Gv2y

SAT NO. 250.02

IMPROVEMENT OF SAFETY OF PIPING SYSTEMS USING NONLINEAR ANALYSIS METHODS

SBIR Phase I Final Report

October 1986 - July 1987

Structural Analysis Technologies, Inc.
10440 South De Anza Boulevard, Suite D7
Cupertino, CA 95014

Prepared for
US Nuclear Regulatory Commission
Washington, D.C. 20555

This material is based upon work supported by the Nuclear Regulatory Commission under award no. SBIR NRC-04-86-129. Any opinions, findings, and conclusions or recommendations expressed in the publication are those of the author(s) and do not necessarily reflect the views of the Nuclear Regulatory Commission.

SAT No. 250.02

IMPROVEMENT OF SAFETY OF PIPING SYSTEMS USING NONLINEAR ANALYSIS METHODS

SBIR Phase I Report

Prepared by

Structural Analysis Technologies, Inc.
10440 South De Anza Boulevard, Suite D7
Cupertino, CA 95014
(408) 446-1319

July, 1987

Prepared for

US Nuclear Regulatory Commission
Washington, D.C.

ABSTRACT

This report presents the research and development work performed in Phase I of the SBIR project on improvement of safety of nuclear piping systems, subjected to dynamic loads, using nonlinear analysis methods. The current procedures and criteria were studied first and it was demonstrated that nonlinear analysis procedures are feasible. Preliminary development was then carried out of a simplified nonlinear analysis procedure. A strain criterion was also recommended based on available test results. Benchmark nonlinear analyses were then carried out using the simplified and detailed time history procedures on a piping system to be tested under ETEC test program. The purpose of these analyses was preliminary validation of the simplified nonlinear analysis method against detailed analysis results, and prediction of failure locations (and loads) for the test program for further validation of the simplified method against test results. Recommendations were then presented for research work in Phase II.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

SUMMARY

This report presents the research and development work performed in Phase I of the SBIR project on improvement of safety of nuclear piping systems, subjected to dynamic loads, using nonlinear analysis methods. With the use of nonlinear (inelastic) analysis methods, it can be shown that the piping systems have significant additional energy absorption capacity, and are thus (inherently) substantially safer than presently believed based on the linear elastic concepts.

The primary objective of these efforts was to study current procedures and criteria used for the analysis of piping systems, demonstrate that use of nonlinear analysis procedures is feasible, and carry out preliminary development of criteria and analytical techniques for nonlinear analysis so that they can be used by engineers on a routine basis in the nuclear industry. Since the major hurdles in the use of nonlinear analysis methods are that they are expensive to use, require specialized knowledge and expertise, and need strain-based acceptance criterion for their use, the major goals of these Phase I efforts were to perform a preliminary development of a realistic simplified nonlinear analysis method and to develop a strain-based criterion based on available test results.

The scope of work consisted of seven major tasks. In Task I, a review of recent work by HEDL (USNRC-sponsored) and Rockwell (EPRI-sponsored) on simplified nonlinear analysis methods, as well as methods available in other literature, was performed. Included were Inelastic Response Spectra methods, Dynamic/Static Margin Ratio methods, and Equivalent Static-g Limit (Static Progressive Limit) Analysis method. Task II consisted of a review of data from high-level ANCO component tests and the ETEC pipe fragility tests for incorporation into the strain criteria development. In Task III, it was demonstrated that the use of nonlinear analysis procedures can show significantly improved safety of nuclear piping systems based on past sample examples; and the feasibility, licensability, ease of use, and economics of nonlinear analysis procedures for application to piping systems were investigated.

Task IV consisted of development of strain-based criteria for use in conjunction with nonlinear analysis procedures, and their possible incorporation in ASME format. This consisted of development of an "equivalent" ductility factor including ratchetting behavior. In Task V, preliminary development was carried out of a simplified nonlinear analysis procedure for routine nonlinear analysis of piping systems, which is simple to use, while at the same time is able to predict adequate and reliable results (including failure predictions).

In Task VI, benchmark analyses were performed using a detailed time history (step-by-step) nonlinear dynamic analysis method, as well as the simplified nonlinear analysis method developed in Task V. The analyses were performed on a piping system to be tested on the ETEC test program under USNRC/EPRI sponsorship. The nonlinear analysis methods were used to predict dynamic response, failure locations and failure loads of this piping system, and to validate the simplified nonlinear analysis method. Finally, in Task VII, conclusions were presented and recommendations were developed for research and development efforts in Phase II.

As a result of the Phase I research and development efforts, presented in this report, the following conclusions were reached.

- On the basis of the review of the available literature, it was concluded that the currently available simplified nonlinear analysis methods have deficiencies and limitations and new simplified methods need to be developed which are not only simple to use but also provide adequate and realistic results.

- On the basis of the available test results, it was concluded that the primary mode of failure in piping systems is of a ratchetting type and that piping systems can withstand significantly higher strains than it is generally believed.

- It was concluded, on the basis of several past sample examples, that nonlinear analysis procedures can show significantly improved safety of piping systems, and that they are feasible and licensable and can be developed into easy to use and economical tools for routine application in the industry.

- It was concluded that current criteria are very conservative and more rational criteria (including strain and related criteria) need to be developed. Also, on the basis of test results, it was further concluded that a limiting strain criterion of 2% can be safely used for design purposes, in conjunction with nonlinear analysis.

- It was concluded, on the basis of development of a new simplified nonlinear analysis procedure and its application to sample problems, that the procedure was simple and cost effective and could predict realistic response and failures (including ratchetting failure), as well as displacements, accelerations and support forces, for a wide range of piping systems for seismic and other dynamic loads.

- On the basis of benchmark analysis using a detailed time history nonlinear analysis procedure, it was predicted that the first failure for the 6" pipe would most likely occur either at node 2 (close to the fixed end at Shaker Table #4) or at node 72 (close to the connection of the piping system to the pressure vessel at Shaker Table #1). For the 3" pipe, the failure would most likely occur at node 34 (at the connection to the 6" pipe on the north side). It was also predicted that the first failure load would be about 20g ZPA based on an assumed failure strain of 5%, and would occur at node 34 (in the 3" pipe at the connection to the 6" pipe). Similar failure locations were predicted using the simplified nonlinear analysis method, except that a higher failure load (on the order of 23g ZPA) was predicted.

Finally, the following recommendations were developed for Phase II research and development efforts:

- A more detailed development of strain criterion, including development of limiting strains for different base materials and welds, different components, different types of failure modes, the representation of these strain criteria in the form of easy to use formulas and tables, further validation using additional ETEC test results, and proposal of a code case for possible incorporation of these criteria into the ASME code.

- Further refinement and development of the simplified nonlinear (inelastic) analysis method including development of a technique for estimation of ratchetting cycles for calculation of ratchetting ductility factors, various different procedures for combination of modal responses, extension to include multiple support anchor movements, inclusion of combination of internal pressure and bending using a 'modified' strain yield criterion , inclusion of different types of damping (e.g., PVRC damping), and development of a computer program based on this simplified nonlinear analysis method.

- Extensive testing of the simplified nonlinear analysis method, in conjunction with strain criteria, for a range of problems, including snubber reduction.

- Comparison of ongoing ETEC test results on Piping Systems against analytical results based on detailed time history and simplified nonlinear methods for further validation of simplified method and strain criteria, as well as general analytical assistance to the test program.

- Development of a manual for the use of simplified nonlinear analysis method (and the computer program based on this method), in conjunction with strain criteria, and its use in the design of piping systems and supports using the ASME code.

1. INTRODUCTION

This report presents the research and development work performed in Phase I of the SBIR project on improvement of safety of nuclear piping systems, subjected to dynamic loads, using nonlinear analysis methods. The work was performed for United States Nuclear Regulatory Commission.

With the use of nonlinear (inelastic) analysis methods, it can be shown that the piping systems are (inherently) substantially safer than presently believed based on the linear elastic concepts, due to the utilization of the significant additional energy absorbtion capacity available in these systems. Thus, the probability of the loss of coolant accident due to possible failure of piping systems can be shown to be much lower than that calculated using linear elastic methods, providing a significant improvement in the confidence level associated with the safety of light water reactors.

Thus, the primary objective of these Phase I efforts was to study current procedures and criteria used for the analysis of piping systems, demonstrate that use of nonlinear analysis procedures is feasible, and carry out preliminary development of criteria and analytical techniques for nonlinear analysis so that they can be used by engineers on a routine basis in the nuclear industry.

The major hurdles in the use of nonlinear analysis methods on a routine basis for the analysis of piping systems and supports are the following:

- o they are expensive to use in their present form.
- o their use requires specialized knowledge and expertise in nonlinear mechanics.
- o they require strain-based acceptance criterion for their use, not currently available in the ASME code.

Thus, the major goals of the Phase I efforts were as follows:

- o to demonstrate the feasibility and effectiveness of nonlinear analysis methods in showing that nuclear piping systems are (inherently) significantly safer than presently believed.
- o to perform a preliminary development of a simplified nonlinear analysis method, including realistic failure criteria (e.g., failure by ratchetting).
- o to develop strain-based acceptance criteria for incorporation in the ASME code.

Available results of the ETEC tests, under a USNRC/EPRI sponsored research program, as well as available results from other major test programs, were used for the development of the strain criteria. Additional results from ETEC tests on piping systems will be available in the future, and will be used (in Phase II) for the further validation of the simplified nonlinear analysis procedure. Conversely, the results of nonlinear analyses (from simplified and detailed time history analyses) in Phase I may be used for the prediction of dynamic response and failures (potential failure locations and failure loads) in the ETEC tests. This can provide valuable assistance to this important test program.

2. TECHNICAL BACKGROUND, OBJECTIVE AND TASKS OF PHASE I

2.1 TECHNICAL BACKGROUND

The use of nonlinear analysis methods can help improve the safety of piping systems in the following different ways:

- o By demonstrating that the real forces in the piping systems are substantially lower than those predicted by linear methods currently used in the industry (see Figures 5-2 and 5-6).

- o By helping significantly reduce the number of snubbers on piping systems, and thus improving their safety. Recent studies have clearly shown that the reduction of snubbers on piping systems improves their safety, by making them more energy absorbent. Use of nonlinear analysis procedures can reduce snubbers by as much as 90% (See Table 3-2).

- o By helping to reduce the response of piping systems to some high frequency loadings (e.g., pressurized thermal shock, water hammer, SRV, Condensation Oscillation, Annulus Pressurization, and similar loadings), in addition to reducing the response to low to medium frequency loadings (e.g., seismic).

- By predicting the "real" nonlinear behavior of piping systems and thus demonstrating that the actual strains (or ductilities) are lower than the limiting strains(or ductilities).

There are, however, some major hurdles in the use of nonlinear analysis methods on a routine basis in the industry, as well as some other related issues, which need to be thoroughly studied. They include the following:

- The use of nonlinear procedures must be based on strain criteria. The current ASME code procedures are, however, based primarily on stress criteria. Thus, strain-based criteria need to be incorporated in the ASME code. Any changes in the criteria must also account for system flexibility and energy absorbing capacity of the piping system associated with nonlinear behavior under dynamic loads. Another important consideration in the development of the new strain-based criteria should be the failure mechanism. Recent ETEC tests, conducted under a USNRC/EPRI sponsored project, have shown that the controlling failure mechanism for dynamic loads may be of the fatigue-ratchetting type. Thus, a fatigue-ratchetting type of failure mode, along with other potential failure modes, must be considered in criteria development. Also, possible ASME code modification to reclassify dynamic loads (such as seismic) from the primary to the secondary should be considered.

- The currently available nonlinear analysis procedures are expensive to use, and can be used primarily by engineers especially trained in their use. It is therefore not easy to use nonlinear analysis procedures, as currently available, on a routine basis by piping engineers. Simplified methods are therefore needed.

- The nonlinear analysis procedures, both simplified and detailed, need to be extensively validated by test results (e.g., ETEC tests, conducted currently under a USNRC sponsored project). The use of nonlinear analysis procedures will also significantly help this major test project by predicting realistic failure locations and load levels at which these failures may occur.

- The application of nonlinear analysis procedures, both simplified and detailed, to a range of piping systems and loadings and to specific practical applications, e.g., snubber reductions, needs to be demonstrated. Thus, several analytical sample examples, with varying parameters of critical importance to the piping response and potential failures, need to be solved (in Phase II) using simplified as well as detailed (time history) nonlinear analyses.

2.2 OBJECTIVE AND TASKS OF PHASE I

The objective of the subject Phase I efforts has therefore been to initiate preliminary studies in the above areas so that nonlinear analysis procedures can be accepted as feasible, effective and licensable, and can be used (as a result of Phase I and II efforts) on a routine basis (in a cost effective manner) by piping engineers, based on modified ASME code criteria incorporating strain limits.

Significant progress has been made in Phase I work reported herein in achieving the above objective. This has consisted of a detailed review of literature and available test results; investigation of the feasibility, licensability, ease of use and economics of nonlinear analysis procedures; preliminary investigation of strain-based criteria; preliminary development of a simplified nonlinear analysis method; and benchmark analyses on a piping system to be tested as part of ETEC tests under a USNRC sponsored program.

Specifically, Phase I consisted of the following tasks.

Task I. Review And Critique of Recent Work by HEDL (NRC-sponsored) and Rockwell (EPRI - sponsored) on Simplified Nonlinear Analysis Methods.

Task II. Review And Incorporation of Data From High-Level ANCO Component Tests And The ETEC Pipe Fragility Tests.

Task III. Demonstration that the use of nonlinear analysis procedures can show significantly improved safety of nuclear piping systems. Investigation of the feasibility, licensability, ease of use, and economics of nonlinear procedures for analysis of piping systems and supports.

Task IV. Investigation of development of strain-based criteria, for use in conjunction with nonlinear analysis procedures, which can be validated by available test results, and their possible incorporation in ASME format.

Task V. Investigation of the development of a simplified nonlinear analysis procedure for routine nonlinear analysis of piping systems, after review of existing simplified methods, and initiation of preliminary development of such a method to ensure its feasibility, applicability, licensability, and cost effectiveness (so that, in Phase II, the further detailed development of this method and an accompanying computer program, with application to numerous piping examples, including snubber reduction, can be completed).

Task VI. Performance of benchmark analyses on a typical piping example, considering variation of critical parameters, in conjunction with strain criteria.

Task VII. Development of conclusions and recommendations, including preliminary suggestions for ASME code revisions for strain criteria, considering proposal of a code case, as well as recommendations for a detailed scope of work for Phase II.

These tasks are described in the following chapters.

3. TASK I - REVIEW AND CRITIQUE OF RECENT WORK BY HEDL AND ROCKEWLL ON SIMPLIFIED NONLINEAR ANALYSIS METHODS

This task consisted of a review of reports on recent NRC sponsored work by HEDL (Ref. 1) and EPRI sponsored work by Rockwell (Ref. 2) on simplified nonlinear analysis methods. The following is a discussion of the methods used in these reports and our comments on these methods.

3.1 HEDL WORK (REF. 1)

The following simplified methods were considered in the HEDL work.

1. A standard ASME Class 2 method.
2. The Newmark inelastic response spectra (IRS) method (Ref. 3).
3. The dynamic/static margin ratio method (Ref. 4).
4. A static progressive hinge limit analysis method (Ref. 5).
5. A nonlinear transient dynamic inelastic analysis method.

Following is a brief discussion of these methods.

The standard ASME Class 2 method was based on conventional linear elastic analysis methods utilizing modal supersposition procedure in conjunction with a response spectrum approach. The piping stresses so computed were compared against ASME allowable limits which are very conservative.

The Newmark inelastic response spectrum (IRS) method was based on the development and use of elastic-plastic response spectra from given linear elastic spectra by using criteria based on system ductility ratios. Different reduction factors were used in the amplified spectral acceleration, velocity and displacement regions. Conventional linear elastic analyses were then used, and the piping stresses so computed were compared against allowable values related to material yield stress. Failure was supposed to occur at a location when a plastic hinge formed, i.e. the piping section became fully plastified. The system was supposed to fail when a complete mechanism formed causing instability.

The dynamic/static (D/S) margin ratio method was based on the modification of the linear elastic dynamic analysis results by a dynamic/static (D/S) margin factor. This factor is a measure of conservatism inherent in designing piping systems and components subjected to dynamic loads based on static criteria. The dynamic margin is defined as dynamic load to cause failure divided by the dynamic load that results in a predicted elastic response equal to a specified stress acceptance criterion. The static margin is similarly defined as the static failure load divided by the static load that results in a predicted elastic response equal to a specified stress acceptance criterion. D/S factor so computed is a function of the frequency content and the duration of the load, frequency of the structure, as well as the system ductility of the piping system.

The static progressive hinge method was based on an assessment which utilizes the equivalent static loading combined with material yielding and plastic hinge formation at specific locations. The method consists of a series of static analyses. After each static analysis, the piping model is modified by inserting a rusty hinge at the location of the plastic hinge developed in the analysis. The procedure is repeated until a collapse mechanism (static instability) is resulted which provides the load carrying capacity of the piping system.

The nonlinear inelastic transient dynamic inelastic analysis method utilized a standard computer program for such analysis based on a step-by-step time history analysis utilizing direct integration technique. Material nonlinearities were included; damping was modeled using Rayleigh damping (mass and stiffness proportional damping).

The above simplified (as well as detailed) nonlinear analysis methods were used to predict pre-test failures of the NRC/ETEC piping fragility demonstration tests. It was found that all the simplified methods underestimated the ability of the piping system to withstand high level seismic loads without collapse. The Newmark and D/S ratio methods indicated collapse at about 10 g's. The static progressive hinge method predicted collapse at about 8 or 16 g's depending on use of a dynamic magnification factor of 2 or 1, respectively. The test actually withstood 25 g's without collapse. The detailed transient dynamic analysis method predicted no collapse load up to 20 g's.

The failure of ETEC demonstration piping system involved a ratchetting type of failure involving bulging of the pipe and resulting in local cracking and section rupture near pipe leg support.

3.2 ROCKWELL WORK

The following simplified methods were considered in the Rockwell work.

1. Inelastic response spectrum (IRS) methods (Refs. 6, 7, 8, 9, 10, 11, 12, 13, 14).
2. The equivalent static-g limit analysis method (Ref. 15).
3. The equivalent resistance method (Refs. 15, 16).
4. The modified modal method (Ref. 17).
5. The energy balance method (Ref. 18).

Following is a brief description of these methods.

The inelastic response spectrum (IRS) method was discussed previously for the HEDL work (Newmark method). Seven different versions of IRS approaches were considered in the Rockwell report. They included the IRS from basic principles (generation from a given time history), Newmark approach (discussed previously for

HEDL work), Newmark-Hall approach (very similar to Newmark approach except it utilizes different frequency ranges for reduction from elastic to inelastic spectra), Riddle-Newmark approach (based on use of statistically best agreement between predicted spectral accelerations obtained from inelastic time history and Riddle-Newmark approach, using ten ground motions), substitute-structure method primarily developed for reinforced concrete structures utilizing adjusted structural frequencies and dampings based on structural degradation, Iwan's approach based on use of statistical best agreement between predicted spectral accelerations using six different models, ATC-3 approach utilizing simplified modal analysis, SMA/WCC approach based on good agreement between predicted spectral accelerations from inelastic time history and SMA/WCC approach using 12 different ground motions, Zahrah-Hall method based on a statistical study of energy input of eight different ground motion time histories and response computations for two SDOF systems, and the general shifting approach based on nine separate methods utilizing equivalent elastic methods for simple hysteretic structures applicable primarily to building type structures.

The equivalent static-g analysis method consisted essentially of a combination of equivalent static-g analysis with limit analysis and was described previously for the HEDL work as the static progressive hinge limit analysis method.

The equivalent resistance method was based on an iterative analysis approach utilizing a modal superposition technique and assumed that the total inelastic response could be obtained by summing modal responses using a modified structural model which was basically a pseudo elastic model (where the elastic stiffness and damping values for those elements that would have yielded in the previous linear elastic analysis were replaced with effective equivalent inelastic stiffness and damping values.) At the end of each iterative analysis, the predicted ductility in each element was compared to the assumed ductility until a good agreement was obtained.

The modified modal method was developed for multi-degree-of-freedom structural systems consisting of members with bilinear hysteresis, and utilized an iterative technique in which the original elastic system was continuously modified to reflect yielding in the system. The iterative procedure was stopped when a preset convergence criterion on the maximum element ductilities was met.

The energy balance method was composed of two distinct steps. First, the method performs a functionality check of the piping system by comparing the maximum earthquake energy imported into the piping system to the maximum strain energy available in the piping system. If the available earthquake energy can be absorbed by the piping system in the form of strain energy, then the piping system is assumed to have passed the functionality check.

3.3 COMMENTS BASED ON THE REVIEW OF HEDL AND ROCKEWLL REPORTS

3.3.1 HEDL Report

Out of all the analysis procedures used by HEDL, the first one, namely, the ASME Class 2 procedure, is the most conservative procedure since linear elastic response spectrum analyses are performed and the piping stresses so obtained are compared against ASME allowable limits which are significantly lower than failure conditions to assure safety. Furthermore, the redistribution of forces due to inelastic behavior, frequency shifts into possible lower acceleration regions, energy absorption and the associated hysteretic behavior due to inelasticity are not taken into consideration. Such a linear elastic procedure however forms a standard base line, being the most widely used current procedure, against which nonlinear analysis procedures can be compared.

The nonlinear inelastic transient dynamic analysis procedure used by HEDL is a detailed step-by-step time history analysis procedure which includes material nonlinearities (as well as geometric nonlinearities, when present). This procedure can provide a good indication of the actual inelastic behavior as well as failure based on plastic collapse mechanism. Ratchetting type of failure is usually not predicted by such a method directly. However, such a detailed dynamic nonlinear analysis procedure can be very expensive to use on a routine basis, especially for large piping systems and supports. It is especially costly to use for high frequency dynamic loads requiring very small time steps with a very large number of total time steps, in particular if significant incursions into nonlinear range are expected. Furthermore, specialized expertise is required for such nonlinear analyses in modeling, analyses, and interpretation of results. Such expertise is usually not present at most companies.

The simplified inelastic procedures used in the HEDL work included the Newmark's inelastic response spectrum procedure, Dynamic/Static (D/S) margin ratio procedure, and the static progressive hinge procedure.

The Newmark's inelastic response spectrum method (and numerous variations thereof), as well as D/S methods, utilize a system ductility concept which provides a measure of the inelastic behavior of the overall system which may be significantly different from the local inelastic behavior of individual spans of piping system at critical locations where failures can (and do) occur. Thus, inability of these methods to consider local nonlinear (inelastic) behavior is a serious drawback in their use for predicting failures, and especially local ratchetting type of failures, of piping systems. Most of these methods also do not properly consider the change in the flexibility of the piping system due to inelastic behavior and it's interaction with dynamic loadings.

Furthermore, the D/S methods require not only detailed knowledge of the ground motions but also use of certain structural parameters which need to be calculated by performing detailed nonlinear dynamic analyses for different types of systems and earthquakes.

Furthermore, the inelastic response spectrum methods and D/S methods, as postulated in the work reviewed, are normally unable to adequately predict displacements, boundary forces, and accelerations for use as design parameters for interfacing supports, valves, nozzles, etc.

The static progressive hinge method, considered in the reviewed work, is approximate since it is not applicable to dynamic loads which are either very cyclic or have a broad range of frequency content. Furthermore, this method can not adequately take into consideration frequency shifts due to inelastic behavior or energy dissipation associated with inelastic behavior. For situations where significant inelastic incursions are expected, in conjunctions with numerous loadings and unloadings of plastic zones, this method may not predict realistic inelastic dynamic response. Also, this method may not be able to predict ratchetting types of failures which depend on cyclic dynamic behavior superimposed over static equilibrium condition.

3.3.2 ROCKWELL WORK

Of all the analysis procedures considered by Rockwell, the inelastic response spectrum method and the equivalent static-g limit analysis method (same as static progressive hinge limit analysis method considered by HEDL) have already been discussed previously in discussion of HEDL work. Rockwell, however, considered various different versions of the inelastic response spectrum methods. Most of these versions are either not directly applicable to piping systems or require tedious statistical correlations, e.g., Riddle-Newmark, Substitute-Structure, Iwan, Zahrah-Hall and General Shifting Methods. The practical and applicable (to piping systems) inelastic response spectrum methods considered by Rockwell are the Newmark, Newmark-Hall, and SMA/WCC methods. The Newmark-Hall method is a slightly modified version of the standard Newmark method where certain corner point frequencies are fixed a priori and a modified frequency range is considered. The SMA/WCC method considers entering linear elastic response spectra with modified frequency and damping to develop inelastic response spectra and is a good simplified procedure, but is based on a certain knowledge of the ground motions (12 ground motions were used in the SMA/WCC work).

The other simplified methods considered by Rockwell were the equavalent resistance method, modified modal method, and energy balance method. The equivalent resistance and modified modal methods utilize modal superposition procedures based on an iterative technique. In the equivalent resistance method, effective inelastic stiffness and damping values (being functions of original stiffness, damping, and ductility) are estimated in the beginning and predicted ductility is compared against assumed ductility at each iterative step (linear elastic analysis) until convergence is obtained. In the modified modal method, the system is modified at each iterative step to reflect inelastic behavior using assumed and predicted ductility ratios until convergence is obtained. These procedures require a series of linear elastic analyses and computer software development and may not predict adequate results for significantly nonuniform structures. The Energy Balance method is impractical for piping systems, since it requires testing for determination of seismic-based strain deformation factors.

4. TASK II - REVIEW AND INCORPORATION OF DATA FROM HIGH-LEVEL ETEC PIPE FRAGILITY TESTS AND GE/EPRI COMPONENT TESTS

The recent (available) data from high-level ETEC pipe fragility tests and GE/EPRI tests were reviewed for incorporation of data obtained from these tests in the development of strain criteria and simplified nonlinear analysis methods. These results are discussed below.

4.1 ETEC SEISMIC FRAGILITY TESTS ON 6-IN. DIAMETER PIPES (REF. 19)

The objective of these tests was to investigate the ability of representative piping systems to withstand high level dynamic siesmic and other loadings by testing a representative 6-in diameter nuclear piping system; characterizing the high level dynamic response; identifying failure modes; and providing a benchmark test for quantifying conservatisms in ASME code criteria, several nonlinear analysis methods and probabilistic risk assessment methods.

The piping systems tested included 48 ft. of 6-in. diameter and 17 ft. of 3-in. diameter carbon steel piping systems and components and a valve assembly. Instrumentation included 6 accelerometers, 30 strain gages at 18 locations and 1 pressure transducer. The piping systems were to be internally pressurized at 1000 psi and were to be subjected to three levels of dynamic tests, namely, 5g, 14g and 25g nominal ZPA. Three sine burst tests were also to be performed following seismic testing, if failure did not occur, using 4 Hz. (8 cycles of ± 7 in. max. displacement), and 5 Hz. (11 cycles of ± 5 in. max. displacement) sine bursts.

It was found that actual rupture of the piping system did not occur during seismic testing. However, a 2-in. wide circumferential bulge, indicative of ratchetting, was observed as a result of 30g ZPA seismic test in a vertical leg of the system. Subsequently, actual rupture occurred during second sine burst test (5 Hz. sine burst) in the form of a circumferential break in the bulge. The circumferential and radial residual strains at the failure locations were 9.2% and 12%, respectively.

Based on the maximum zero period acceleration (ZPA) of 30g observed during the high level seismic tests, lower bounds on the factor against actual failure of at least 15 or higher were obtained for allowable g loadings based on ASME code criteria; at least 3 or higher for one or more nonlinear analyses performed by HEDL; and at least 1.9 and 1.2 (or higher) for failure analyses performed by ETEC and AI (Atomics International), respectively. Factors of 3 or higher were obtained for the probabilistic risk assessment analyses performed by HEDL.

4.2 GE/EPRI DYNAMIC RELIABILITY PROGRAM TESTS (REF. 20)

The objectives of this test program are to demonstrate that piping systems can tolerate dynamic loads well in excess of present code limits, demonstrate that the behavior of short dynamic loads has the effect of being more like secondary than primary, determine loading conditions and calculational procedures for fatigue ratchetting behavior, show that damping present in piping systems is greater than currently permitted by codes, propose ASME code revisions to realistically account for dynamic loads, and propose methods to assess fatigue damage under ratchet conditions.

Three 6-in. carbon steel elbows, two Schedule 80 and one Schedule 40, were tested on ANCO test sled. Simulated seismic inertia loading was applied to two of the elbows loaded in-plane and to one of the elbows loaded out-of-plane. Five time history inputs, each of about 20 seconds duration with a peak shake table acceleration of about 18 g's, were planned for each component. It was found that the Schedule 80 component did not collapse or develop a through-wall crack during testing. The Schedule 40 component did develop a through-wall crack after 2 1/2 input excitations. Piping system tests will be performed next.

4.3 COMMENTS ON THE ETEC AND GE/EPRI TEST RESULTS

Comments are presented herein on ETEC and GE/EPRI test results.

4.3.1 ETEC Tests

As discussed above, in the ETEC seismic fragility tests, the failure of the piping system did not occur during seismic testing; but, subsequently, ratchetting type of failure occurred during the sine burst tests. Most of the inelastic analytical procedures (whether simplified or detailed) predict plastic collapse type of failures (and not ratchetting type of failures). Thus, the tests demonstrated that ratchetting type of failures should also be incorporated into the current inelastic analysis procedures. This can be done by considering plastic strains indicative of the ratchetting phenomena. These strains can then be compared against criteria strain developed on the basis of ETEC and other similar tests to predict ratchetting type of failure, in addition to plastic collapse type (and other types) of failure.

The ETEC tests indicated circumferential and radial residual strains at the failure locations of 9.2% and 12%, respectively. These strain results, in combination with similar future test results, can be readily incorporated in the development of strain criteria, which can ultimately be made part of the ASME code.

It was interesting to note that failure did not occur in any of the locations of high stresses considered to be critical in accordance with the ASME code procedure. This indicates that current ASME code procedure, based on conservative linear elastic techniques, is inadequate for prediction of failures, and nonlinear (inelastic) procedures are required for prediction of failures. Furthermore, major parameters used in conjunction with nonlinear analyses need to be thoroughly examined for conservatism, e.g., damping, ductility, rate of strain hardening, and failure criteria.

It was also interesting to note that all analytical procedures underpredicted failures (ASME code by a factor of 15 and higher, nonlinear analyses by HEDL by a factor of 3 and higher, and ETEC by factors of 1.9 and higher). Thus, it is clear that piping systems are significantly more resistant to dynamic loads than predicted by analytical procedures. This also indicates that not only the nonlinear inelastic analytical procedures need to be used more often, but major parameters used in conjunction with these analyses need to be examined for conservatism. In addition, modeling techniques need to be reviewed for conservatism and modified accordingly.

4.3.2 GE/EPRI Tests

The GE/EPRI test program is quite impressive, with important objectives. The component tests have been performed. The tests showed that the failure modes were of the fatigue rachet type, and the inherent strengths of the components were significantly higher than expected (a factor of 15 and higher). It was also interesting to note that the damping was measured to be about 34%, much higher than RG 1.61 damping, and significantly higher han used in any current analytical procedures. Thus, as discussed before, damping is a very significant parameter that must be examined in detail in the development of analysis procedures. The % cyclic strain varied from 1.5 to 2.0%. This and similar future data can be extremely useful in the development of criteria which could ultimately be incorporated in ASME.

Thus, the GE/EPRI test results indicated a trend similar to that indicated by ETEC tests. The results of these and future tests can be incorporated in the development of realistic simplified inelastic analysis procedures, in conjunction with strain criteria (which can, in future, form the acceptance criteria for comparison of inelastic analysis results and can become a significant feature of the ASME code).

5. TASK III - DEMONSTRATION THAT USE OF NONLINEAR (INELASTIC) ANALYSIS PROCEDURES CAN SHOW SIGNIFICANTLY IMPROVED SAFETY OF NUCLEAR PIPING SYSTEMS

This task consisted of demonstration that use of nonlinear (inelastic) analysis procedures can show significantly improved safety of nuclear piping systems. It also consisted of investigation of the feasibility, licensability, ease of use, and economics of nonlinear (inelastic) procedures for analysis of piping systems, and for snubber reduction.

5.1 SAMPLE EXAMPLES

To demonstrate that the use of nonlinear (inelastic) analysis procedures can show significantly improved safety of operating plants (and can significantly improve safety of plants under construction and future plants), three sets of nonlinear (inelastic) analyses (from past projects, performed by the Principal Investigator) were used as sample examples, two analyses performed on mainframe computers, and one analysis performed very recently on a microcomputer. These are described below:

1. Nonlinear Inelastic Analysis of A Piping System (Piping System No. 1)

   Figure 5-1 shows the piping system No. 1 for which these analyses were performed (on a past project); table 5-1 shows the pipe rupture loading which was applied at nodal point number 5 of the piping system. Figure 5-2 shows the variation of restraint force with time for nonlinear (inelastic) and linear (elastic) cases.

As the results indicate, the maximum nonlinear (inelastic) restraint force was found to be about 45% lower than maximum linear (elastic) force. Thus, it is clear that it can be shown using nonlinear (inelastic) analyses that the <u>real</u> forces in piping systems and supports are significantly lower that those calculated by conventional linear elastic analysis procedures. Thus, the safety of the piping systems (and the resulting safety of the plants) can be shown to be significantly higher using nonlinear (inelastic) analysis procedures.

2. <u>Snubber Reduction Analysis of A Piping System (Piping system No. 2)</u>

   Figure 5-3 shows the piping system No. 2 for which the analyses were performed (on a past project). An artificial earthquake time history matching USNRC type spectrum was use for analyses. Table 5-2 shows the results of snubber reduction based on the nonlinear analyses, compared against snubber reduction based on linear analyses.

As Table 5-2 shows, if the analyses are based on nonlinear (inelastic) analysis procedures, the snubbers can be practically completely eliminated, thus significantly improving the safety of piping systems. This is primarily because piping systems designed to have more flexibility with few or no snubbers usually have higher energy absorbing capabilities to accommodate existing loads as well as dynamic loads, especially if nonlinear (inelastic) behavior of the piping systems is taken into consideration. The use of fewer or no snubbers can also help in improving the operations of the nuclear power plants since snubbers interface with regular maintenance activities, interface with in-service inspection, require periodic inspection themselves, cause unnecessary occupational exposure, and failures and delays result in loss of plant availabilities.

3. Nonlinear (inelastic) Analysis of A Piping System (Piping System No. 3)

Figure 5-4 shows the piping system No. 3 for which the analyses were preformed (on a past project using a main-frame computer; and very recently, using an IBM-PC/AT); figure 5-5 shows the pipe rupture loading which was applied at nodal point no. 188 of the piping system. Figure 5-6 shows the variation of maximum bending moment with time for nonlinear (inelastic) and linear (elastic) cases.

As the results indicate, the nonlinear (inelastic) bending moment is lower than linear (elastic) bending by almost 60%. Thus, this example also shows that if nonlinear (inelastic) analyses are used, the real forces in piping systems are significantly lower than those calculated by conventional linear elastic analysis procedures. Thus, the safety of piping systems (and the resulting safety of the plants) can be shown to be significantly higher using nonlinear (inelastic) analysis procedures.

5.2 GENERAL COMMENTS

Based on the results of analyses presented above, the feasibility, licensability, ease of use, and economics of nonlinear (inelastic) procedures for analysis of piping systems, and for snubber reduction, are discussed below.

Feasibility

It is clear from the results of sample analyses presented above that the use of nonlinear (inelastic) analysis procedures for the improvement of the safety of piping systems is definitely feasible. The use of nonlinear (inelastic) analyses clearly showed that the real applied forces and moments in the piping systems, as well as the support forces, were found to be substantially lower than those predicted by conventional linear elastic methods.

It is also clear, based on the results of sample example no. 2 for seismic loading, that use of nonlinear (inelastic) analysis procedures can help substantially reduce the snubbers on piping systems, and thus significantly improve their safety.

In addition, the above results also indicate that the use of nonlinear (inelastic) analysis procedures also helps in reducing the dynamic response of piping systems for high frequency impulsive types of loadings.

Thus, it can be concluded that the use of nonlinear (inelastic) analysis procedures for improvement of safety of nuclear power plants (both operating and under construction) is definitely feasible.

Licensability

One of the major issues in the use of nonlinear (inelastic) analysis procedures for piping systems and supports in the nuclear industry is their licensability for routine use. One of the major tasks of this research and development effort (Phases I and II) is to develop sufficient justification for the use of these procedures on a routine basis. One of the current main hurdles in the licensability of these procedures is the fact that use of nonlinear (inelastic) analysis procedures has to be based on a strain criterion. The current procedures (e.g. ASME procedures) are based on a stress criterion (although stresses can be converted into "equivalent" strains, but this is approximate).

A strain criterion is being developed in this research and development effort, to be validated by ongoing ETEC tests, which could be incorporated (in Phase II) into the ASME code format. Other recommedations will also be developed for changes to the ASME code requirements (a code case may be proposed). This is discussed further in Chapter 6.

The other hurdle in the licensability of the nonlinear (inelastic) analysis procedures and their use on a routine basis is the fact that use of such procedures requires detailed and complex analytical procedures (based on a time history approach) and specialized computer programs. Appropriate application of these procedures (and programs) and determination of reliable response requires specialized knowldege and advanced training. Use of these procedures, in their present form, by inexperienced personnel is undesirable. These procedures are also very expensive to use (both computer costs and labor costs are high). The solution to this problem is discussed below.

Ease of Use and Economics

To solve the problem that specialized knowledge and advanced training are required in the use of nonlinear (inelastic) analysis precedures in their present form, and to significantly improve their cost effectiveness, simplified nonlinear (inelastic) analysis methods are being developed on this project which can be used very easily and inexpensively, for preliminary design purposes, on a routine basis by engineers without specialized knowledge and advanced training. This is discussed further in Chapter 7.

In addition, as a separate in-house effort, the detailed and sophisticated nonlinear time history analysis procedures have been incorporated for use on microcomputers. The program NPIPE, developed by Structural Analysis Technologies, Inc. for nonlinear (inelastic) analysis of three-dimensional piping systems, can be used on an IBM-PC/AT. In fact, as mentioned previously, the sample example for Piping System No. 3 was solved on an IBM-PC/AT with great success, and without loss of accuracy. Thus, in future, as this tool is made available to the nuclear industry, it will be possible for engineers to perform even detailed time history nonlinear (inelastic) analysis, for final design purposes, inexpensively on microcomputers.

Table 5-1. Dynamic Load Used for Analysis of Piping System No. 1

Time (sec.)	Load (Lbs.)
0.0	0.0
0.0001	373,300
0.002	68,000
0.016	74,000
0.0161	100,000
0.20	100,000

Table 5-2. Summary of Results of Seismic Snubber Reduction for Piping System No. 2

		Snubber* Reduction
Current Standard Procedure -	Envelope Spectrum Peak Broadening RG 1.61 Damping	0%
Linear Response Specturm Approach (Reduced Conservatism) -	Multiple Input Response Spectrum Peak Shifting PVRC Damping	50%
Nonlinear Time History Approach -	Multiple Input Time History Material/Geometric Nonlinearity Realistic Damping Failure Strain Assumed 5%	90%

* Not Including Replacement of Snubbers with Rigid Supports

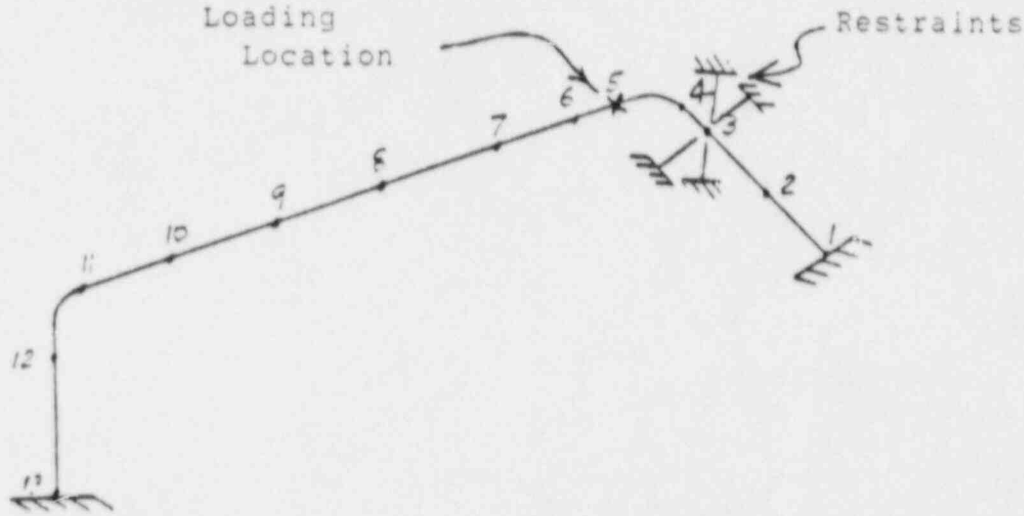


Figure 5-1. Isometric View of Piping System No. 1

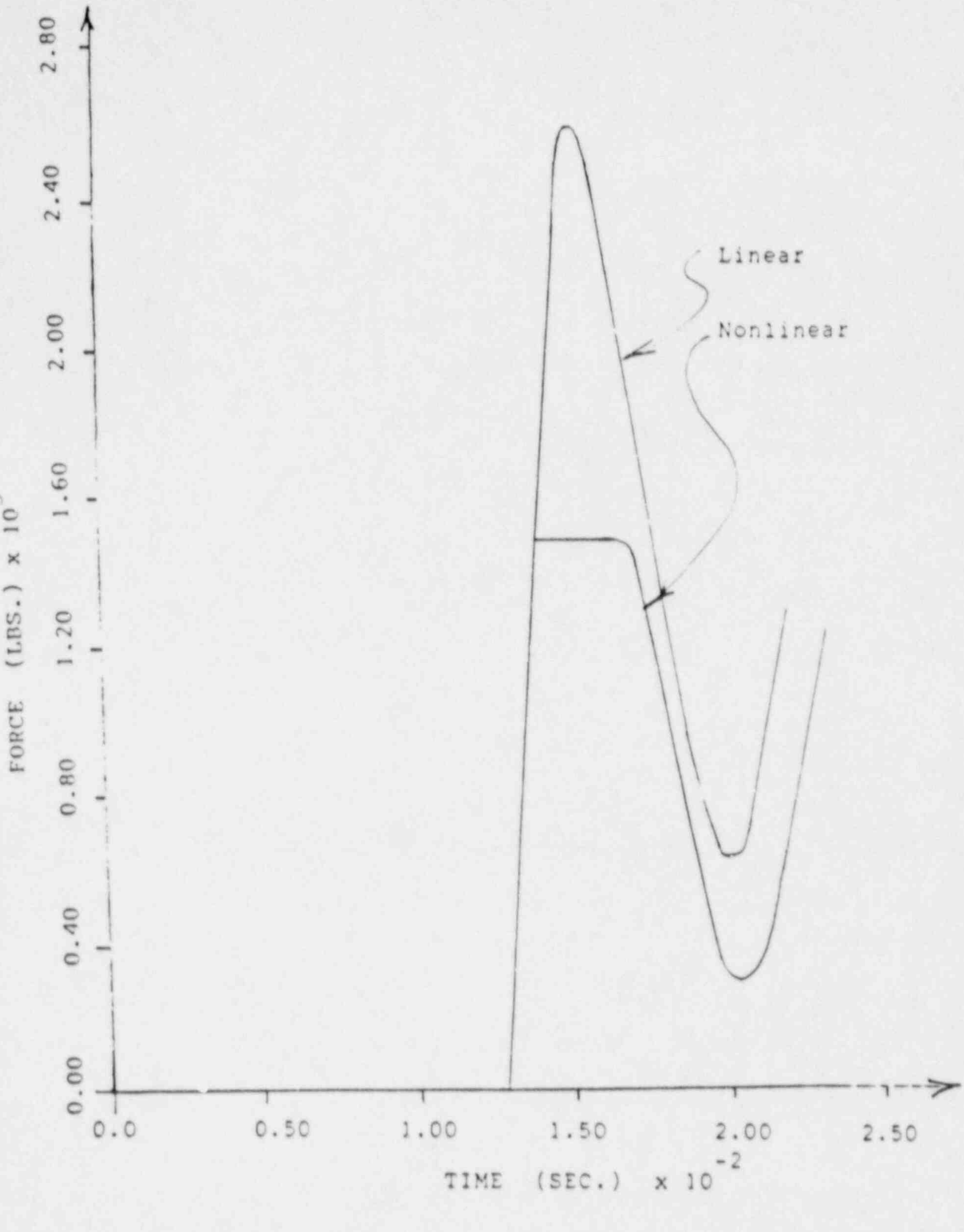


Figure 5-2. Variation of Pipe Support Force for Piping System No. 1 With Time, Based on Nonlinear (inelastic) and Linear (elastic) Procedures

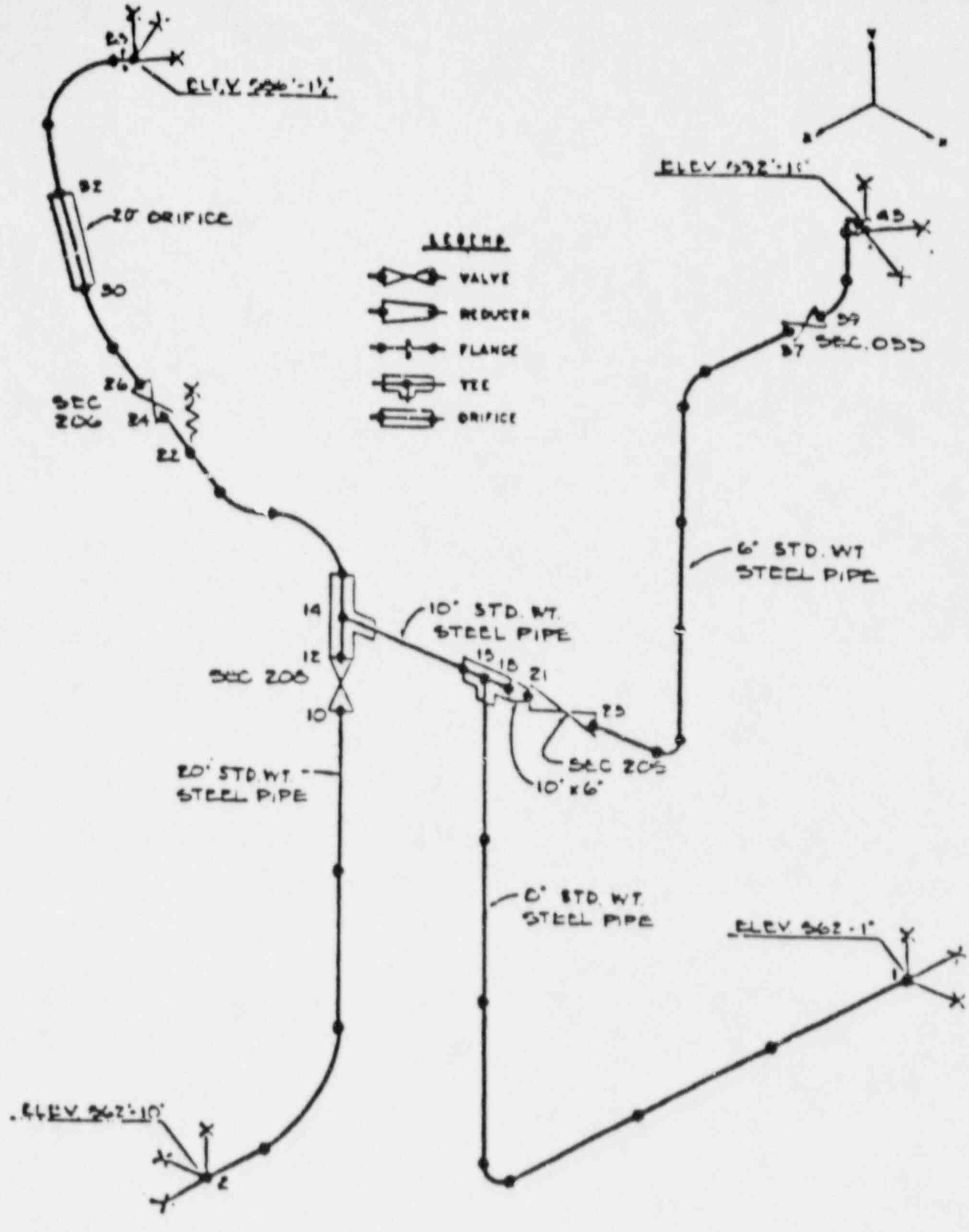


Figure 5-3. Isometric View of Piping System No. 2

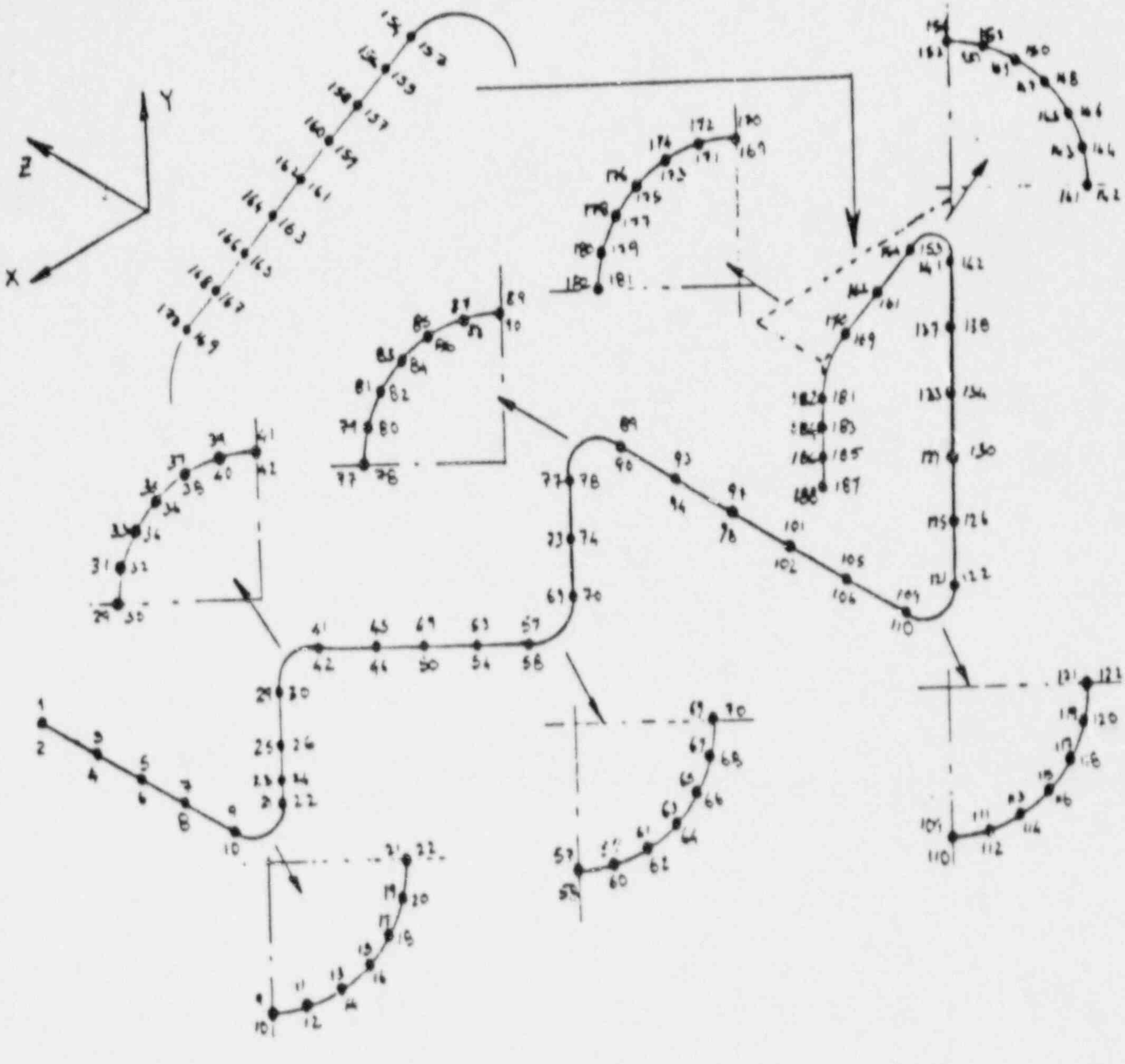


Figure 5-4. Isometric View of Piping System No. 3

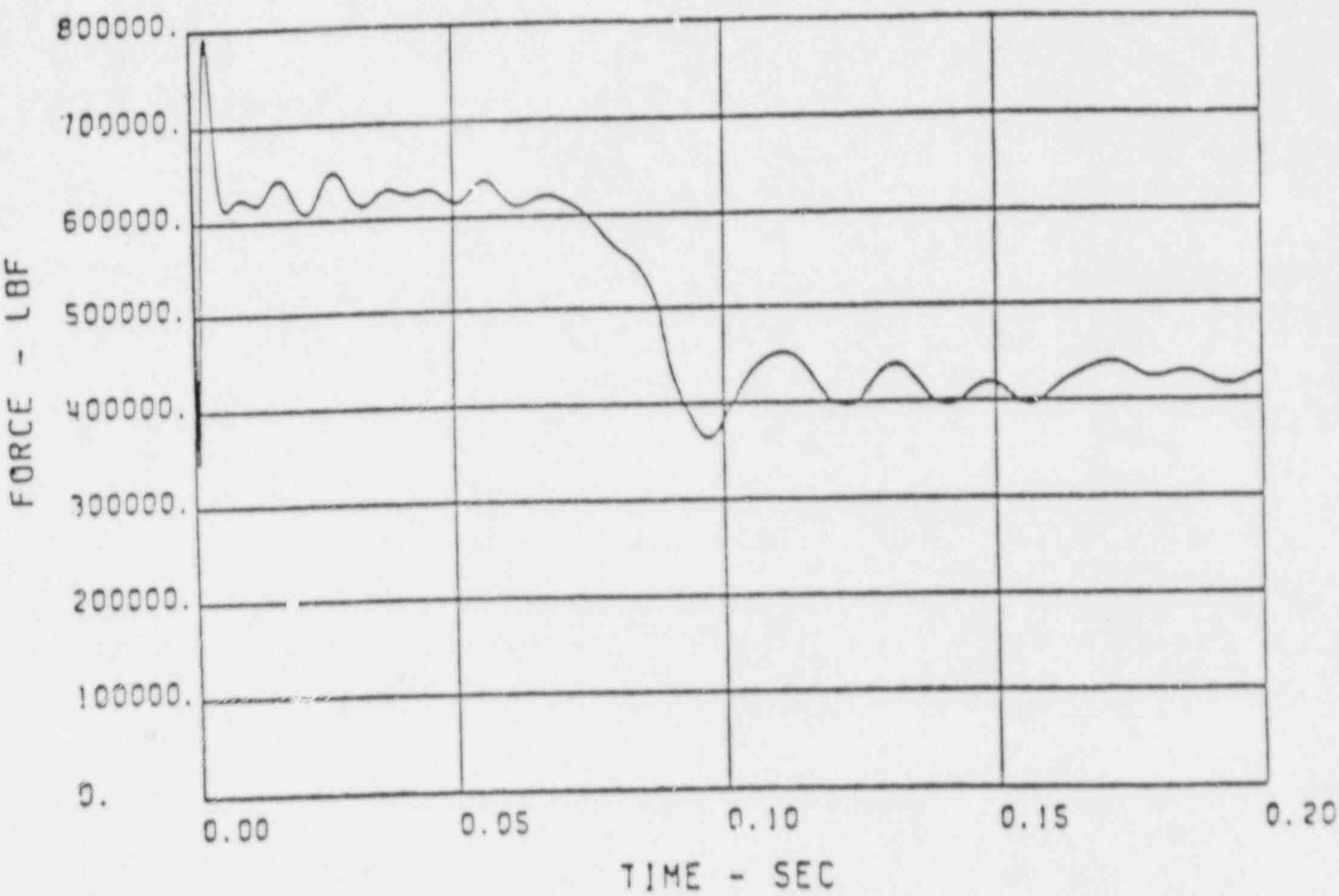


Figure 5-5. Dynamic Loading Used for Analysis of Piping System No. 3

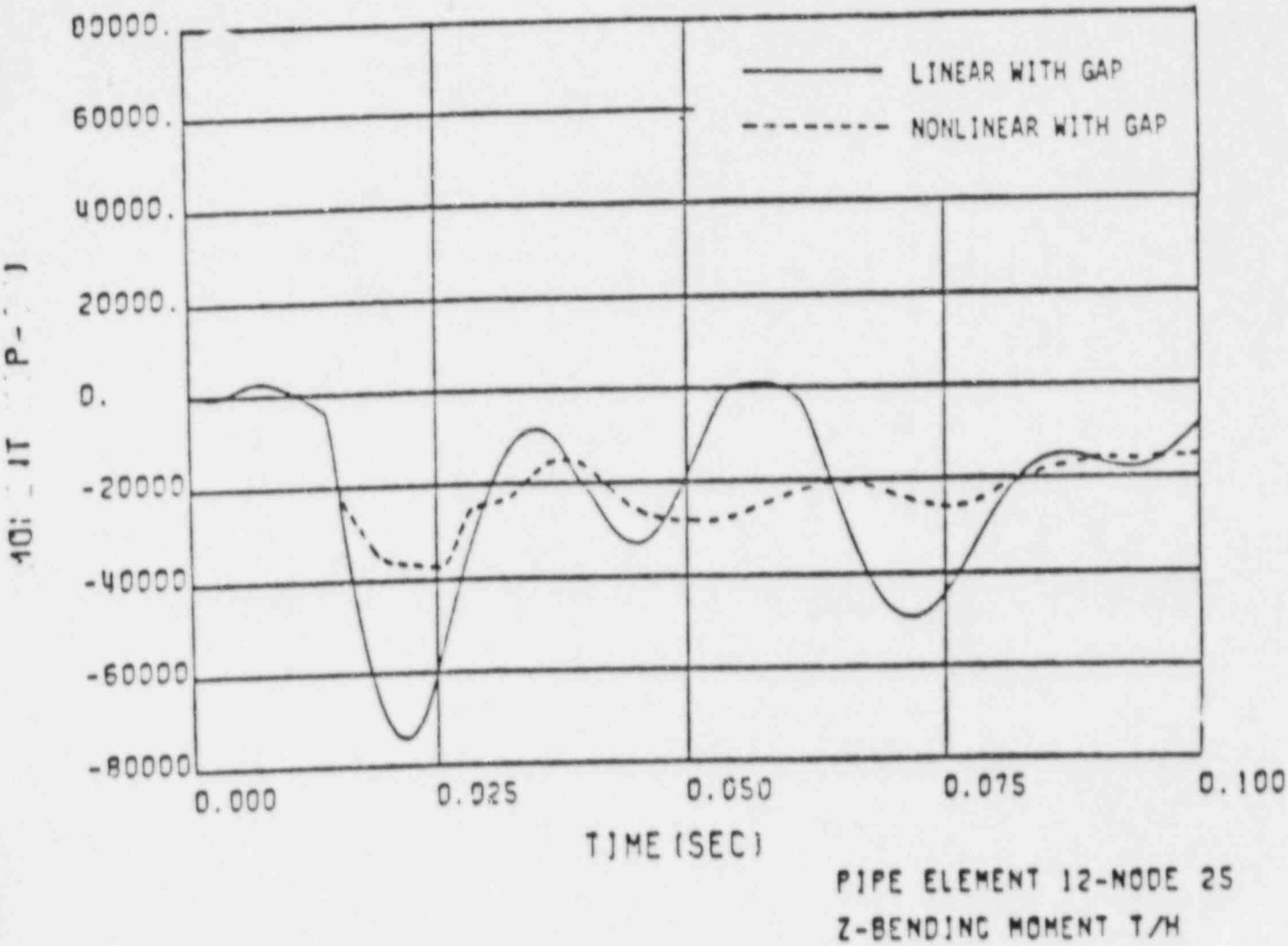


Figure 5-6. Variation of Maximum Bending Moment in the Piping Systems No. 3 With Time, Based on Nonlinear (inelastic) and Linear (elastic) Procedures

6. TASK IV - INVESTIGATION OF DEVELOPMENT OF STRAIN-BASED CRITERIA FOR USE IN CONJUNCTION WITH NONLINEAR ANALYSIS PROCEDURES

This task consisted of development of strain-based criteria for use in conjunction with nonlinear (inelastic) procedures, which can be validated by available test results, and their possible incorporation in ASME format. Failure mechanisms, including ratchetting, were considered.

A comprehensive literature survey was performed on available results of tests in U.S., Germany and other countries. This included ETEC tests (USA), MPA tests (West Germany) and others. A detailed list of references on these tests is enclosed at the end of this report, along with other references.

It was quite clear, based on the review of the available test results, that the current procedures for the design of piping systems, based on the ASME code, are very conservative. It was also clear that more rational design criteria for nuclear piping systems need to be developed, especially if nonlinear (inelastic) analysis procedures are to be used on a routine basis for piping analysis and design. This will result in improved safety of piping systems by utilizing their significant energy absorbing capacity. As discussed previously, one of the major problems in the use of nonlinear procedures is the fact that the current ASME criteria are based primarily on stress. Strain or deformation based criteria are needed if nonlinear (inelastic) analysis procedures are to be used on a routine basis in the nuclear industry.

Based on a comprehensive review of the available test results in this task, it is clear that piping systems can withstand significantly higher strains before failure than it is generally believed. Table 6-1 shows a summary of strains from available test results on piping systems. (Tentative results of tests in progress are not included). As the table shows, the lowest maximum strain at failure was about 5%. Considering the uncertainties in material properties and the behavior of piping systems to dynamic loads, as well as potential defects in piping materials, a safety factor of 2.5 may be used. <u>Thus, it is recommended that, for design purposes, a strain criterion of 2% be used, in conjunction with nonlinear (inelastic) analysis procedures, i.e. the "maximum strain" in a given direction must not be allowed to exceed 2%.</u> Please note that weldments may be less able to withstand inelastic strains than base material. Also, the branch welds may be subjected to biaxial and triaxial strains and welds may be made between ferritic and austenitic steel. A multi strain criterion will be developed in Phase II, as discussed in Chapter 9.

The SSE acceptance criteria for earthquakes, based on nonlinear (inelastic) analyses and strain based failure criteria, will certainly result in more flexible designs, and indeed, designs that are more energy absorbent and forgiving for normal loading conditions. However, this will only be true if the SSE loading conditions govern design.

In current practice, much of the piping system/support design is controlled by the OBE because the ASME allowable stresses for Level B Service Conditions (OBE) are approximately 1/2 of those for Level D Service Conditions (SSE). This results in inconsistent designs, because full advantage of the 'real' margins in a piping system because of inelastic behavior cannot be taken into account.

The OBE design criteria issue, although not necessarily a nonlinear (inelastic) analysis issue, is therefore inextricably linked with the level of safe seismic design that can be produced for the SSE. A comprehensive evaluation of both the OBE and the SSE, along with load combinations required for each, and service category of the loads, is needed to establish consistent criteria.

In this study, the main emphasis is on SSE criteria based on inelastic pipe/support response. However, recommendations on how to handle criteria for the related issue of OBE design will be provided.

Another important consideration in the development of a new criterion is the failure mechanism. Recent tests (e.g., ETEC) have shown that controlling failure mechanism for dynamic loads may be of the fatigue-ratchetting type. Thus, possible ASME code modification to reclassify dynamic loads (such as seismic) from the primary (load controlled) to the secondary (displacement controlled) may be seriously considered. However, the calculation of ratchetting strains must also be properly considered in the development of any simplified nonlinear (inelastic) analysis procedure, as well as detailed time history nonlinear dynamic analysis procedure.

For the simplified nonlinear (inelastic) analysis procedure, being developed on this project (Chapter 7), an approximate procedure for consideration of ratchetting strain has been incorporated. This approximate procedure calculates a modified value of ductility factor for ratchetting, based on the number of cycles of ratchetting, rate of strain hardening, and the ratio of stress at static load to yield stress.

The modified ductility ratio considering ratchetting, μ', is given by:

$$\mu = 1 + \frac{\mu' - 1}{N \left[1 + K_s \left(\frac{N-1}{N}\right) (\mu - 1) - r \right]}$$

Where:

μ = Standard Ductility Ratio (without ratchetting)

N = No. of Cycles of Ratchetting

K_s = Rate of Strain Hardening

r = Ratio of Stress at Static Load to Yield Stress

(The detailed derivation of this formula is included in Appendix A.)

Table 6-1. Summary of Strains from Available Test Results on Piping Systems*

TESTING ORGANIZATION	FAILURE STRAIN(S)	COMMENTS	REFERENCE
ETEC/GE	9.2% (Circum) 12.0% (Radial)	Ratcheting Cracks	(19)
MPA (West Germany)	5.75%	Crack & Leak	(24)
MPA/HDR (West Germany)	7.0%	Crack & Leak	(23)
Not Known	5.0%	Collapse	(27)

* Carbon Steel Material

7. TASK V - INVESTIGATION OF DEVELOPMENT OF A SIMPLIFIED NONLINEAR ANALYSIS PROCEDURE FOR ROUTINE NONLINEAR ANALYSIS OF PIPING SYSTEMS.

This task consisted of investigation of the development of a simplified nonlinear analysis procedure for routine nonlinear analysis of piping systems, after extensive review of existing simplified methods, and to initiate preliminary development of such a method to ensure its feasibility, applicability, and cost effectiveness.

A review of the available simplified nonlinear methods was performed in Task I, and the results of the review were summarized previously (Chapter 3). Most of these methods have deficiencies, as pointed out earlier. A simplified nonlinear analysis method must be easy to use, should not require specialized knowledge in nonlinear mechanics and inelastic analysis techniques, and should be cost effective; but at the same time, it must provide adequate and reliable results (including failure predictions) and should also be able to adequately predict displacements, boundary forces, and accelerations for use as design parameters for interfacing supports, valves and nozzles, etc. The key to the development of a simplified nonlinear analysis method is a balance between simplicity on the one hand and the adequacy and reliability of the results (including failure predictions) on the other. The available simplified methods do not provide this balance. Either they are so approximate that they do not provide accurate results for many desired situations (viz, complex piping systems with multiple dynamic modes and loadings with a broad range of frequency content), or they provide adequate results, but are not really simplified -- requiring detailed time history nonlinear analyses to develop certain factors which are used by them.

The primary objective of this task was to develop a simplified method which was simplified enough so that it could be easily and cost effectively used by piping engineers on a routine basis; while at the same time, providing adequate and realistic results (including failure predictions) for a very wide range of piping systems and loadings. Thus, the user should not have to wonder every time he uses the method whether the method will provide him accurate results for his particular problem, since he does not have the specialized expertise to make this judgment.

The simplified nonlinear analysis method developed and proposed herein is based on the use of a nonlinear inelastic response spectrum approach (since the piping engineers are, in general, familiar with a response spectrum approach and use it on a routine basis for linear elastic analysis), but attempts to make significant improvements over available inelastic response spectrum analysis approaches.

The following are the salient features of the proposed simplified nonlinear analysis method:

- It is simple to use since it is based on a response spectrum approach with which piping engineers, in general, are very familiar and use it on a routine basis for linear elastic analysis.

- The procedure, although requiring 2 to 3 iterations, is very cost effective.

- The procedure will be completely automated in Phase II, and the computer program so developed would be made available for general use. However, the procedure can also be applied by piping engineers for simplified nonlinear analyses, utilizing their existing computer programs (for response spectrum linear elastic analysis), with minor additional calculations.

- The piping engineers do not have to make any judgmental decision requiring specialized knowledge about nonlinear behavior of piping systems.

- The procedure employs "local" ductilities, in addition to "modal" ductilities, for better prediction of the local nonlinear behavior and potential failures at critical locations.

- The method can predict "ratchetting" type of failure (in addition to standard "plastic failure"), using "modified" ductility ratios based on ratchetting behavior. (Please recall that GE/ETEC and other available test results indicate that piping failures mostly occur in a ratchetting mode.)

- The change in system flexibility due to inelastic behavior is considered by using "modified" frequencies.

- The method can reasonably accurately (within the limitations of the "simplified" approach) predict: 1) the forces and stresses in the piping system and supports, 2) potential failures at critical locations, and 3) displacements, accelerations, and boundary forces which can then be used as design parameters for interfacing supports, valves and nozzles, etc.

- The method is applicable to a range of piping systems from very simple to complex, including those with multiple dynamic modes.

o The method will be applicable not only to seismic loads but to other dynamic loads with higher frequency content, e.g. SRV, pipe rupture, water hammer, pressurized thermal shock, and annulus pressurization loads.

The method is outlined below, in its preliminary form.

Basic Steps of the Proposed Simplified Nonlinear Analysis Method

1. Perform static analysis of the piping system, for static loads only. Calculate joint displacements, member forces, and member deformations.

2. Perform eigenvalue solution (calculation of natural frequencies and modeshapes).

   Let n be the natural frequencies
   and n be the mode shapes
   where n = mode number

3. Perform standard response spectrum dynamic analysis of the piping system using linear elastic response spectrum. Combine static and dynamic response results. Let ui be the displacement at node i, fj be the force

in member j, and ej be the deformation in member j (e.g., the rotation).

4. Calculate ductility ratio, μj, for each member j, as follows:

$$\mu j = \frac{ej}{eyj} \qquad \text{if } ej > eyj$$

$$= 1 \qquad \text{if } ej < eyj$$

$$j = 1, 2, \ldots\ldots\ldots\ldots NMEM$$

5. Using N versus μ relationship (to be developed in Phase II for typical ground motions, see Appendix D), calculate modified ductility factor considering ratchetting behavior, $\mu' j$ for member j, as follows:

$$\mu j = \frac{\mu' j - 1}{N \left[1 + Ks \left(\frac{N-1}{N}\right) (\mu - 1) - r \right]} + 1$$

where,

μj = Standard Ductility Ratio, Without Ratchetting

$= \frac{ej}{eyj} = \frac{Mj}{Myj}$ (If curvature or rotation deformation is used)

Mj = Applied Moment

Myj = Yield Moment

N = Number of Cycles of Ratchetting

Ks = Rate of Strain Hardening

r = Ratio of Static Stress to Yield Stress

j = Member Number

6. Calculate effective member stiffnesses, Kej, corresponding to Modified Ductility Ratio, $\mu'j$. See Figure 7-1. (In a simplified form, the effective member stiffness, Kej, can be shown to be equal to $Kj/\mu'j$).

7. Assemble modified effective stiffness matrix, Ke, from member stiffness Kej.

8. Calculate modified estimates of natural frequecies as follows:

For mode n, Effective Modal Stiffness,

$$\dot{Kn} = [\,\Phi n\,]^T [\,Ke\,]\,[\,\Phi n\,]$$

Effective Modal Mass,

$$\dot{Mn} = [\,\Phi n\,]^T [\,M\,]\,[\,\Phi n\,]$$

so that, Modified Frequency For Mode n

$$\dot{\omega n} = \sqrt{\frac{\dot{Kn}}{\dot{Mn}}}$$

where Φn = Mode Shape for Mode n

If it is desired to use hand calculations, the above calculations is Steps 7 and 8 can be simplified as follows:

Calculate "Average" member ductility ratio for the structure, by averaging all member ductility ratios, μ'_{Av}.

It can be shown that, in a very simplified form, the modified frequency for each mode is $\omega'_n = \dfrac{\omega_n}{\sqrt{\mu'_{Av}}}$

9. Calculate modal ductility factors n, as follows,

$$\mu'_n = \frac{E}{E_y}$$

where E = Modal Energy = $\sum_{j=1}^{NMEM} 1/2\ K_j e_j^2$

and E_y = Modal Energy Corresponding To Yielding of the System

$$= \sum_{j=1}^{NMEM} 1/2\ K_j\ (e_j/\mu'_j)^2$$

If hand calculations are desired to be used, the above calculations can be simplified by calculating an "Average" modal ductility (which can be used later, in Step 10, to reduce the complete spectrum from elastic to inelastic for all modes).

It can be shown that the "Average" modal ductility, in a very simplified form, is equal to μ'^{2}_{Av}, if the piping system has the same size and type of pipe throughout, where μ'_{Av} is the "Average" member ductulity.

10. Develop a modified "inelastic" response spectrum using "modal ductilities" corresponding to modified natural frequency for each mode, as shown in Figure 7-2. (Alternately, an "Average" modal ductility can be used for reducing the complete spectrum for all modes, in a very simplified form of this method.)

11. Perform standard response spectrum dynamic analysis using the reduced "inelastic" response spectrum (calculated in Step 10 taking into consideration the inelastic behavior in the form of "modal ductilities" as well as frequency shifts due to inelastic behavior), and using the modified frequencies calculated for the modified (flexible) system, and the modeshapes already calculated in Step 2. Combine dynamic and static results.

12. Calculate new member ductilities, μ''_j.

13. Compare computed member ductilites, μ''_j, against member ductilities calculated previously, μ'_j.

14. If $\mu_j'' - \mu_j' \leq 10\%$ (or some other pre-specified criterion), and μ_j'' < allowable ductility (based on strain criterion, developed as part of this research), then convergence has occurred.

15. If $\mu_j'' - \mu_j' > 10\%$, repeat Steps 3 through 14. (It is anticipated that, usually, no more than 3 iterations will be required for convergence. The calculations for these iterations are very inexpensive.)

16. If μ_j'' > allowable ductility (based on strain criterion, developed as part of this research), then failure has occurred.

17. Once convergence has occurred, using the latest stiffness matrix, Ke, perform an eigenvalue solution to compute final frequencies and modeshapes, for confirmatory purposes. (This is an optional step.)

18. Using the final frequencies and modeshapes, perform a final response spectrum analysis using the latest "inelastic" spectrum to calculate member forces, stresses, displacements, accelerations, and boundary forces for design purposes.

Note: Please note that, although the procedure appears to be long because of a detailed explanation, herein, it is a very simple and straight forward procedure. Only expensive calculation is the eigenvalue solution at the beginning of the procedure, and possibly at the end (optional) for confirmatory purposes only. Other calculations for each iteration are minor and inexpensive. The procedure is easily programmable and can also be incorporated in an existing response spectrum analysis program, with minor additional calculations.

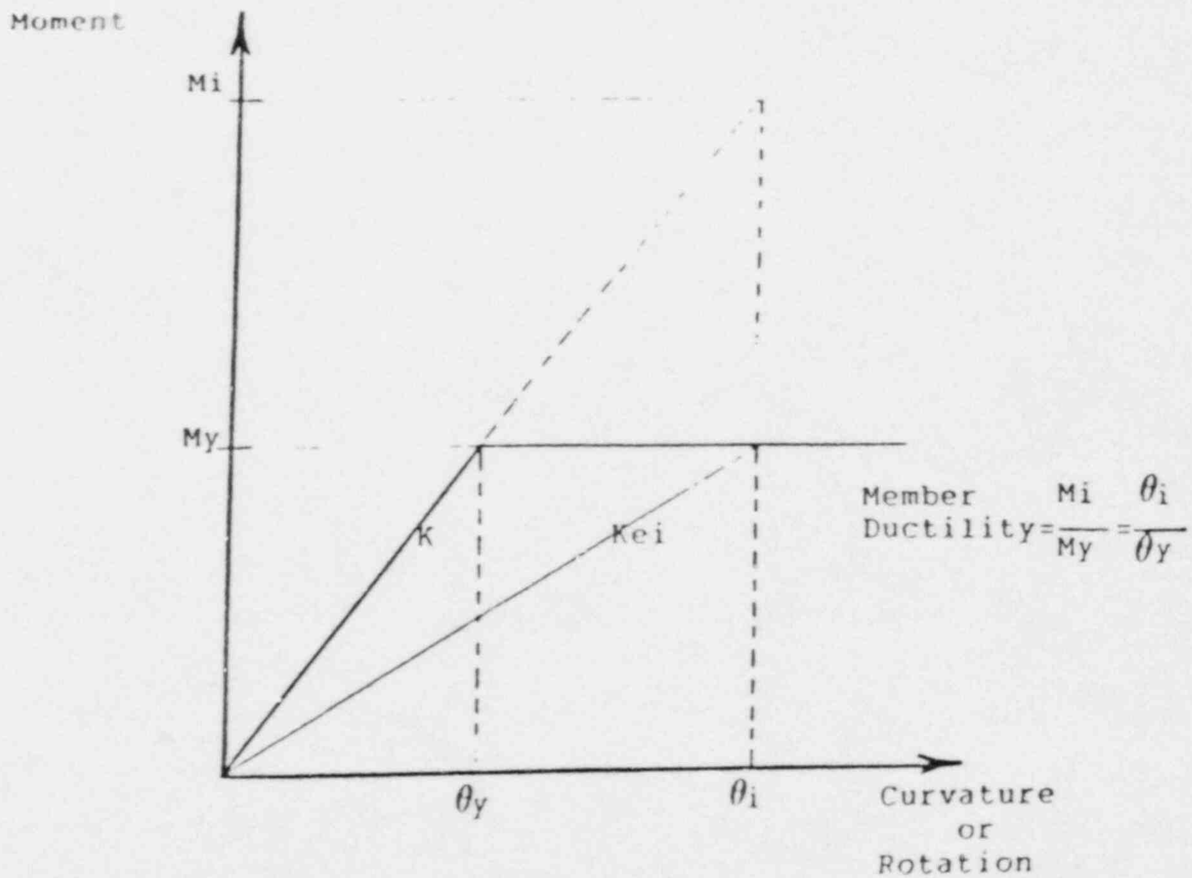


Figure 7-1. Calculation of "Equivalent" Stiffness, Kej, of Member j, From Member Ductility, μj.

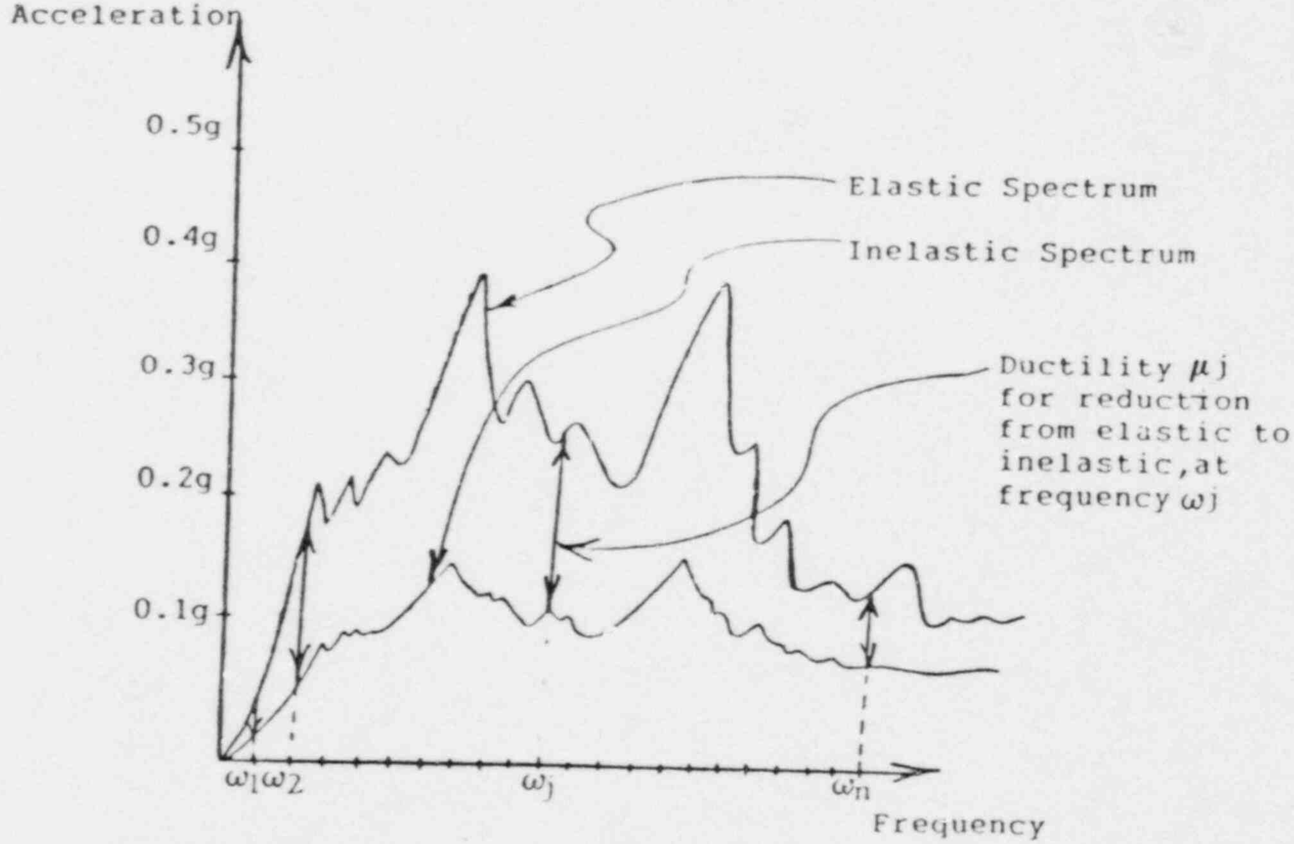


Figure 7-2. Development of Nonlinear (Inelastic) Response Spectrum From Linear Elastic Response Spectrum Using "Modal" Ductilities Corresponding to "Shifted" (Modified) Frequencies for Modified Flexible System

8. TASK VI - BENCHMARK ANALYSES

This chapter presents the results of the benchmark nonlinear analyses performed in Phase I. It was decided, in consultation with USNRC, that one of the piping systems to be tested in the very near future by ETEC, under the USNRC/EPRI sponsored piping and fitting dynamic reliability program (Ref. 20) will be used for this purpose. Piping System No. 1 (Ref. 20) was selected for these analyses. This piping system is shown in Figure 8-1. The purpose of these benchmark nonlinear analyses were three-fold:

- o To compare the results of the simplified nonlinear analysis method against those obtained using detailed step-by-step time history nonlinear analysis.

- o To compare the results of the analyses against the results of the tests on the piping system to be conducted in the near future.

- o To predict the nonlinear response of the piping system, including failure location, and failure loads, to provide assistance to the ETEC/GE test program.

To achieve these objectives, the following different analyses were performed.

- o Static Analysis of the Piping System

- o Eigenvalue Solution (Calculation of Natural Frequencies and Modeshapes)

- o Linear Time History Dynamic Analysis Using the Given Test Loading Time History, with a ZPA of 1.8g.

- o Nonlinear Dynamic Time History Analysis Using the Given Test Loading Time History, for Failure Prediction, by Increasing the Magnitude of Loading To Up To a ZPA of 20g (corresponding to an assumed limiting failure strain of 5%).

- o Nonlinear Simplified Analysis Using a Response Spectrum (Developed for the Given Test Loading Time History), with a ZPA of 23g (corresponding to an assumed limiting failure ductility ration of 20).

A description of the piping system is presented below, followed by descriptions of the above analyses.

8.1 DESCRIPTION OF THE PIPING SYSTEM

The piping system used for the analyses (Piping System No. 1 of Ref. 20) is shown in Figure 8-1. The node numbers and element numbers are shown in Figures 8-2 and 8-3, respectively. The system is fixed at nodes 1 and 112 (at Shaker Tables #4 and #2, respectively). At node 75, it is connected to the pressure vessel, which is fixed at node 77 (at Shaker Table #1).

The piping system consists primarily of a 6" Sch. 40 pipe, except for a small portion of 3" Sch. 40 (from node 34 to 79). The pressure vessel consists of 18" Sch. 30. A hanger (B-26, Size 7) is provided at node 45. All valves (located at nodes 13, 61, 99, and 124) are modeled using single-mass rigid cantilevers. The cross-sectional and material properties of the piping system are shown in Table 8-1.

For the analyses, no thermal and internal pressure were considered. Only static (gravity) and dynamic (earthquake) loads were used.

8.2 COMPUTER PROGRAMS

Two computer programs were primarily used for these analyses. For the static analysis and eigenvalue solution (calculation of frequencies and modeshapes), the program SATRAN was used. This is a program for general purpose three-dimensional linear static and dynamic analysis for use on micro-computers, such as IBM/AT, developed in-house, and is briefly described in Appendix B. For nonlinear static and dynamic (time history, step-by-step) analysis, the program NPIPE was used. This is a special purpose computer program for nonlinear analyses (static and dynamic) of three-dimensional piping systems of any arbitrary shape for any kind of static or dynamic loadings (seismic, hydrodynamic, etc.) for use on micro-computers, such as IBM/AT, developed in-house, and is described briefly in Appendix C.

For simplified nonlinear analyses, based on a response spectrum approach, the computer program SATRAN was repeatedly used, except for additional calculations for member ductilities, modal ductilities and equivalent (modified) frequencies, for which additional (separate) calculations were used. In Phase II, if awarded, a separate computer program will be developed for such simplified nonlinear analyses on microcomputers, such as IBM/AT.

8.3 STATIC ANALYSIS

The static analysis was performed for the gravity loads. The static loads used are shown in Table 8-2. The results of the static analysis for selected elements are shown in Table 8-3.

8.4 EIGENVALUE SOLUTION (CALCULATION OF NATURAL FREQUENCIES AND MODESHAPES)

The first seven (7) natural frequencies (up to 33 Hz) were calculated, along with modeshapes, and are shown in Table 8-4.

8.5 LINEAR TIME HISTORY DYNAMIC ANALYSIS

Linear time history (step-by-step) dynamic analysis was performed using the given test loading time history, with a ZPA of 1.8g. A mass and stiffness proportional damping, corresponding to a 2% damping in the piping system, was used in consultation with ETEC personnel. The analysis was performed using the program NPIPE.

However, since the amplitudes were relatively small, the bending moments and forces in the piping system remained significantly within the linear elastic range. The time history loading is shown in Figure 8-4. The time history loadings were applied simultaneously, at the three supports in the X-direction, to be consistent with ETEC tests. Since the structure behaved linearly, a time step of 0.002 secs., in conjunction with the complete time history, was used. The results for bending moments in selected elements are shown in Table 8-5.

8.6 NONLINEAR DYNAMIC TIME HISTORY ANALYSES

A series of nonlinear dynamic time history (step-by-step) analyses were performed by increasing the magnitude of the loading, for failure prediction. The results of nonlinear dynamic analysis using the time history with a ZPA of 20g are presented herein. The mass and stiffness proportional damping, corresponding to 2% damping in the piping system, was used. Since the piping system behaved significantly nonlinearly, it was necessary to use a time step of 0.0005 secs. for stable solution. Since it was impractical (and unnecessary) to use the complete time history with such a small time step, the portion of the time history up to (and including) the most severe part of the loading, was used for this analysis.

The results of this analysis are shown in Figure 8-6. As the results indicate, since the strain level at critical location was higher than the assumed failure strain (5%)*, failure was considered to have occurred at the location, shown in the figure. As the results indicate, the critical failure locations were found to be at nodes 2 (close to the fixed end at Shaker Table #4) and 72 (close to the connection of the piping system to pressure vessel at Shaker Table #1) for the 6" pipe, and node 34 (at the connection of the 3" pipe to the 6" pipe on the north side) for the 3" pipe.

The failure would likely occur first at node 34 in 3" pipe at a load level of about 20g.

8.7 SIMPLIFIED NONLINEAR ANALYSIS

The simplified nonlinear analysis was performed using the inelastic response spectrum based procedure presented in Chapter 7. The response spectrum, corresponding to the ETEC test time history, used for these analyses, is shown in Figure 8-5. The results of the simplified method are presented in Figure 8-7. As the results indicate, the most likely critical failure locations were found to be the same as from the detailed time history nonlinear analysis above. However, it was found that the failure would most likely

* Please note that since failure is being predicted for the test piping system, a realistic failure strain of 5% based on previous test results is used. For <u>design purposes</u>, a conservative limiting strain of 2% (failure strain of 5% divided by a factor of safety of 2.5) was recommended in Chapter 6.

occur first at node 34 in 3" pipe, according to this analysis, at a load level of approximately 23g. This was based on an assumed local failure ductility ratio of approximately 20 (which corresponds to a 5% strain). The ductility ratios for the elements were calculated considering ratchetting. Six ratchetting cycles were used for the calculation of modified ductility ratios. The calculated ductility ratios at failure locations are shown in the figure.

8.8 DISCUSSION OF ASSUMPTIONS ASSOCIATED WITH NONLINEAR ANALYSIS METHODS

It needs to be pointed out that the detailed nonlinear time history analysis method, as well as the simplified nonlinear analysis method, have certain assumptions associated with their application to this problem in the calculation of the response and the failure, especially the simplified method. This is discussed below.

8.8.1 Detailed Nonlinear Time History Analysis Method

This method consists of a detailed nonlinear time history (step-by-step) nonlinear dynamic analysis. This is a sophisticated analysis method and is usually reasonably accurate in predicting dynamic response as well as failure predictions. However, in the use of this method for the subject analyses of the ETEC piping system, especially in the prediction of failures, the following assumptions were involved.

- It was assumed that the failure would occur at a strain of 5% based on past test results. Because of the uncertainties in material properties, behavior of the piping system to dynamic loads, and inherent material flaws, it is possible that the actual failure may occur at a different strain.

- Since the ETEC time history was of a long duration (17 seconds) and the nonlinear analysis required a very small time step (0.0005 sec.), it was impractical to use the complete time history. Thus, only a portion of the time history, including the most intense motion, was used for this analysis. This could have resulted in under-prediction of failure load and strain.

- The yield criterion and the failure law, used herein, are applicable primarily to a collapse type of failure, although ratchetting type of behavior is approximately considered. (For Phase II, a complete ratchetting model will be incorporated).

- There are certain analytical modeling considerations which were reasonable, but may not be completely consistent with the test fixtures. For example, the analytical model was assumed to be completely fixed at all the three supports. If there is a slight flexibility at these supports, the test results could be different from analytical results.

- The material properties, such as yield stress, damping, modulus of elasticity, Poisson's ratio, etc., were based on the known standard properties for the type of material used, in consultation with ETEC personnel (to be consistent with tests). If the actual properties for the test piping system are somewhat different due to inherent uncertainties, there could be a deviation between the test and analytical results.

- If there are any undetected flaws in the piping material, premature failures could occur at these locations in test, unpredictable by analyses.

It is therefore suggested that once the test results are available, in Phase II, a thorough comparison should be made between the test results and the analytical results presented herein. If there are significant deviations, the reasons for such deviations must be explored. A reanalysis must then be performed, after adjustment of parameters and other inconsistencies in the test and analytical models, to obtain a closer match.

8.8.2 Simplified Nonlinear Analysis Method

This method, as discussed in Chapter 7, is "simplified" and has certain inherent assumptions and limitations associated with it. These are discussed below.

- It was assumed that the failure would occur at a ductility ratio of 20. Because of uncertainties in material properties, behavior of piping systems to dynamic loads, and inherent material flaws, it is possible that the actual failure may occur at a different ductility ratio.

- The method does not perform a step-by-step nonlinear analysis using the actual time history of input motion. Rather, it utilizes an "equivalent" nonlinear approach based on iterative analysis using an inelastic response spectrum.

- The "local" and "modal" ductilities are calculated using linear response, although they are then modified in the next iteration considering change in the behavior of the system due to nonlinearities and the associated energy absorption.

- The natural frequencies of the system are modified to take into consideration the nonlinear behavior of the system; however, the 'shapes' of the modes are assumed to remain the same. This is a reasonable assumption in general, except when very significant concentrated local yielding occurs at one location and the plasticity is not uniformly distributed.

- The yield criterion and failure law model include ratchetting failure in an approximate manner by modification of local ductilities using cyclic behavior. This is a reasonable consideration, but requires estimation of the number of cycles N beyond yield (Please see Appendix D).

- o There are certain analytical modeling considerations which were reasonable but may not be consistent with the test fixtures. For example, the analytical model was assumed to be completely fixed at all three supports. If there is a slight flexibility at these supports, the test results could be different from analytical results.

- o The material properties, such as yield stress, damping, modulus of elasticity, Poisson's ratio, etc., were based on the known standard properties for the type of material used, in consultation with ETEC personnel (to be consistent with tests). Due to the inherent uncertainties in these properties, if the actual properties of the test piping system are somewhat different, there could be a deviation between the test and analytical results.

- o If there are any undetected flaws in the piping material, premature failures could occur at these locations in test, unpredictable by analyses.

It is therefore suggested that once the test results are available, in Phase II, a thorough comparison should be made between the test results and the analytical results presented herein. If there are significant deviations, the reasons for such deviations must be explored. A reanalysis must then be performed, after adjustment of parameters and other inconsistencies in the test and analytical models, to obtain a closer match.

Furthermore, as discussed in the next chapter, the simplified nonlinear analysis method presented in this report will be further developed and validated in Phase II. Suggested improvements are presented in the recommendations for Phase II research and development in the next chapter.

TABLE 8-1

CROSS-SECTIONAL AND MATERIAL PROPERTIES OF THE PIPING SYSTEM

PIPE	OUTSIDE DIAMETER (IN.)	THICKNESS (IN.)	WEIGHT DENSITY (LBS./IN.^{3})	AREA (IN.^{2})	FLEXURAL MOMENT OF INERTIA (IN.^{4})	TORSIONAL MOMENT OF INERTIA (IN.^{4})	MODULUS OF ELASTICITY (PSI)	STRAIN HARDENING MODULUS (PSI)	POISSON'S RATIO	YIELD STRESS (PSI)
6"	6.625	0.280	0.47	5.58	28.10	56.2	28×10^6	0.0001	0.3	47,000
3"	3.500	0.216	0.40	2.23	3.10	6.04	28×10^6	0.0001	0.3	47,000

TABLE 8-2

STATIC GRAVITY LOADS

NODE NUMBER	LOAD (LBS.)
13	150
14	50
61	150
62	50
99	150
100	50
124	175
125	90

TABLE 8-3

RESULTS OF STATIC ANALYSIS

MAXIMUM BENDING MOMENTS IN SELECTED ELEMENTS

PIPE SIZE	ELEMENT	BENDING MOMENT (LBS. - IN.)
6"	1	24,625
	2	19,051
	3	2,895
	4	2,406
	29	8,469
	30	21,385
	31	23,057
	32	30,967
	34	30,967
	45	6,153
	46	5,589
3"	50	2,289
	51	2,720
	54	4,718
	64	2,213

TABLE 8-4

NATURAL FREQUENCIES OF PIPING SYSTEM

MODE	FREQUENCY (Hz.)
1	9.3
2	13.5
3	15.1
4	18.2
5	20.6
6	25.3
7	31.8

TABLE 8-5

RESULTS OF LINEAR DYNAMIC ANALYSIS USING TEST TIME HISTORY (1.8g ZPA),

MAXIMUM BENDING MOMENTS IN SELECTED ELEMENTS

PIPE SIZE	ELEMENT	BENDING MOMENT (LBS. - IN.)	MOMENT CAPACITY (LBS. - IN.)
6"	1	70,216	530,160
	2	64,820	"
	3	49,418	"
	4	59,727	"
	29	51,205	"
	30	66,725	"
	31	68,859	"
	32	78,809	"
	34	87,737	"
	45	38,584	"
	46	36,072	"
3"	50	17,060	109,706
	51	8,735	"
	54	11,145	"
	64	10,369	"

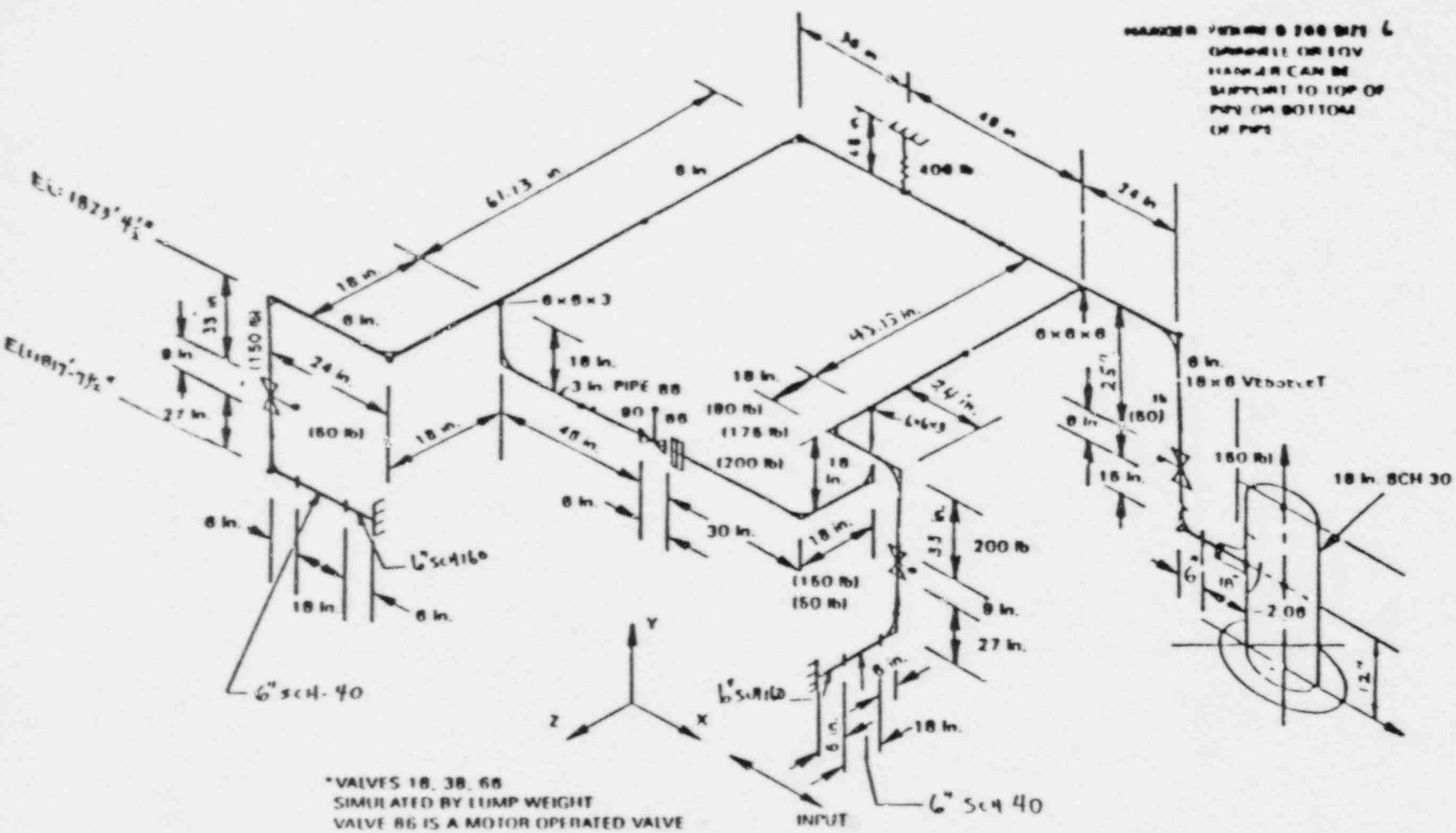


FIGURE 8-1. PIPING SYSTEM FOR BENCHMARK ANALYSES

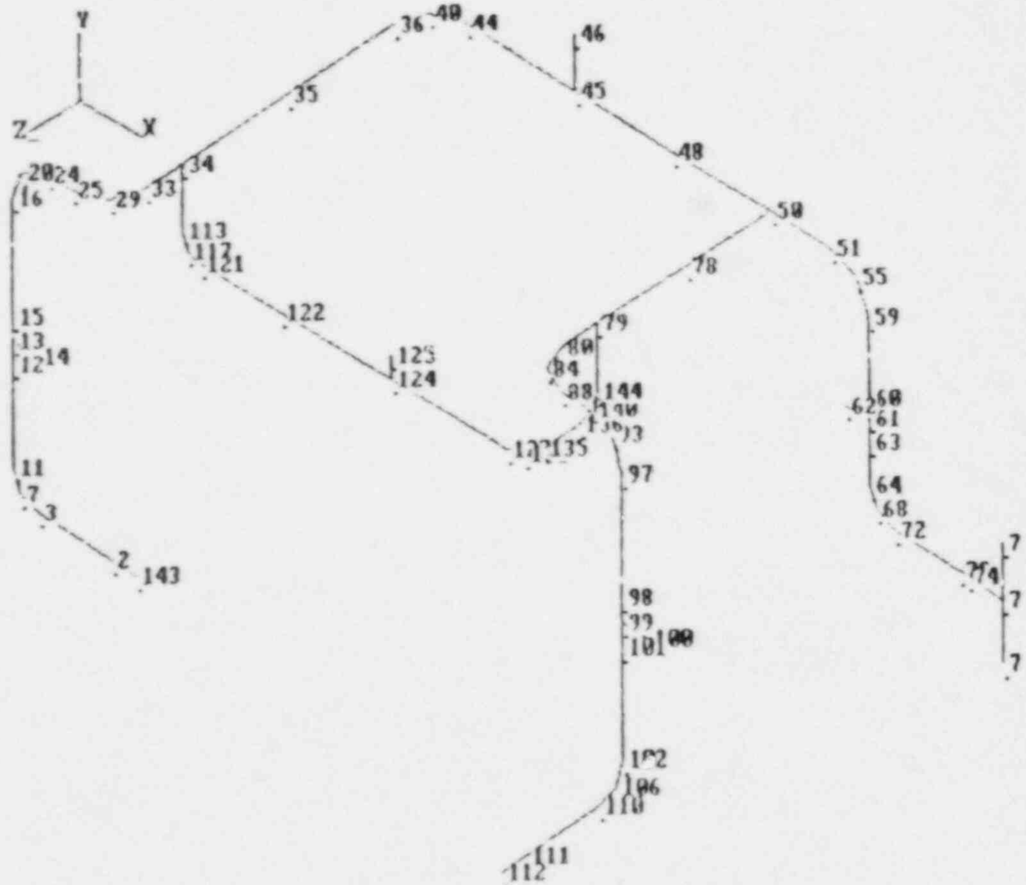


FIGURE 8-2. PIPING SYSTEM MODEL WITH NODE NUMBERS

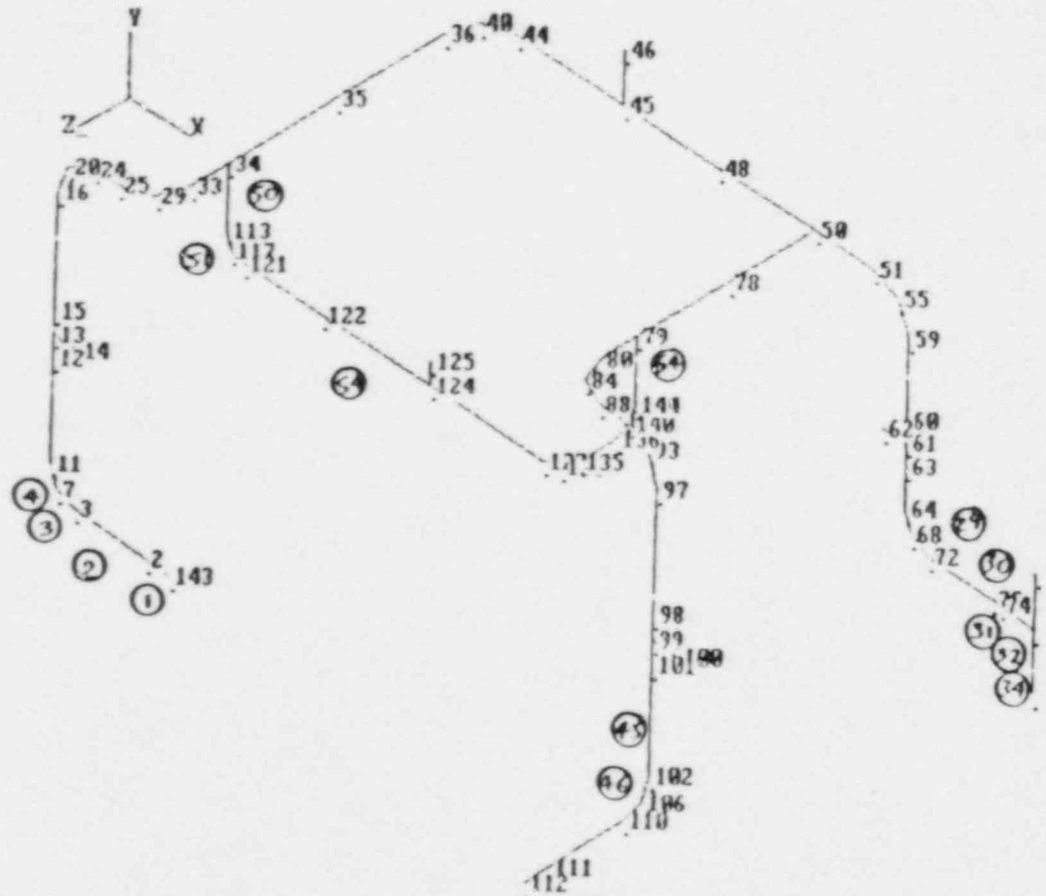


FIGURE 8-3. PIPING SYSTEM MODEL WITH ELEMENT NUMBERS

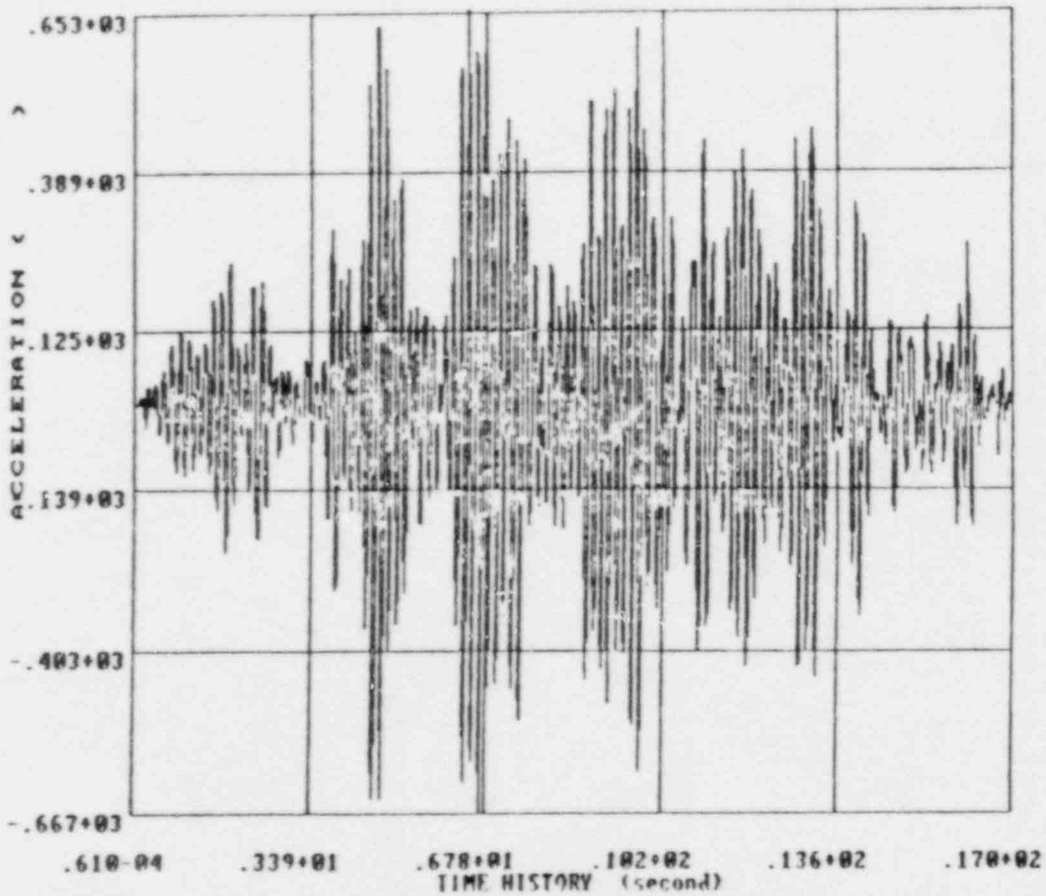


FIGURE 8-4. ETEC TEST TIME HISTORY, USED FOR DETAILED TIME HISTORY ANALYSIS

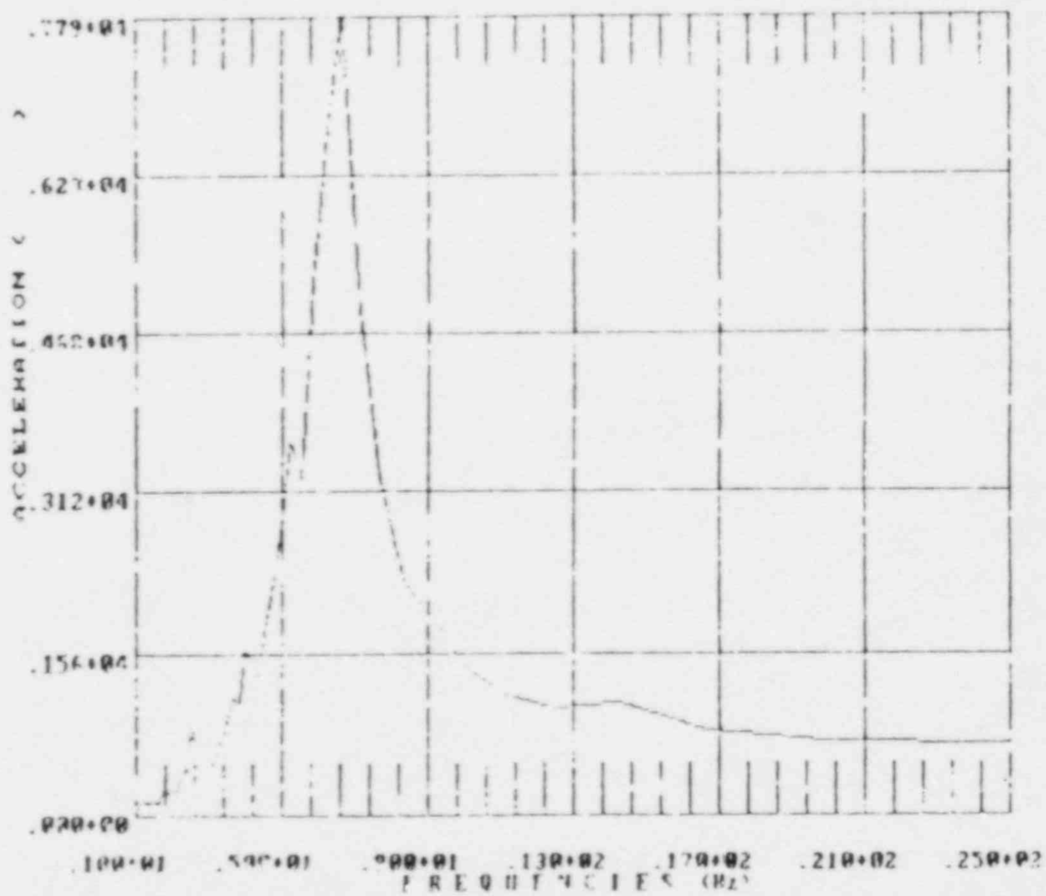
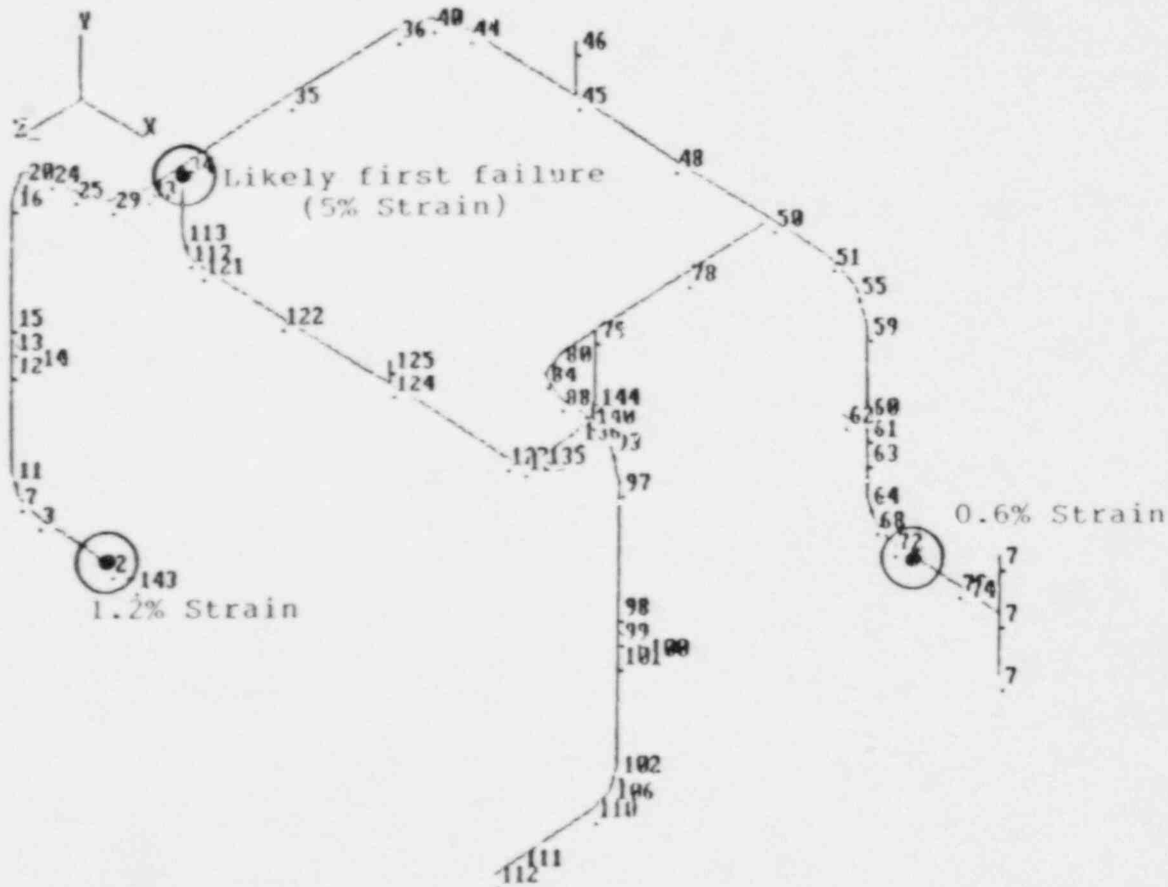
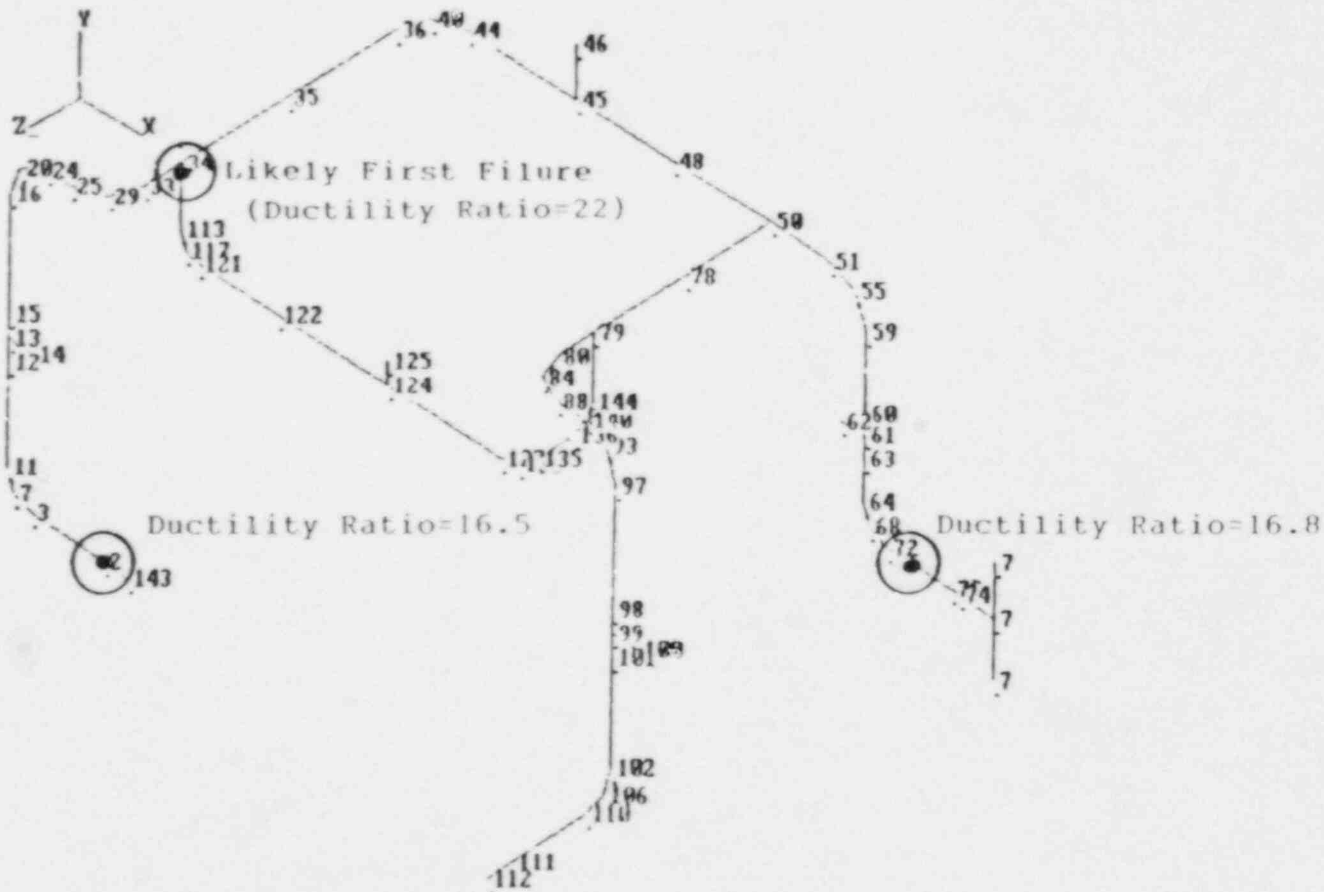


FIGURE 8-5. RESPONSE SPECTRUM CORRESPONDING TO ETEC TEST TIME HISTORY, USED FOR SIMPLIFIED NONLINEAR ANALYSIS



Limiting Failure Strain = 5% (Assumed)
Predicted Failure Load =20g

FIGURE 8-6. RESULTS OF NONLINEAR DYNAMIC ANALYSIS USING TEST TIME HISTORY WITH INCREASED ZPA OF 21g, DEPICTING POTENTIAL FAILURE LOCATIONS AND FAILURE LOAD



Limiting Local Failure Ductility Ratio =20(Assumed)
Number of Ratchetting Cycles Used = 6
Predicted Failure Load =23g

FIGURE 8-7. RESULTS OF SIMPLIFIED NONLINEAR DYNAMIC ANALYSIS, FOR RESPONSE SPECTRUM WITH ZPA OF 25g, DEPICTING POTENTIAL FAILURE LOCATIONS AND FAILURE LOAD

9. TASK VII - CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

9.1 CONCLUSIONS

Descriptions of the various tasks of the Phase I research and development efforts were presented in the previous chapters. The following conclusions are reached on the basis of these Phase I efforts.

- On the basis of a review of the reports on recent work performed by HEDL (NRC-sponsored) and Rockwell (EPRI-sponsored) on simplified nonlinear analysis methods, as well as a detailed review of literature on available simplified nonlinear analysis methods (including those not covered in the HEDL and Rockwell reports), it was concluded that all available methods have deficiencies and limitations. Either they ar too approximate and can not adequately predict dynamic response, as well as failures, except for very simple piping systems; or they are too detailed (not simplified at all). In any case, none of the methods can adequately predict local failures (especially ratchetting type failures) and displacements, accelerations and boundary forces for interfacing nozzles, valves, and supports, as well as dynamic response and potential failures of piping systems subjected to dynamic loads other than seismic loads (e.g., SRV, Water Hammer, Condensation Oscillation, Annulus Pressurization, and

Pressurized Thermal Shock) involving high frequency loads. Thus, it was further concluded that there is a definite need for the development of a realistic and balanced simplified nonlinear analysis procedure which is simplified, while at the same time it can predict realistic dynamic response and local (as well as overall) failures (including ratchetting failures) for seismic and other dynamic loads including forces, stresses, strains, displacements, accelerations and boundary forces.

o On the basis of a very detailed review of the available test results on components and piping systems from US (e.g., ETEC tests), Germany (e.g., MPA and KWU tests), Japan, and other countries, it was concluded that ratchetting types of failure occurred most frequently during tests and must therefore be incorporated into the nonlinear inelastic analysis procedures (both simplified and detailed). It was also concluded that most analytical procedures underpredicted failure loads, and the ASME code procedures were unable even to predict failure locations. Finally, it was concluded that piping systems can withstand significantly higher strains before failure than it is generally believed.

o It was concluded on the basis of the results of several past nonlinear analysis sample examples, for a variety of piping systems and seismic as well as other dynamic loadings, that nonlinear analysis procedures can show significantly improved safety of nuclear piping systems. It was also concluded that nonlinear procedures, for application to piping systems and supports, are feasible and licensable, and can be developed into easy to use and economical tools for routine use in the industry, in conjunction with strain criteria.

- o It was concluded that current criteria, as well as procedures, for the design of piping systems and supports, are very conservative, and more rational design criteria (including strain and associated criteria) need to be developed, especially if nonlinear analysis procedures are to be used on a routine basis in the industry. Based on a very comprehensive review of the available tests in this task, it was further concluded that it may be possible to safely use a strain criterion of 2% for design purposes, in conjunction with nonlinear analysis procedures.

- o A simplified nonlinear (inelastic) analysis procedure for piping systems and supports, based on the use of an inelastic response spectrum (with significant improvements over available procedures) was developed. It was concluded that the salient features of this proposed method consisted of the following:

  - It is simple to use.
  - It is very cost effective.

- It is easy to use in conjunction with existing response spectrum analysis computer programs (although the procedure will be completely automated in Phase II).
- It does not require users to make judgmental decisions based on specialized knowledge about nonlinear analysis.
- It employs "local" ductilities, in addition to "modal" ductilities, for better prediction of local response and failures.
- It can predict "ratchetting" failure (in addition to standard "plastic" failure).
- It considers change in system flexibility due to inelastic behavior using "modified" frequencies.
- It can predict displacements, accelerations and boundary forces (for interfacing supports, valves and nozzles) in addition to forces, stresses and failures.
- It is applicable to a range of piping systems, including complex systems with multiple dynamic modes.
- It is applicable to seismic as well as other dynamic loads.

o On the basis of benchmark analyses using a detailed time history (step-by-step) nonlinear dynamic analysis approach (based on the computer program, NPIPE, developed in-house), it was concluded that failure locations for the sample piping system (Piping System No. 1 of the ETEC test program, sponsored by USNRC) would be most likely node 2 (near one fixed end at Shaker Table #4) and node 72 (near pipe connection to pressure vessel at Shaker Table #1) for 6" pipe, and node 34 for 3" pipe (near connection to 6" pipe on the north side), and the first failure would occur most likely at node 34 in 3" pipe at about 20g ZPA. Using the simplified nonlinear analysis method, same critical failure locations as those predicted by the detailed method were determined. However, the failure load was predicted to be about 23g (also at node 34 in 3" pipe). Thus, it was concluded that the simplified nonlinear analysis method has the potential to be a feasible, effective, efficient and cost effective method for routine use in the nuclear industry, in conjunction with strain criteria, especially after it is refined and validated further in Phase II.

9.2 RECOMMENDATIONS FOR PHASE II RESEARCH AND DEVELOPMENT

Based on the preliminary research and initial development of procedures and criteria for nonlinear analysis of piping systems performed in Phase I, a further extension and detailed development is recommended to be carried out in Phase II. This will include extensive testing and validation of these procedures and criteria, their application to different practical problems, including snubber reduction, and their development into formal tools in an ASME format for easy and cost effective use on a routine basis in the nuclear industry.

The following research and development efforts are recommended for Phase II.

o It is recommended that the strain criteria, for use in conjunction with nonlinear analysis, be further developed, verified and incorporated in the ASME format, along with other supporting criteria.

  As described previously, a comprehensive literature survey was performed in Phase I of available test results from US (e.g. ETEC tests), German (KWU and MPA tests), and other tests to determine a realistic and conservative strain criterion. On the basis of these test results, it was proposed that a criterion with a strain limit of 2% should be considered.

  It is recommended, however, that, in Phase II, a more detailed development of this strain criterion be carried out and recommendations be developed for its incorporation into the ASME code, along with other supporting criteria. This may consist of several major steps, as discussed below.

  - Development of strain limits may be studied specifically for different types of base materials, as well as weldments. For example, appropriate strain limits for an annealed austenetic steel may be higher than for a bolting material. Furthermore, weldments may be less able to withstand inelastic strains than the base materials. In piping systems, there are a large number of girth butt welds and, in addition, welds between run pipes and branch connections. The branch welds may be subjected to bi-axial or tri-axial strains. The welds may be used for cast steel components (e.g., valve bodies) and also between ferritic steel and austenitic steel. Different kinds of materials and weldments may be considered in establishing appropriate strain limits.

- Development of strain limits may be studied for different components of a piping system, e.g. elbows, straight pipes, etc., taking into consideration different types of structural behaviors, e.g., membrane, membrane plus bending, compressive, compressive plus bending, especially including potential buckling considerations.

- Development of strain limits may be studied for different types of failure modes, e.g., plastic collapse failure, fatigue-ratchetting type failure, and buckling type of failure. In addition, other definitions of failure may be considered, e.g., onset of tensile instability (tensile necking), low-cycle fatigue, onset of compressive wrinkling (local buckling, as compared to overall buckling), excessive deformations resulting in more than 15% reduction in cross-sectional flow area.

- Representation of strain based acceptance criteria in the form of easy to use formulas, in terms of major piping parameters, such as thickness, radius, material type, configuration, etc., for ready use by piping engineers may be studied. Alternately, development of strain based acceptance criteria in a tabular form may also be studied, again for ready use by piping engineers.

- The strain based acceptance criteria, developed as discussed above, may be further validated and refined by utilizing results of ETEC tests (under USNRC sponsorship) as well as other U.S. and foreign tests, e.g. ongoing German tests at KWU and MPA. This may include component tests, as well as tests on piping systems.

- Recommendations for incorporation of the strain based acceptance criteria in the ASME code format, along with supporting criteria may be developed. (A code case may be proposed).

The present ASME code criteria, with respect to seismic design of piping systems, consists primarily of two checks:

Satisfaction of Code Equation (9).

Satisfaction of Fatigue Criteria.

The seismically induced moments, used therein, are further classified as those due to seismic input (SI) or those due to seismic anchor movement (SAM).

It also needs to be pointed out that the treatment of primary and secondary stresses, in the current procedure, is different at Service Level D than it is at Service Level B. Secondary stresses such as those due to SAM can be ignored at Service Level D. This needs to be reviewed in depth for the criteria development.

It should also be recalled that the current procedure allows the SSE SI stress to be combined with other primary stresses and then compared either against the primary stress allowables of Equation (9) of the ASME code or against the criteria of Appendix F to the ASME code. When Equation (9) is used, a linear (elastic) piping analysis is supposed to be performed. With the use of Appendix F, either a linear (elastic) or nonlinear (inelastic) piping analysis can be performed. However, even when a nonlinear (inelastic) analysis is allowed to be performed, the acceptance criteria consist of comparing computed stresses against static allowable stresses. Thus, the advantage of accounting for nonlinear (inelastic) energy absorption due to nonlinear (inelastic) hysteretic behavior under dynamic loadings cannot be fully obtained because of lack of an allowable strain criterion. Thus, limiting strain criteria has to be included into the ASME format.

In addition, it is proposed that, as part of this criteria development, recommendations be developed on how the SI and SAM moments should be treated, and how the OBE and SSE should be considered in the ASME code, in conjunction with the use of the strain criteria. As discussed previously, the current practice of comparing inertially induced stresses with primary static stress limits results in excessive conservatism in the treatment of inertial effects because it ignores the inelastic energy absorption capability of the piping system. Also, as discussed previously, the current practice of treating seismic support movement as secondary stresses and thus ignoring these stresses at Service Level D needs to be reviewed. Resolution of the above two areas can be partially found in the use of limiting strain criteria, since potential failures of piping systems are directly related to the occurrence of large strains, which can be produced from either inertial effects or seismic anchor movements.

The possibility of the use of an alternative performance criterion for the SSE, and the establishment of a minimum required factor of safety against failure for the SSE combined with other loadings may also be studied. One possible approach may be to factor all loads upwards using the required minimum safety factors and demonstrate that the computed strains from these factored loadings are lower than those associated with any of the failure modes. Both SI and SAM effects can be required to be included in this alternate approach. This alternate performance criterion approach can have a potential advantage of allowing appropriate consideration for inelastic energy absorption capacity of a piping system and to compare both SI and SAM effects against strain criteria.

All these basic issues associated with the use of strain criteria in the ASME code, in conjunction with nonlinear (inelastic) analyses, may be studied. Existing criteria may be reviewed and recommendations may be developed for modification of the criteria and possible incorporation of these modified criteria in the ASME code. A code case may be proposed for this purpose.

- It is recommended that the simplified nonlinear (inelastic) analysis method be further developed and refined so that it is applicable to a range of piping systems and loadings, compared against (and validated by) results of ongoing ETEC tests, as well as detailed nonlinear time history analyses, and further modified as necessary based on these comparisons. A computer program based on the simplified method may then be developed.

As described previously, a preliminary development of the simplified method was carried out in these Phase I efforts. As already pointed out, the main objective in the development of this method is that it should be simplified enough so that it could be easily and cost effectively used by piping engineers on a routine basis (without requiring specialized knowledge in nonlinear mechanics and inelastic behavior); while at the same time providing adequate and realistic results (including failure predictions) for a wide range of piping systems and loadings.

However, since only preliminary development of the method has been performed herein, detailed development may be carried out in Phase II. Some aspects of the method which were not studied in great detail may be further investigated. This may include, for example, the following:

- Applicability of the procedure to situations where very severe local nonlinearities (the distribution of plasticity may be highly nonuniform) may occur and may require the inclusion of its influence on modeshapes, in addition to frequencies, in all iterations.

- A technique, perhaps 'emperical', based on test results, may be developed for the estimation of number of ratchetting cycles, N, in the calculation of "modified" ductility considering ratchetting behavior. (Please refer to Appendix D).

- The procedure currently employs SRSS combination of modal responses, similar to linear elastic response spectrum procedure. This assumption needs to be reviewed further and modified, if necessary.

o It is recommended that in addition to further study of the method, considering the above and other issues as necessary, and modification to the method, if necessary, especially after further comparison against ongoing ETEC test results, as well as against results of detailed nonlinear time history analyses on selected examples (as discussed later herein), additional capabilities may be incorporated in the method. They may include the following:

  - Extension of the method to incorporate support anchor movements (SAM). This could require use of single as well as multiple inelastic response spectra input. The iterative procedure may also be slightly modified accordingly.

- Inclusion of combination of internal pressure, bending moments, and (possibly) axial loads in the form of a "modified" yield criteria, similar to modified von Mises or Tresca type, but based on 'strains' and not 'stresses'.

- Further Investigation of the method (and possible extension as necessary) to be able to treat other dynamic loads, e.g., impulsive high frequency loads (water hammer, pressurized thermal shock, SRV, annulus pressurization, etc.). Since these loadings consist of high frequency components, the method must be able to include significantly higher modes of the piping system which may interact with the high frequency components of these other dynamic loads. Furthermore, the strain effects on the yield strength and other properties of the piping and support materials should be considered.

- Inclusion of different types of dampings (e.g. PVRC damping, in addition to Regulatory Guide damping).

- Development of a computer program for automated analysis using the simplified nonlinear analysis procedure on a microcomputer, such as IBM/AT. The program so developed can then be used as a formal tool by piping engineers in the nuclear industry for routine use of nonlinear analysis of piping systems in a very cost-effective manner.

- It is recommended that extensive testing of the simplified nonlinear analysis procedure be carried out, in conjunction with strain criteria, for a range of problems, involving piping systems with different complexities, different types of loadings (including seismic and other dynamic loadings). The testing may be performed by comparison of the results obtained by using the simplified method against detailed step-by-step time history nonlinear analyses using the computer program NPIPE, developed by Structural Analysis Technologies, Inc. The following loadings may be considered.

  - Seismic
  - Water Hammer
  - SRV
  - Pressurized Thermal Shock

  All the analyses may be performed using the strain criteria developed as described previously.

- It is recommended that comparison be carried out of the results of ETEC tests, under USNRC sponsorship, on Piping System # 1 against analytical results (predicted by using simplified and detailed time history nonlinear analyses herein), along with validation of the simplified nonlinear analysis procedure, in conjunction with the strain criteria, using the ETEC test results, and assistance in prediction of future test results, e.g., on Piping System # 2, for this ongoing test program.

It appears that the test results for ETEC Piping System # 1 may not be available for about two months. Thus, it has not been possible to compare our predicted analytical results against the test results in Phase I. This can be done in Phase II. This may include comparisons of analysis vs. test results, interpretation of differences in any response parameters (e.g., strains) at different failure locations (if more than one), and modifications to analytical procedures (or strain criteria) if any, and reanalysis for Piping System # 1, if required.

This may be continued in Phase II as the ongoing ETEC tests continue, and nonlinear analyses may be performed for prediction of failures for Piping System # 2 and other tests, etc.

Thus, the subject Phase I and proposed Phase II efforts can also become an integral part of the very important and significant overall piping test program sponsored by USNRC. Our contributions in the form of nonlinear analysis results, in conjunction with the strain criteria, can help the overall success of this USNRC program. Conversely, this program is program is ideally suited and timed to help provide validity to our analysis procedure and strain criteria.

- Finally, it is recommended that a manual for the use of the simplified nonlinear analysis procedure (and the computer program) with sample examples, in conjunction with the strain criteria, and its use in the design of piping systems and supports using the ASME code, may be developed. This can help piping engineers in ready use of this simplified nonlinear analysis procedure, in conjunction with the strain criteria, for routine use in the nuclear industry, at least for preliminary design purposes.

REFERENCES

REFERENCES

1. Severud, L.K., Anderson, M.J., Lindquist, M.R., Wagner, S.E., and Weiner, E.O., "High-Level Seismic Response and Failure Prediction Methods for Piping", HEDL-TME86-11, Prepared by Hanford Engineering Development Laboratory, operated by Westinghouse Hanford Company, Richland, Washington, February 1987.

2. "Summary and comparison of Simplified Methods for Predicting Inelastic Seismic Response of Piping Systems," RI/R886-107, Prepared by Rockwell International for Electric Power Research Institute, May 1986.

3. Newmark, N. M., "A Response Spectrum Approach for Inelastic Seismic Design of Nuclear Reactor Facilities," Transactions of Third International Conference on Structural Mechanics in Reactor Technology, London, Paper K5/1, Vol. 4, 1975.

4. Campbell, R. D., Kennedy, R. P., and Thrasher, R. D., "Inelastic Response of piping Systems Subjected to In-Structure Seismic Excitation," ASME Paper 83-PVP-50.

5. Jaquay, K., "A Simplified Limit Analysis Approach for Seismic Design of Ductile Piping Systems," ASME Winter Annual Meeting, New Orleans, Dec. 1984.

6. Newmark, N. M., Hall, W. J., "Procedures for Criteria for Earthquake-Resistant Design," Building Practices for Disaster Mitigation, Building Sciences Series 46, NBS, 1973.

7. Ridell, R., and Newmark, N. M., "Statistical Analysis of the Response of Nonlinear Systems Subjected to Earthquakes," SRS 468, Department of Civil Engineering, University of Illinois.

8. Shibta, A., Sozen, M. A., "Substitute-Structure Method for Seismic Design in R/C," Journal of Structural Division, ASCE, Vol. 102, ST1, Jan. 1976.

9. Iwan, W. D., and Gates, N. C., "The Earthquake Response of Hysteretic Structures," Proceedings of US-Japan Panel on Wind and Seismic Effects, 1977.

10. Iwan, W. D., "Estimating Inelastic Response Spectra from Elastic Spectra," Journal of Earthquake Engineering and Structural Dynamics, Vol. 8, No. 4, 1981.

11. "Tentative Provisions for the Development of Seismic Regulations of Buildings," Applied Technology Council, NSF Publication 78-8, NBS Special Publication 511, 1978.

12. Kennedy, R. P., Short, S. A., Merz, K. L., Tokarz, F. J., Idriss, I. M., Power, M. S., and Sadigh, K., "Engineering Characteristics of Ground Motion, Task I: Effects of Characteristics of Free-Field Motion on Structural Response," NUREG/CR-3815, May 1984.

13. Zahrah, T. F., Hall, W. J., "Seismic Energy Absorption in Simple Structures," University of Illinois, Department of Civil Engineering, Report UILU-ENGR-82-2011, July 1982.

14. Iwan, W. D., Gates, N. C., "Estimated Earthquake Response of Simple Hysteretic Systems," Journal of the Engineering Mechanics Division, ASCE, Vol. 115, No. EM3, June 1979.

15. Jaquay, K., "A Simplified Limit Analysis Approach for Seismic Design of Piping Systems," ASME Winter Meeting, New Orleans, December 1984.

16. Caughey, T. K., "Random Excitation of a System with Bilinear Hysteresis," Journal of Applied Mechanics, December 1960.

17. Transirikongkol, V., Pecknold, D. A., "Approximate Modal Analysis of Bilinear MDF Systems," Journal of the Engineering Mechanics Division, ASCE, Vol. 116, pp. 361-375, 1981.

18. Impell Corporation, "Conceptual Study to Develop Revised Dynamic Code Criteria for Nuclear Power Plant Piping," Prepared for Electric Power Research Institute, EPRI NP-4210, August, 1985.

19. Chen, W.P., Onesto, A.T., and De Vita, V., "Seismic Fragility Test of a 6-Inch Diameter Pipe System", NUREG/CR-4859, Prepared by Energy Technology Engineering Center, February, 1987.

20. English, W. F., "Piping and Fitting Dynamic Reliability Program, Second Semi-Annual Progress Report, November 1985-April 1986," NEDC-31364, Prepared by General Electric Company, San Jose, Ca., November, 1986.

21. Haas, E., Schrader, W., Eckey, H., Nink, A. and Stoblen, H., "Experimental and Analytical Investigation of Dynamic Response of Branched Piping System Due to Elasto-Plastic Behavior," Paper K15/3, 8th SMIRT Conference, Brussels, 1985.

22. Howard, G. E., Walton, W. B., and Johnson, B. A., "Laboratory Studies: Dynamic Response of Prototypical Piping Systems," Paper K15/2, 8th SMIRT Conference, Brussels, 1985.

23. Kussmaul, K., "Stress and Failure Studies Related to the HDR Pressure Vessel and Piping," Nuclear Engineering and Design Journal, Vol. 88, No. 3, 1985.

24. Muller, K. U., Diem, H., and Hunger, H., "Investigation of Stressing and Failures of Pipe Bends Under Complex Loadings," Nuclear Engineering and Design Journal, Volume 87, 1985.

25. Rodabaugh, E. C., and Moore, S. E., "Evaluation of Plastic Characteristics of Piping Products in Relation to ASME Code Criteria," NUREG/CR-2061, July 1978.

26. Franzin, W. E., and Stokey, W. F., "The Elastic-Plastic Behavior of Stainless Steel Tubing Subjected to Bending, Pressure and Torsion," Second International Conference on Pressure Vessel Technology, San Antonio, 1979, Published by ASME.

27. Sherman, D. R., "Test on Circular Steel Tubes in Bending," Journal of Structural Division, American Society of Civil Engineers, 102, ST11, 1976.

28. Gerber, T. L., "Plastic Deformation of Piping Due to Pipe-Whip Loading," ASME Paper No. 74-NE-1.

29. Belke, L., "A Simple Approach for Failure Bending Moments of Straight Pipes," Nuclear Engineering and Design Journal, Vol.77, 1985.

30. Norris, D. M., Martson, T. V., and Tagart, S. W., "Acceptance Criteria for Circumferential Flaws in Stainless Steel Piping," ASME PVP Conference, June 1982.

31. Campbell, R. D., and Kennedy, R. P., "Dynamic Reserve Margin In Piping Systems Subjected to Seismic Loading," Chapter 4.12 in "Decade of Progress," 1985, pp. 463-482.

32. Jaquay, K.R., Larson, J.E., Tang, H.T., "A Simplified Method for Inelastic Piping System Seismic Response", Symposium on Current Issues Related to Nuclear Power Plant Structure, Equipment and Piping, Raleigh, North Carolina, December 10-12, 1986.

APPENDIX A

DERIVATION OF FORMULA FOR CALCULATION OF DUCTILITY FACTOR FOR RATCHETTING FAILURE

DERIVATION OF FORMULA FOR CALCULATION OF DUCTILITY FACTOR FOR RATCHETTING FAILURE

A simplified approach is presented herein for calculation of ductility factor for ratchetting failure. This simplified model is based on a tension-compression, elastic-plastic single-degree-of-freedom system subjected to static load with superimposed cyclic loadings (Ref. 31). An actual piping system that is subjected to internal pressure may not ratchet to the degree that the simplified model indicates.

This simplified model is conservative in that inelasticity is assumed to occur only in incremental deformation steps. In actual system, energy is absorbed in cyclic plastic deformation.

Consider the idealized force - deformation relationship, shown in Figure A-1. In this case, N cycles of approximately equal ratchetting occur.

In Figure A-1,

F_p = Maximum load at maximum displacement

F_y = Load at Yield

F_s = Static load superimposed

δy = Yield deformation

δfn = Total deformation

$\delta_{f(N-1)}$ = Total deformation after N cycles of ratchetting

K = First slope of the force - deformation relationship

K_s = Slope of strain hardening part of force - deformation relationship

Other definitions and relationships from Figure A-1 are:

$$\text{Ductility Factor, } \mu' = \frac{\delta fn}{\delta y}$$

$$\mu' - 1 = (\delta_{fn} - \delta_y)/\delta y$$

$$r = Fs/Fy$$

$$\delta'_{nL} = \delta_{fn} - \delta_{f(N-1)} = \delta y\ (\mu_1 - 1), \text{ where } \mu_1 = \frac{\delta_{f1}}{\delta y}$$

$$\text{so that } (\mu_1 - 1) = (\mu' - 1)/N$$

In order to equate previous nonratchetting elastic-plastic system to the ratchetting system, an equivalent single cycle force-deformation diagram is defined for the dynamic load ratchet cycle as noted by points A, B, and C on Figure A-1, and is shown in Figure A-2. In Figure A2, F'_p is the total load at maximum deformation δ_f and δ_{ye} is the equivalent yield load at equivalent yield displacement of δ'_{ye}. Therefore,

$$F'_p = F_p = F_s$$

$$F_{ye} = F_p - fK\delta_{nL} - F_s$$

$$\delta'_y = F_{ye}/K$$

$$\delta'_f = \delta y + \delta'_{nL}$$

Therefore,

$$\mu = \frac{\delta'_f}{\delta' y} = 1 + \frac{\delta y}{\delta' y} (\mu_1 - 1)$$

where $\frac{\delta y}{\delta' y} = \frac{1}{1 + r (\mu' - \mu_1) - r}$

so that,

$$\mu = 1 + \frac{\mu' - 1}{N \left[1 + r \frac{(N-1)}{N} (\mu - 1) - r\right]}$$

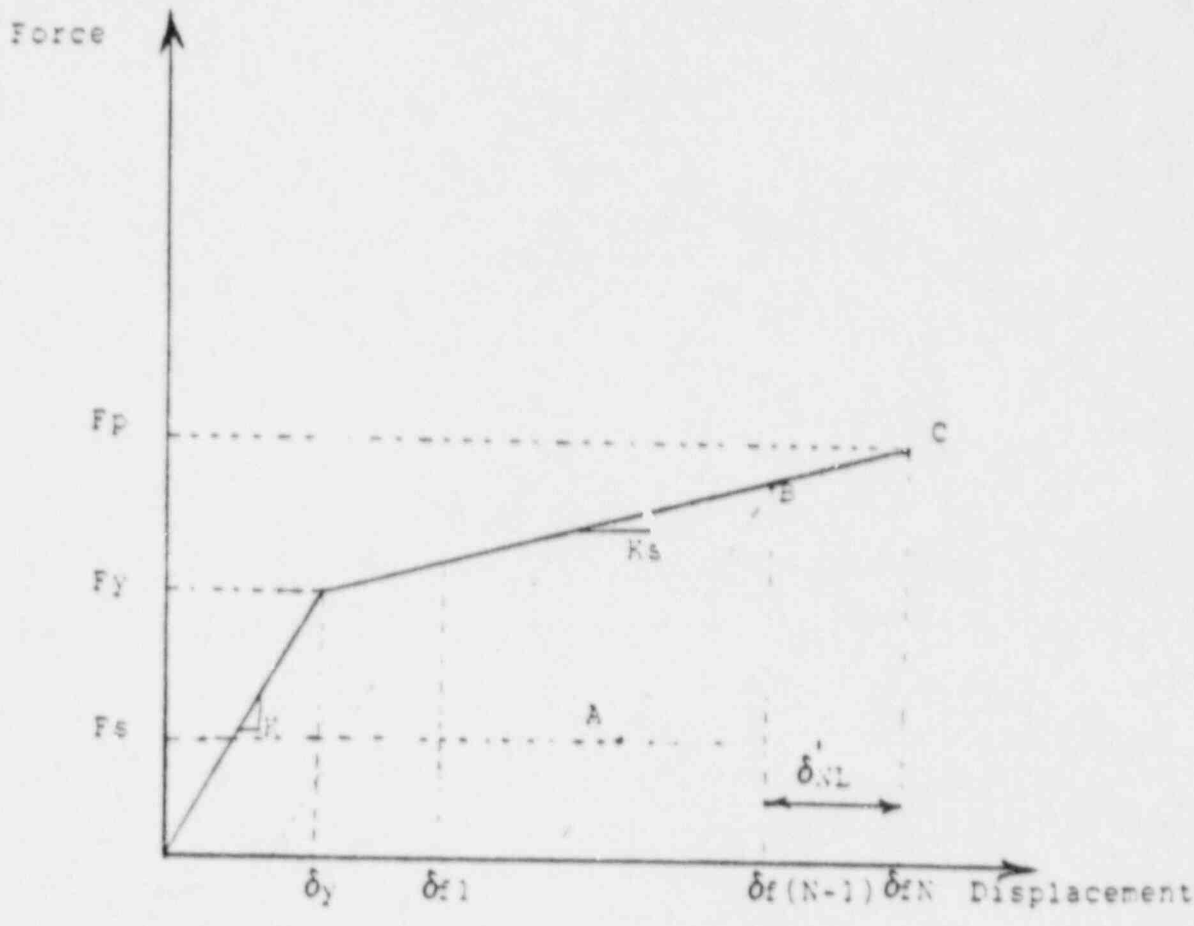


FIGURE A-1. FORCE-DEFORMATION RELATIONSHIP FOR RATCHETTING BILINEAR SYSTEM

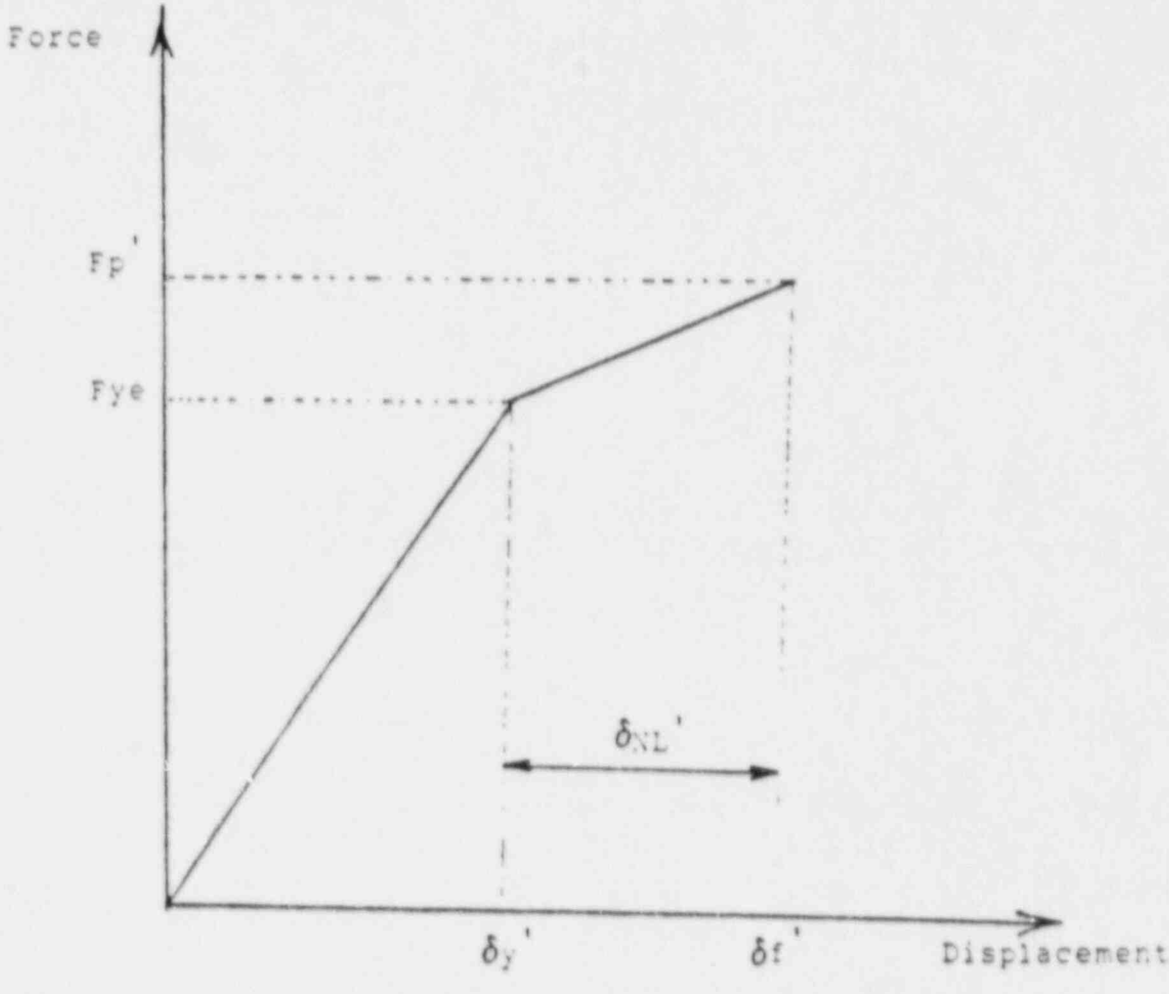


FIGURE A-2. "EQUIVALENT" SINGLE FORCE-DEFORMATION RELATIONSHIP (SINGLE CYCLE)

APPENDIX B

DESCRIPTION OF THE COMPUTER PROGRAM SATRAN

DESCRIPTION OF THE COMPUTER PROGPAM SATRAN

The computer program SATRAN, developed in-house at Structural Analysis Technologies, Inc., is a general purpose finite element analysis program for three-dimensional static and dynamic linear analysis of structures of any shape or type on microcomputers, such as IBM/AT.

SATRAN is based on an extensively modified version of SAP, originially developed at University of California, Berkeley. With the state-of-the-art organization for micro-computers, coupled with dynamic substructuring capabilities, SATRAN has practically no limitations on the size or type of problem.

The salient features of the program are presented below:

Element Library

- 3D Truss (Bar)
- 3D Beam
- Plane Stress and Strain
- Axisymmetric
- Thin Plate and Shell
- 3D Solid (Brick)
- Boundary Spring

Analysis Options

- Static Analysis
- Thermal Stress Analysis
- Frequency Analysis
- Dynamic Analysis
- Seismic Analysis

Solution Techniques

- Blocked Acitve Column Equation Solver
- Double Precision 64-Bit Arithmetic
- Subspace Iteration Eigenvalue Solution

Additional Options

- Automatic Mesh Generation
- Bandwidth Minimization
- Free-field Format
- Dynamic Substructuring

Graphics and Plotting

- Undeformed Structural Geometry
- Deformed Shapes
- Arbitrary Viewing Direction
- Automatic Scaling
- Slicing and "Blow-up" Options
- User-Controlled Scaling of Deformed Shapes

- Modeshapes Animation
- Node and Element Labeling
- Interactive Color Graphics and Plotting

APPENDIX C

DESCRIPTION OF THE COMPUTER PROGRAM NPIPE

DESCRIPTION OF THE COMPUTER PROGRAM NPIPE

The computer program NPIPE, developed in-house at Structural Analysis Technologies, Inc., is a program for nonlinear inelastic static and time history dynamic analysis of three-dimensional piping systems of any arbitrary shape for any type of generic loading, primarily for use on microcomputers, such as IBM/AT.

The piping system is modeled by three-dimensional pipe elements. The valves may be modeled by beam elements, and the hangers, uniaxial rods, and springs may be modeled by boundary spring elements. Various different types of restraints can also be modeled using spring elements with gaps and nonlinear frame elements.

The loading may consist of static or time history dynamic loads. The seismic time history can be applied at supports in three orthogonal directions. Time histories of forces can also be applied at nodal points anywhere in the piping system. For example, dynamic force time histories resulting from circumferential or longitudial breaks in piping systems can be applied in the form of dynamic forcing functions at nodal points.

Material and geometric nonlinearities, such as gaps between piping and restraints, can be modeled, as well as large displacements. For material nonlinearity, an yield criterion, including interaction between the bending moments in the two directions and the torsional moment, is considered. Strain hardening effects are also included.

The program has various additional useful features, e.g., restart options and out-of-care solutions for large problems.

A brief description of the yield criteria, treatment of damping and analytical techniques used in NPIPE is presented below.

C1. Yield Criteria and Nonlinear Moment-Curvature Relationship

Figure C-1 presents the multilinear moment-curvature relationship used in NPIPE. This relationship is modeled in NPIPE using pipe elements acting in parallel, one with an elastic-plastic relationship and the others with linear relationships (modeling slopes of the strain hardening curve). This approach was originally developed at UC Berkeley, and has been used successfully in various computer programs.

A standard von Mises yield criterion is used in conjunction with the multilinear moment-curvature relationship, and given by:

$$\left(\frac{M1}{Mp1}\right)^2 + \left(\frac{M2}{Mp2}\right)^2 + \left(\frac{M3}{Mp3}\right)^2 = 1$$

where M1, M2 and M3 are the applied bending moments about the three axes, and Mp1, Mp2 and Mp3 are the corresponding moment capacities.

C2. Damping

A standard Rayleigh type damping (mass and stiffness proportional) is used, given by

$$\xi = \alpha M + \beta K$$

C3. Analytical Techniques

The program NPIPE determines the nonlinear dynamic response of 3-D piping systems and supports for ground motion time histories applied at the supports or any types of forcing functions applied at nodal points. A static load is first performed for gravity, thermal and pressure loadings before dynamic analysis. The program includes pipe elements, as well as beam elements, boundary elements and special support elements. The inelastic behavior of all types of elements, as well as supports, is taken into account. Geometric nonlinearities and large displacement effects can also be considered. A step-by-step solution of the equilibrium equations is carried out and the structure stiffness is modified at each time step based on the inelasticity in the various piping elements. The out-of-balance moments and forces are corrected at each time step. Time histories of displacements at nodes; moments, forces and deformations in pipe elements and supports are computed. Maximas of these quantities are also calculated.

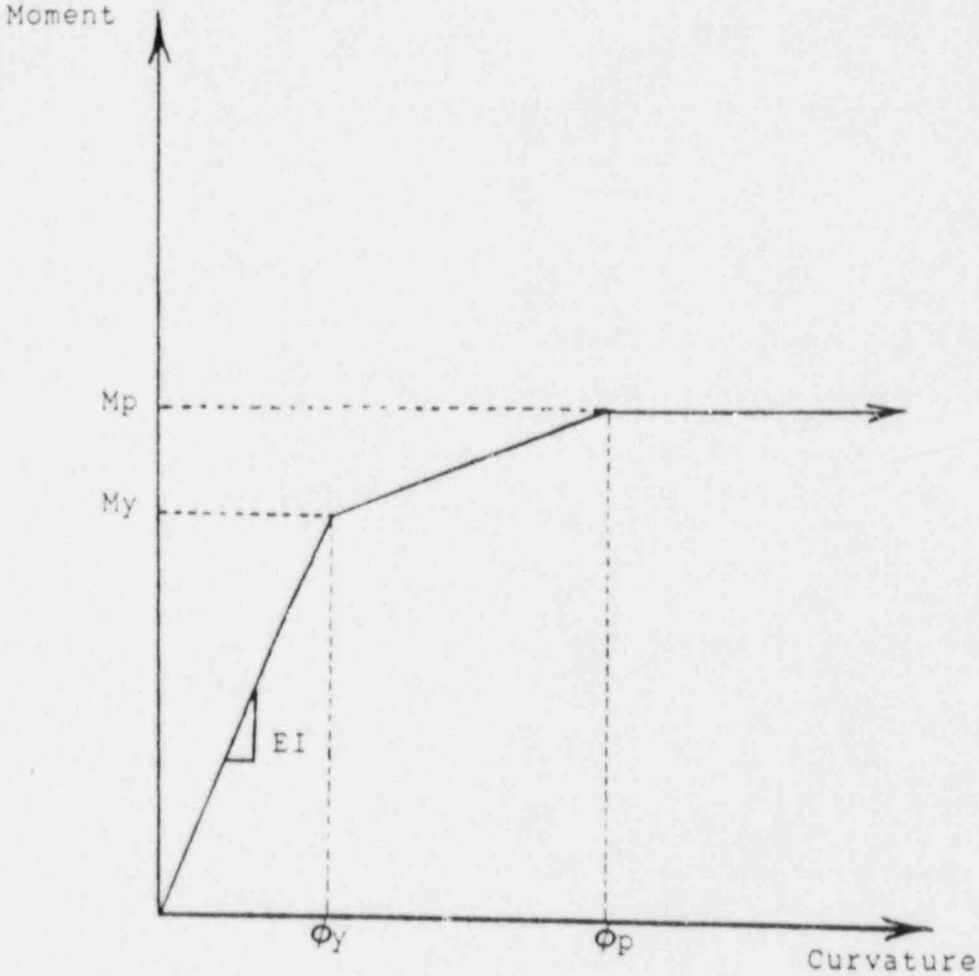


Figure C-1. Moment-Curvature Relationship

APPENDIX D

ASSESSMENT OF N, THE NUMBER OF CYCLES OF INELASTIC RATCHETTING, FOR A PIPE/PIPE-SUPPORT ELEMENT FOR EARTHQUAKE LOADS

ASSESSMENT OF N, THE NUMBER OF CYCLES OF INELASTIC RATCHETTING FOR A PIPE/PIPE-SUPPORT ELEMENT FOR EARTHQUAKE LOADS

The value, N, needed for calculation of modified ductility ratio, considering ratchetting, in the simplified nonlinear procedure, will vary depending upon:

1. The duration and level of earthquake shaking.
2. The level of stress in a given element.

If the level of stress in a given pipe/pipe-support element is represented by the initial ductility ratio, μ (i.e. ratio of stress induced in element from a linear elastic analysis to the yield stress), then we seek to obtain a relationship between N and μ which will, in general, look like that shown in Figure D-1.

The value of N depends upon the nature and duration of the earthquake excitation and can be obtained by the following empirical procedure.

1. Select candidate earthquake excitation records, e.g., earthquake time histories corresponding to typical floor response spectra (Figure D-2).

2. Scale these records so that the peak acceleration is 1.0.

3. Measure the number of excursions that lie above given acceleration value, e.g., 0.6, 0.7, and 0.8 etc. and tabulate as shown below.

TABLE D-1

Excursion Above Selected Acceleration for a Response Time History

Acceleration, $\ddot{u}g$	Cumulative Number of Excursions, N, above $\ddot{u}g$
0.4	40
0.5	35
0.6	30
0.7	25
0.8	10
0.9	5

4. Take the average from a significant number of earthquakes and tabulate.

5. A member ductility of μ implies that member yield occurs at acceleration $1/\mu$. To obtain N for a ductility value, μ, we simply have to find the corresponding N for the acceleration $1/\mu$ which can be read off from the table created in Step 4 giving us the desired N vs. μ curve.

Note: As already stated in the main text, the N vs. μ curve will be derived in Phase II from a large number of actual floor spectra. This relationship will then be built into the computer program for simplified nonlinear analysis of piping systems.

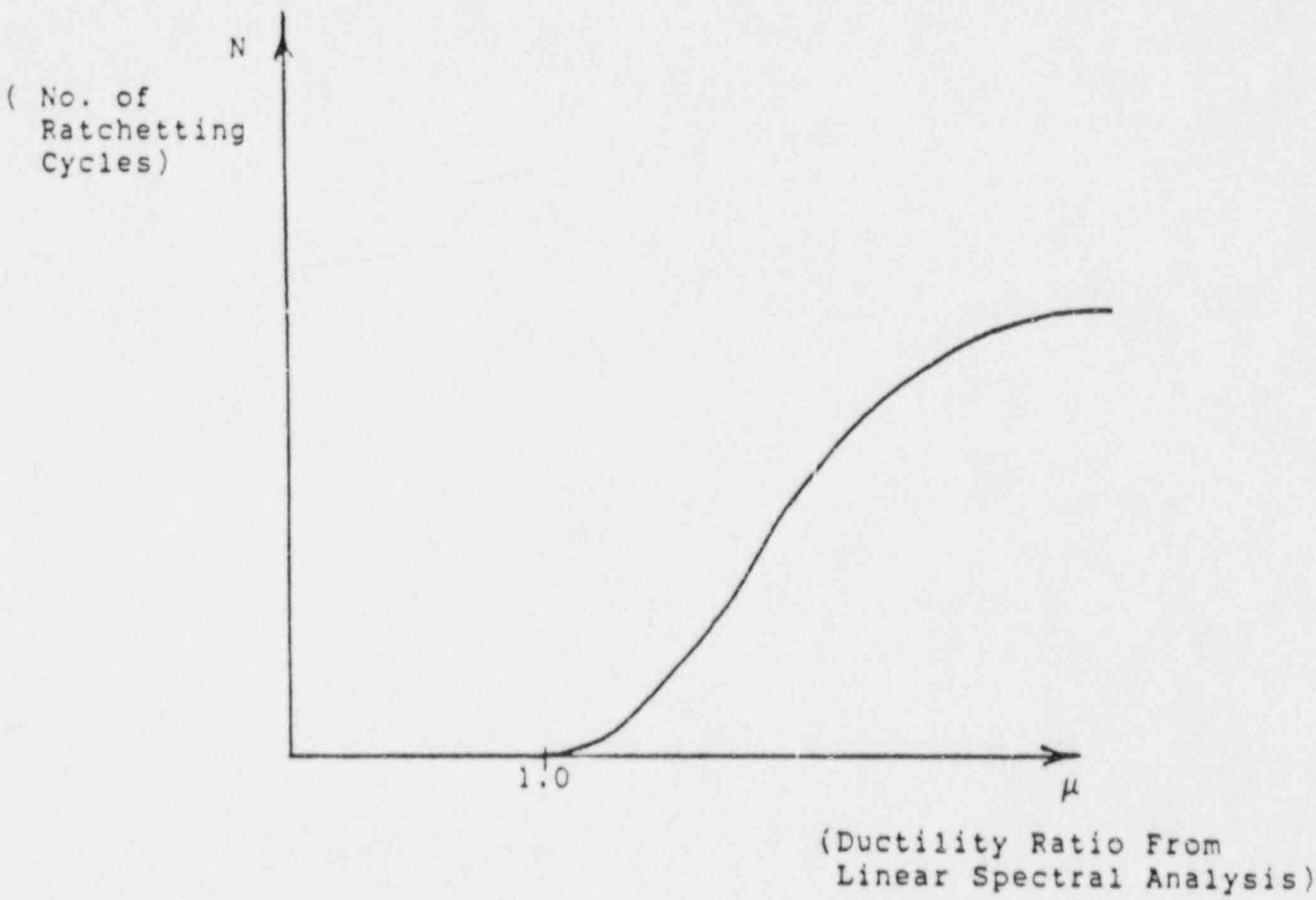


FIGURE D-1. N VERSUS μ CURVE

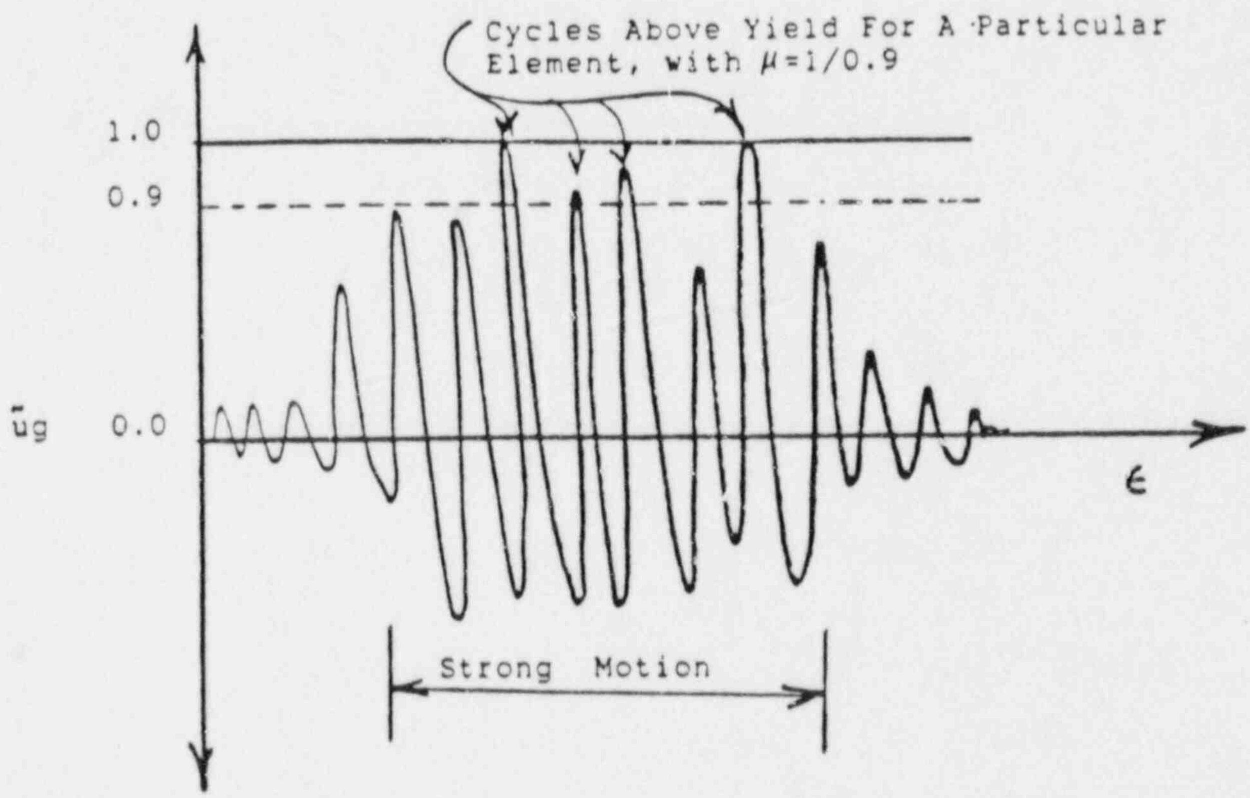


FIGURE D-2. EARTHQUAKE FLOOR EXCITATION TIME HISTORY SCALED TO PEAK ACCELERATION OF 1.0g

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol No., if any)

SAT 250.01

2. TITLE AND SUBTITLE

Improvement Of Safety Of Piping Systems Using Nonlinear Analysis Methods

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
April	1987

5. AUTHOR(S)

Hasan Kamil

6. DATE REPORT ISSUED

MONTH	YEAR
April	1987

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Structural Analysis Technologies, Inc.
10440 South De Anza Boulevard, Suite D7
Cupertino, CA 95014

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER

SBIR NRC-04-86-129

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

SBIR/Office Of Nuclear Regulatory Research
US Nuclear Regulatory Commission
Washington, DC 20555

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

Oct. 1986-April 1987

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

The report presents the research and development work performed in Phase I of the SBIR project on improvement of safety of piping systems, subjected to dynamic loads, using nonlinear methods. The primary objective of the research was to study current criteria and procedures for nonlinear analysis methods, as well as available test results, and carry out preliminary development of a simplified nonlinear analysis method and an associated strain criterion. Benchmark analyses were then performed using simplified and detailed (time history) methods to validate the simplified method, and to predict potential failure locations (and loads) for a piping system to be tested under USNRC/EPRI sponsored test program for further validation of the analysis method and criteria. Recommendations were then developed for future research efforts in Phase II.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS

Piping, Nonlinear Analysis, Strain Criteria, Seismic Loads, ASME Code

b. IDENTIFIERS/OPEN-ENDED TERMS

Nonlinear Analysis Of Piping Systems

15. AVAILABILITY STATEMENT

Unlimited

16. SECURITY CLASSIFICATION

(This page)

Unclassified

(This report)

Unclassified

17. NUMBER OF PAGES

18. PRICE