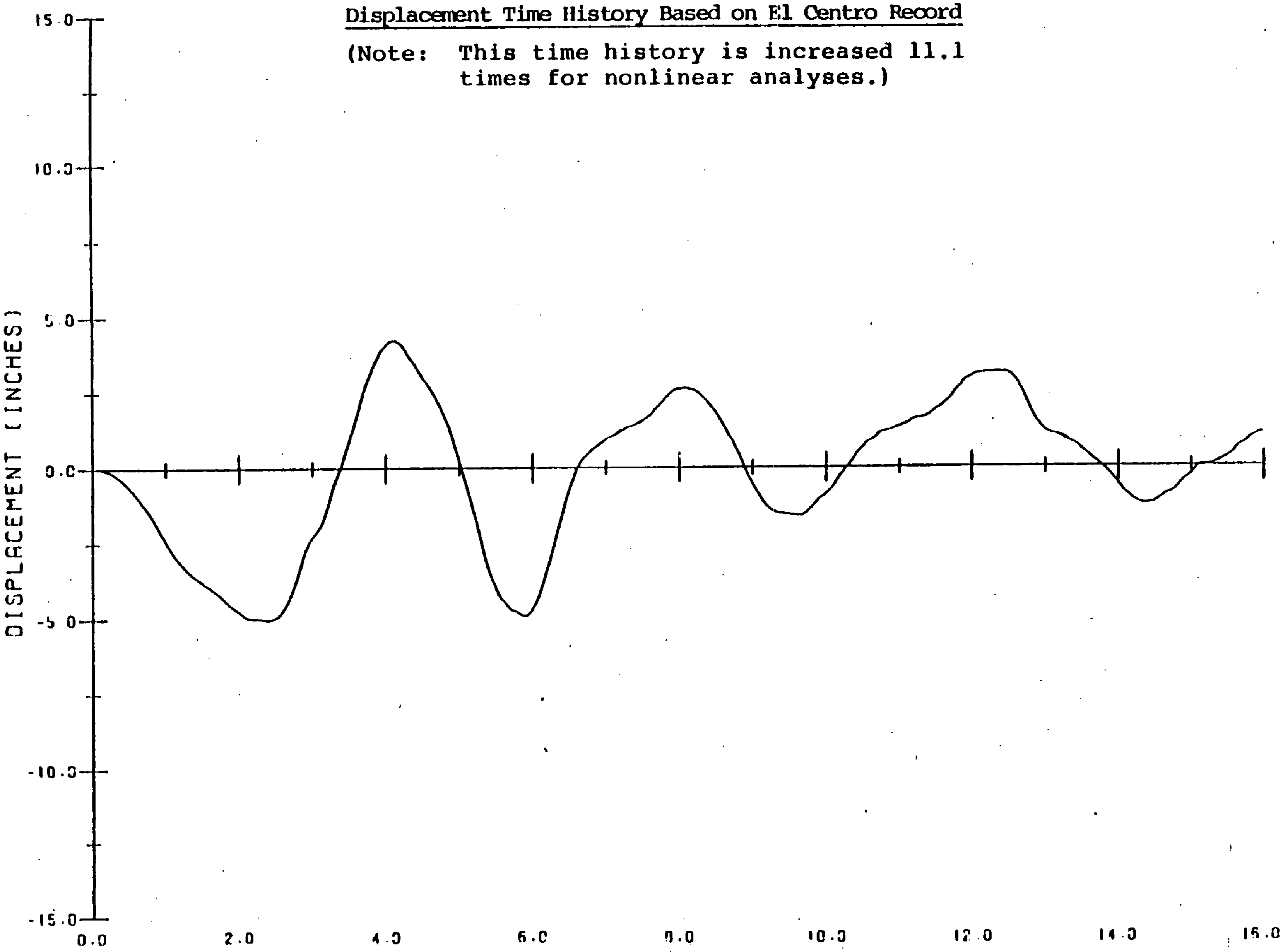


Figure 5.3

Acceleration Time History Based on Pacoima Dam Record

(Note: This time history is increased 11.1 times for nonlinear analyses.)

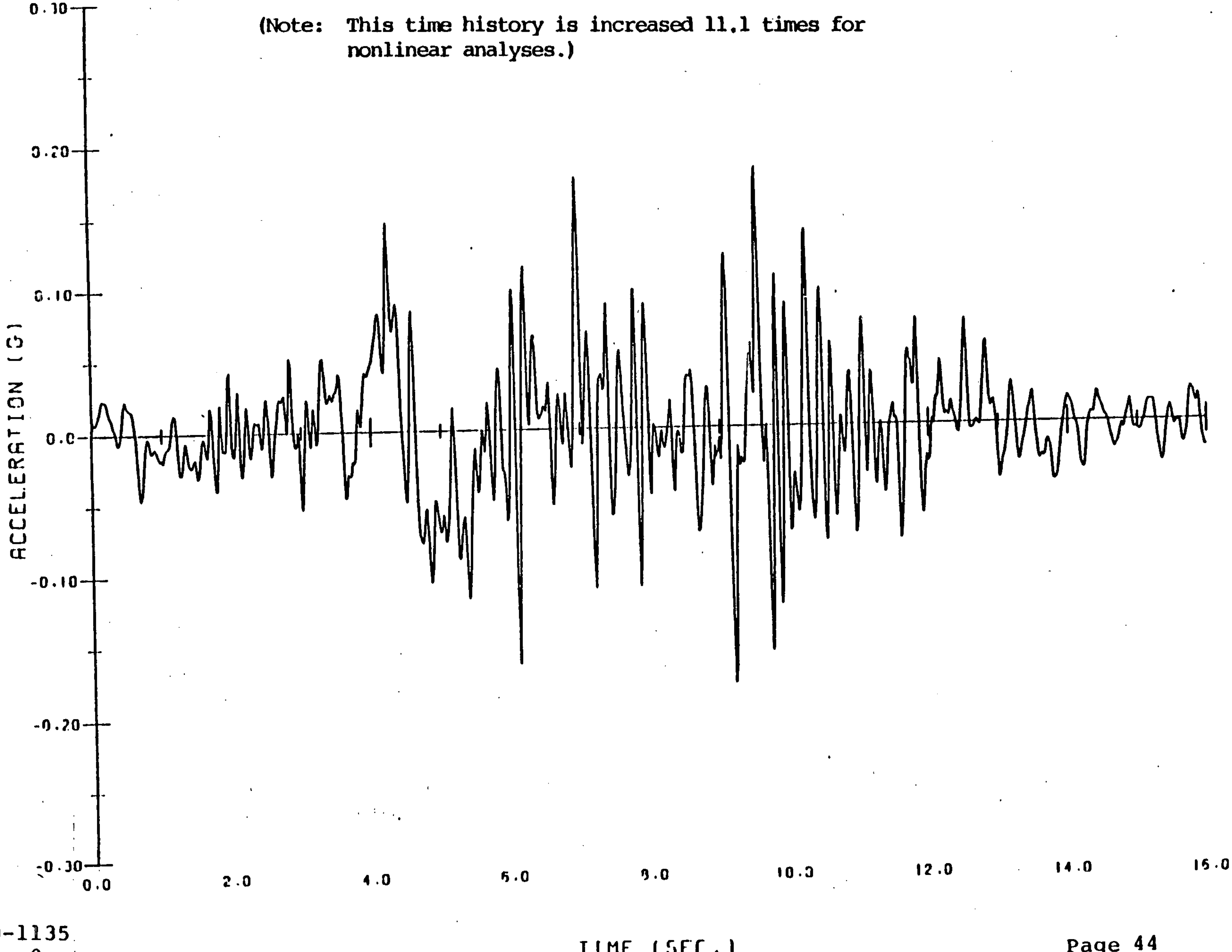


Figure 5.4

Displacement Time History Based on Pacoima Dam Record

(Note: This time history is increased 11.1 times for nonlinear analyses.)

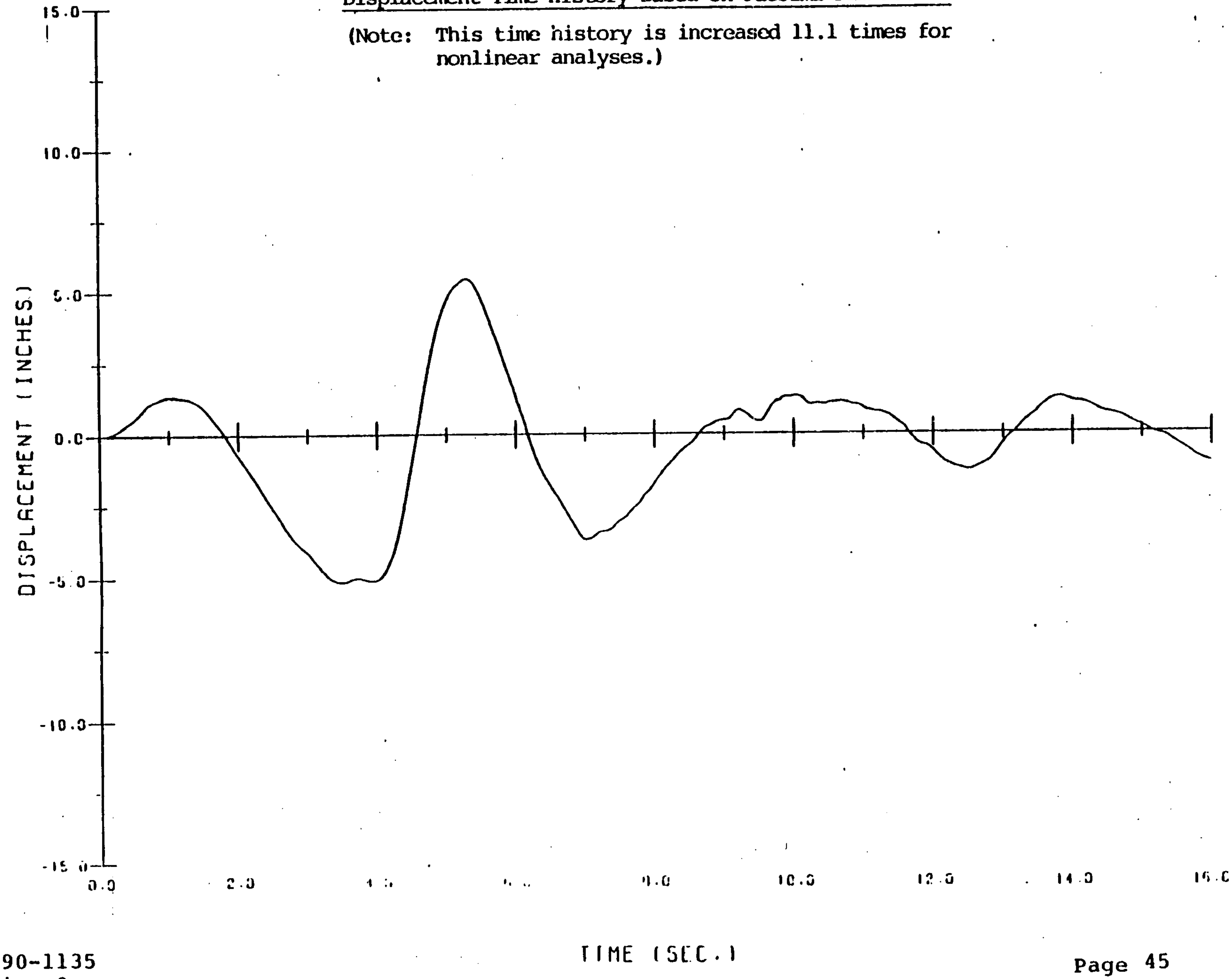


Figure 5.5

Response Spectra Based on El Centro Record

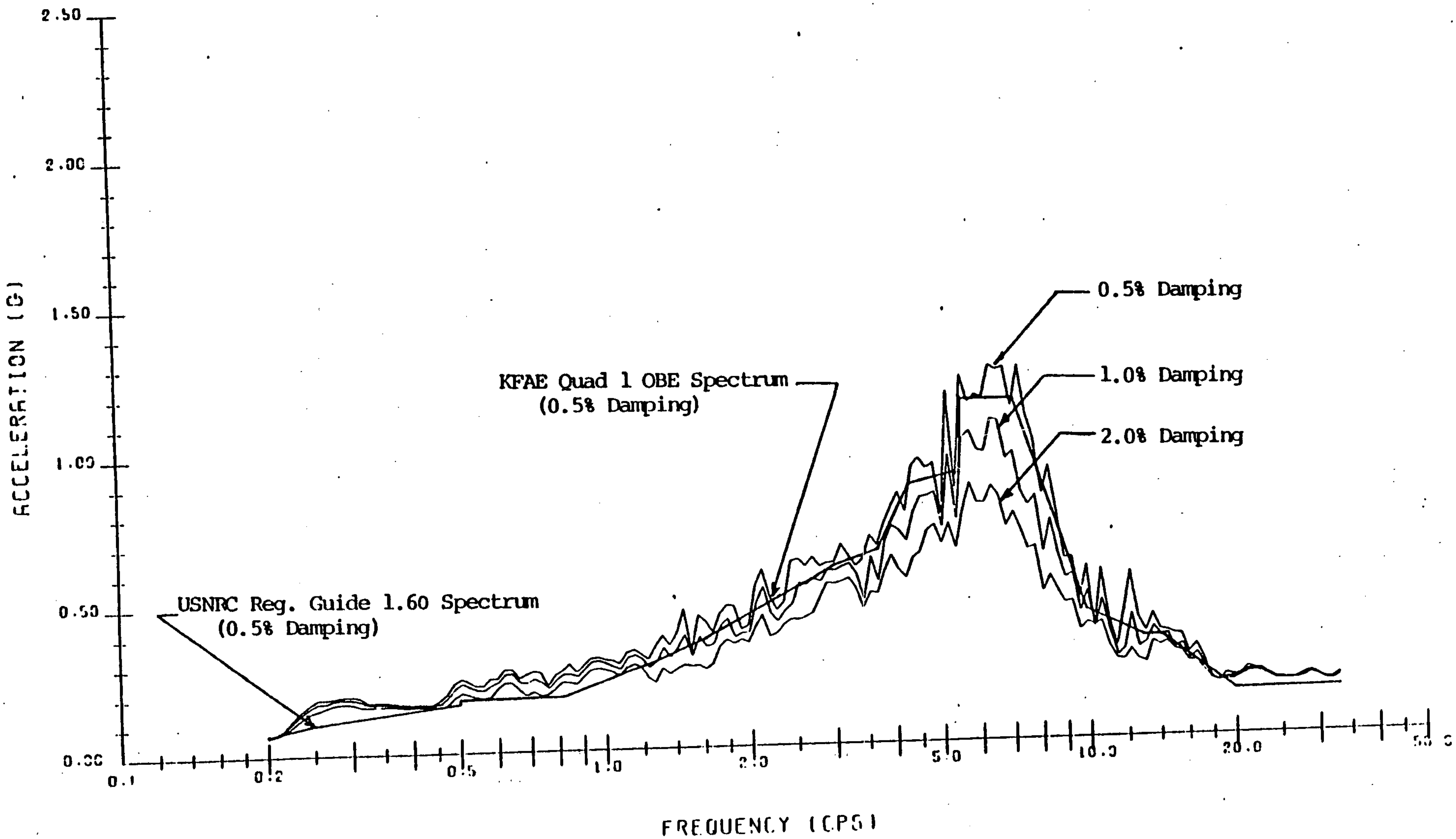


Figure 5.6

Response Spectra Based on Pacoima Dam Record

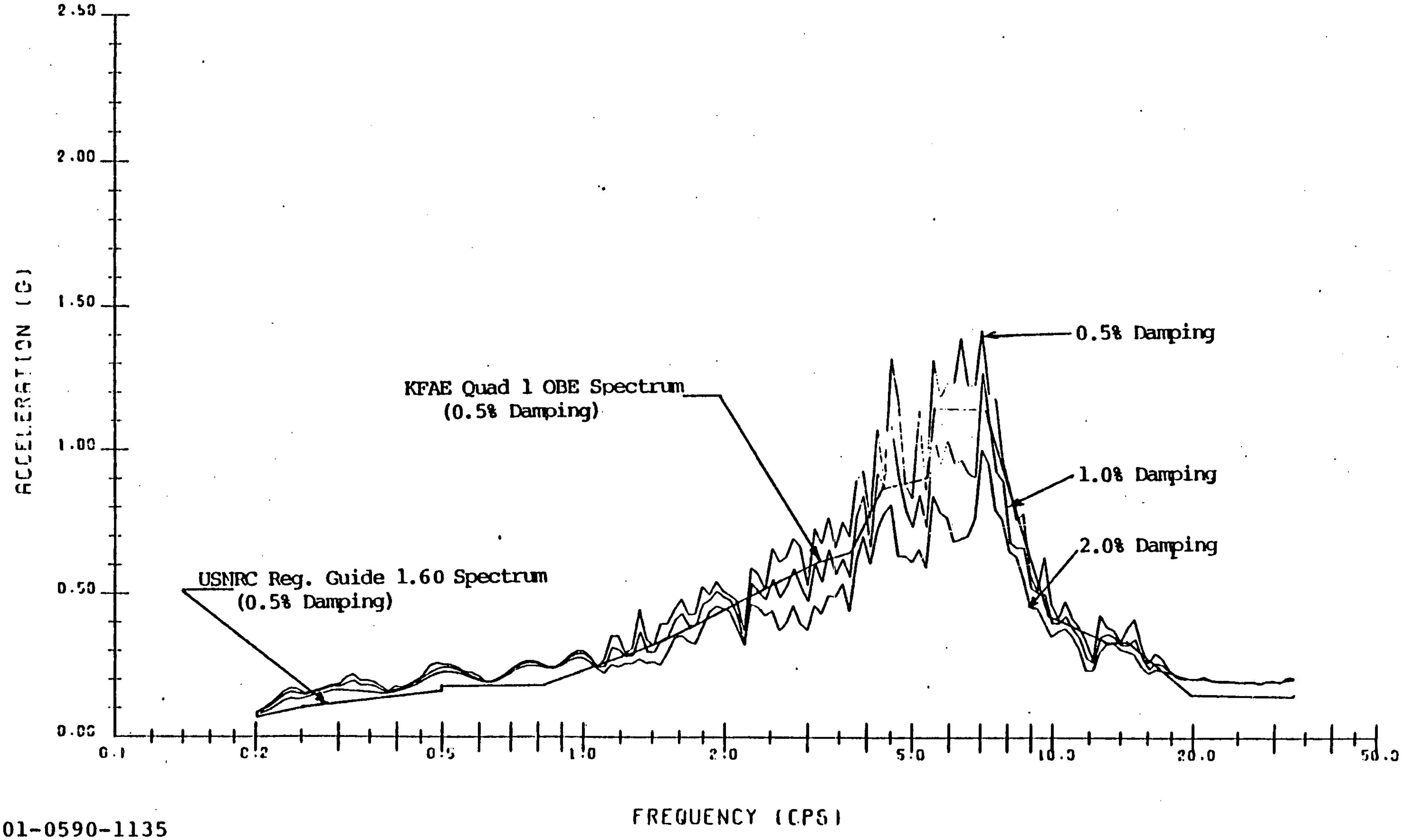


Figure 5.7

Comparison of Damping Levels in Response Spectra

Response Spectrum for the Residual Heat Removal System

Period	Frequency	$\frac{A_{2\%}}{A_{.5\%}}$
.000	---	1.00
.050	20.00	.95
.070	14.29	.82
.080	12.50	.82
.100	10.00	.69
.140	7.14	.65
.180	5.56	.65
.181	5.52	.77
.190	5.26	.77
.191	5.24	.77
.230	4.35	.75
.270	3.70	.74
.330	3.03	.77
.390	2.56	.76
.620	1.61	.77

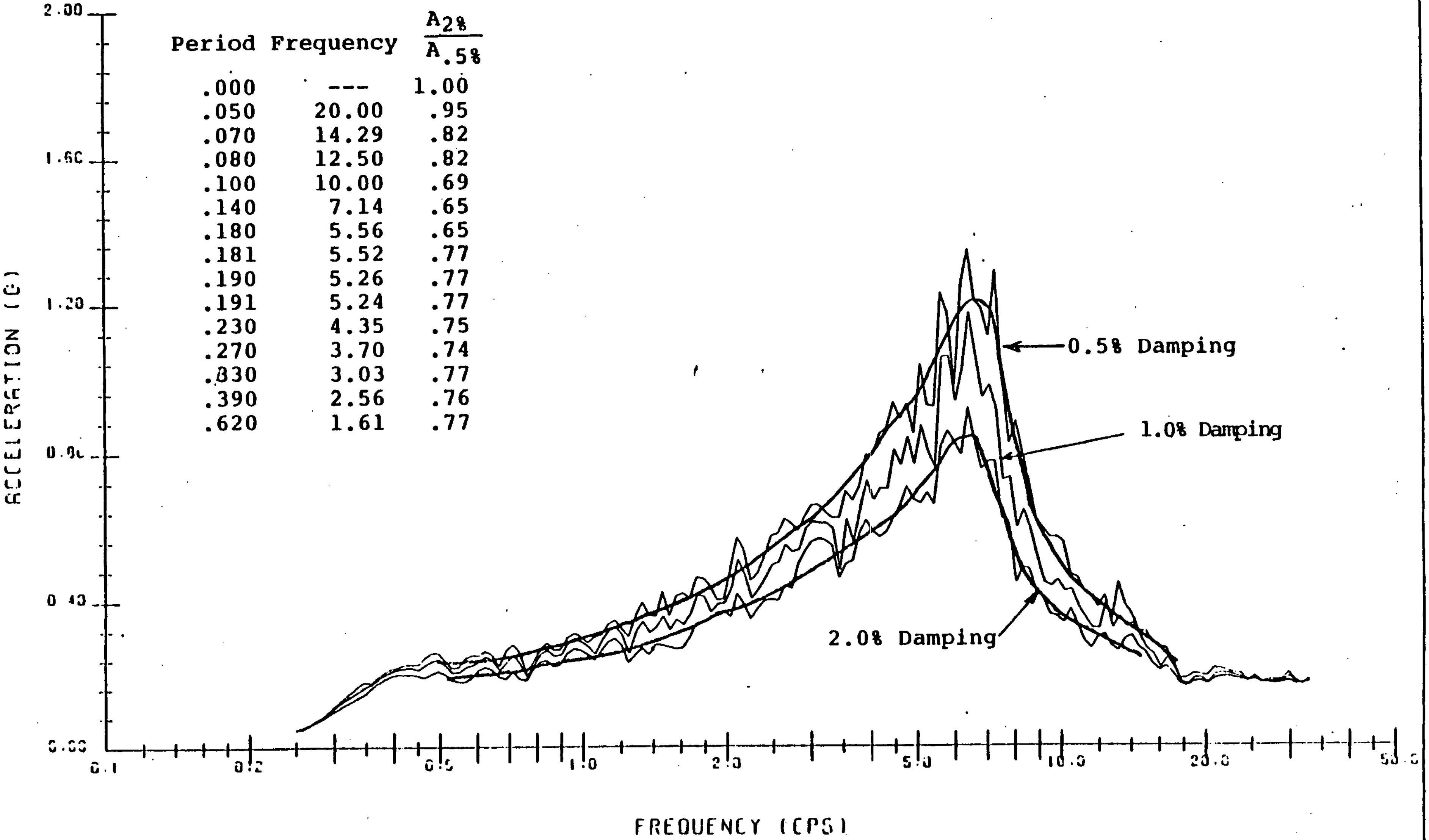


Figure 5.8

Math Model for ANSYS Analysis

RHR System

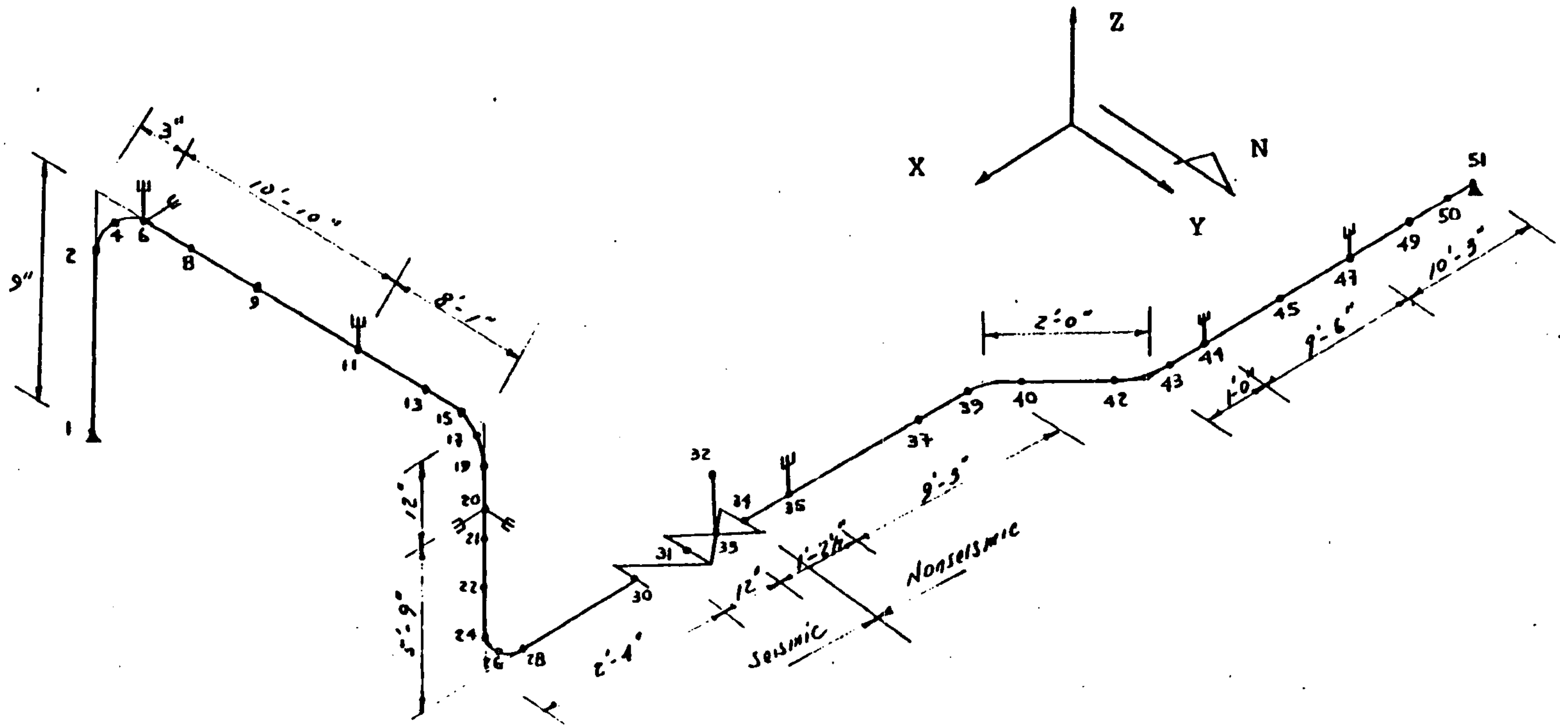


Figure 5.9

Math Model for PWHIP Analysis

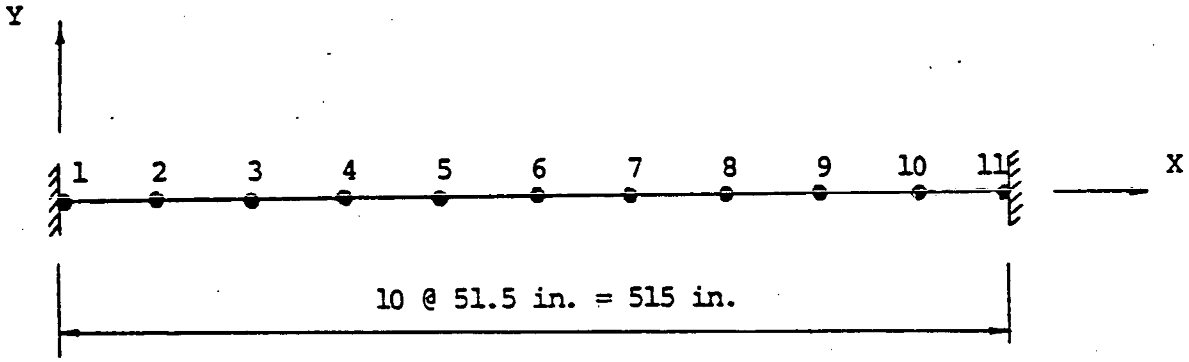


Figure 5.10

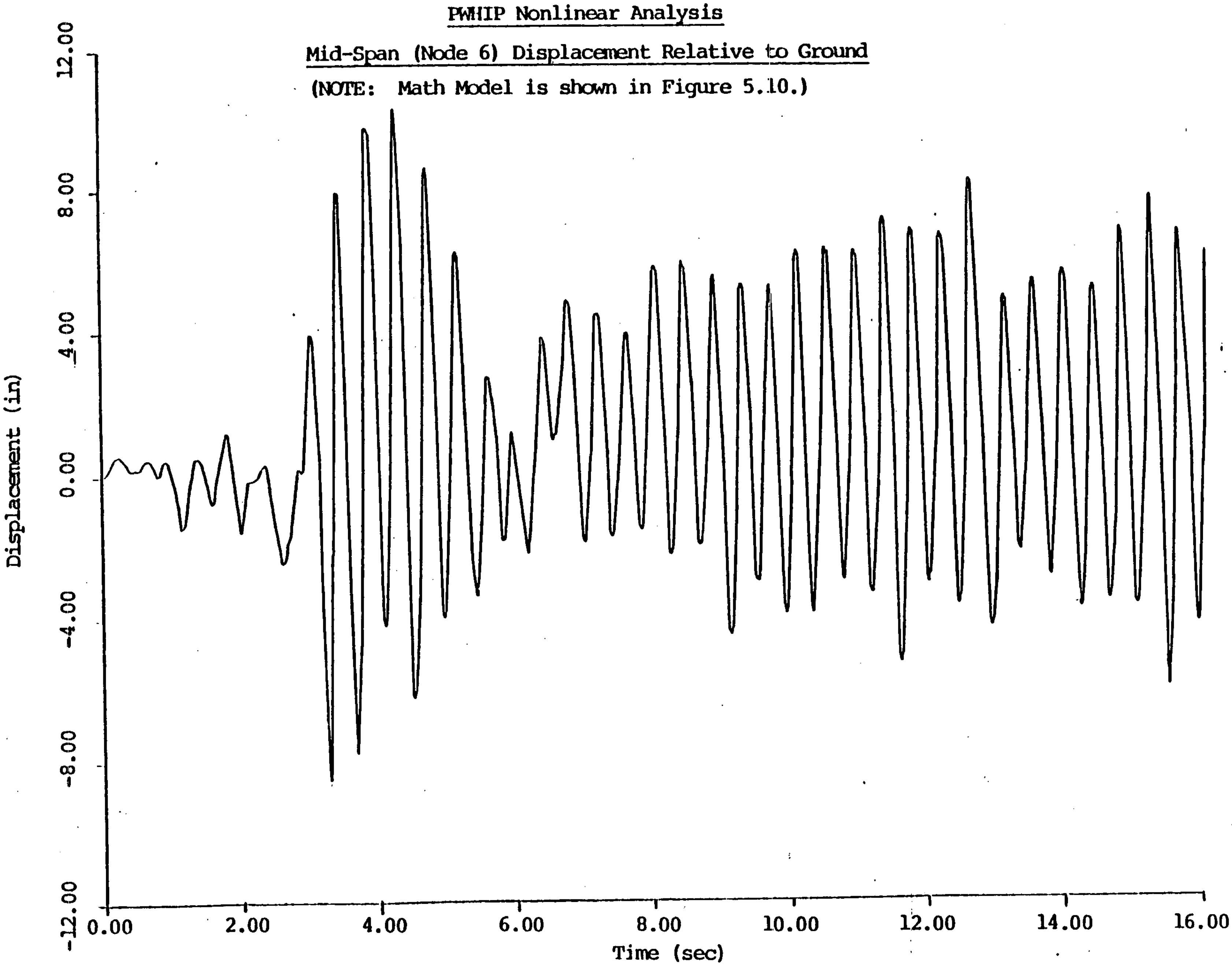

PWHIP Nonlinear Analysis
Mid-Span (Node 6) Displacement Relative to Ground
(NOTE: Math Model is shown in Figure 5.10.)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
Displacement (in)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
Time (sec)

Figure 5.11

PWHIP Analysis

End Moment (Node 11)

(Note: Math Model is shown in Figure 5.10)

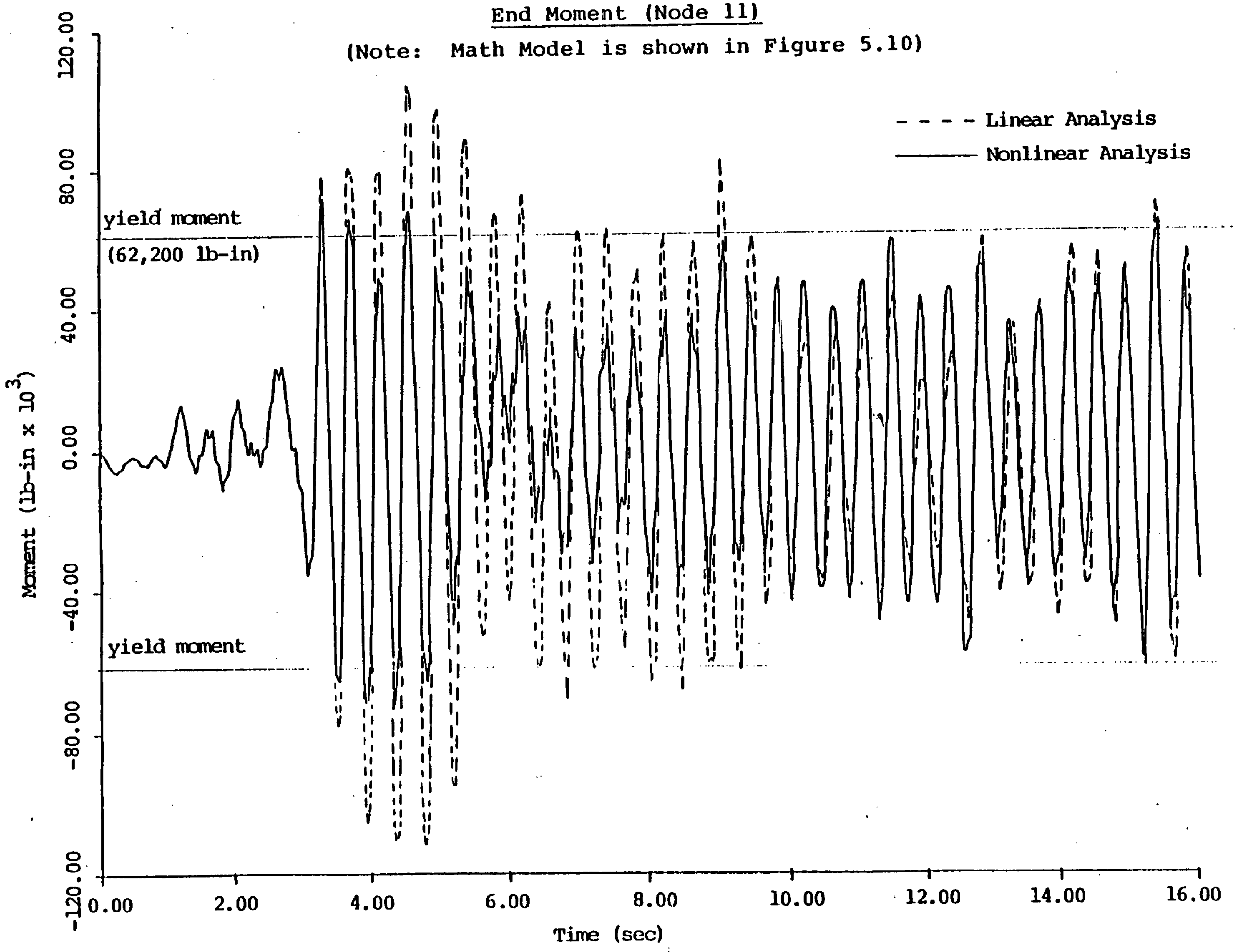


Figure 5.12

ANSYS Analysis

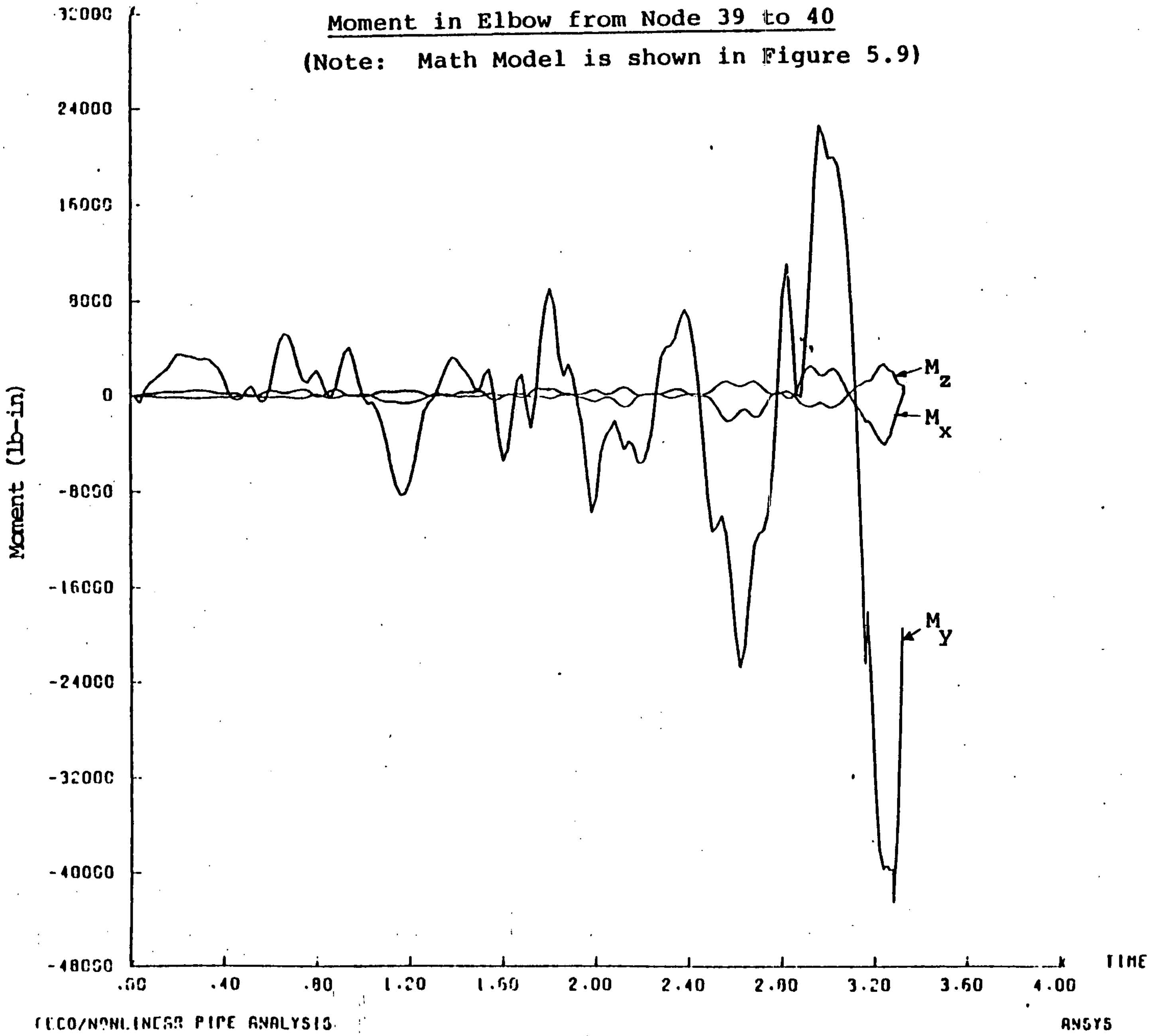
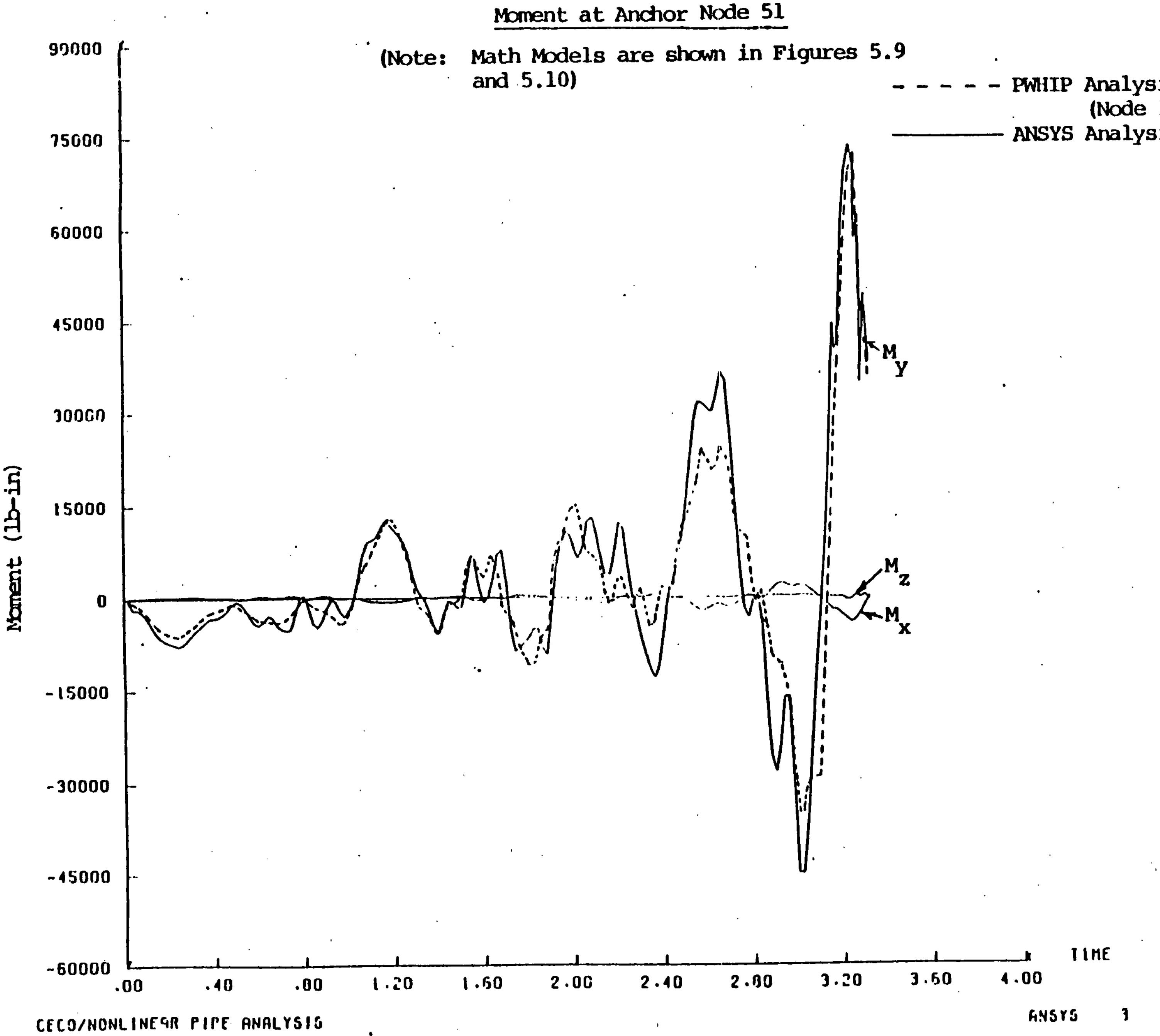


Figure 5.13



Moment at Anchor Node 51
(Note: Math Models are shown in Figures 5.9 and 5.10)
PWHIP Analysis (Node 11)
ANSYS Analysis
90000
75000
60000
45000
30000
15000
0
-15000
-30000
-45000
-60000
Moment (lb-in)
M_y
M_z
M_x
.00
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
3.60
4.00
TIME
CECO/NONLINEAR PIPE ANALYSIS
ANSYS 1

Figure 5.14

APPENDIX A

COMPUTER PROGRAM DESCRIPTIONS