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ALIGN MECHANICAL AND CIVIL-STRUCTURAL EARTHQUAKE DESIGN AND QUALIFICATION RULES FOR ASME B31 PIPING SYSTEMS AND PIPELINES

ASME STANDARDS TECHNOLOGY, LLC

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Prepared by:

George Antaki
Becht Engineering Company

ASME STANDARDS TECHNOLOGY, LLC

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ASME Standards Technology, LLC
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FOREWORD

This report provides recommendations for an improved interface between current seismic design, analysis and qualification codes and standards, as well as recommendations for improvements of these codes and standards, to achieve a consistent, complete, and non-redundant set of requirements and guidance for the design engineers.

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ABSTRACT

The objective of this report is three-fold:

1. Conduct and document a literature search to obtain data on the performance (displacements, support and anchor loads, and failure) of piping subjected to earthquake motions. The document will present in a clear and structured format information concerning seismic performance of piping systems from experimental data and from high magnitude earthquake data on piping performance collected from post-earthquake investigation reports.
2. Provide recommendations for an improved interface between current seismic design, analysis and qualification codes and standards, as well as recommendations for improvements of these codes and standards, to achieve a consistent, complete, and non-redundant set of requirements and guidance for the design engineers.
3. Summarize U.S. seismic shake table test capabilities for piping components and piping systems.

The current situation regarding codes and standards for the seismic analysis and qualification of piping systems needs improvements. In Section 1 of this report, specific recommendations are made for improvement of the interface between ASCE, ASME, and MSS-SP and improvements within ASCE-7 and MSS-SP-127. These recommendations are intended to achieve a better fit between the codes and standards, and clarify their requirements.

A diagram depicts how the interface between ASCE, ASME, and MSS-Sp should work. Annex A outlines the contents of a good piping system seismic analysis and qualification procedure.

Section 2 documents experience in seismic testing of piping components and piping, and their performance in real earthquakes.

Section 3 summarizes capabilities for seismic shake table testing in the U.S.

1 RECOMMENDATIONS FOR SEISMIC DESIGN AND QUALIFICATION

1.1 Objective

This Section provides recommendations for an improved interface between current seismic design, analysis and qualification codes and standards, as well as recommendations for improvements of these codes and standards, to achieve a consistent, complete, and non-redundant set of requirements and guidance for the design engineer.

1.2 Overview: Piping Systems Seismic Design and Qualification Standards

Currently, there are a number of codes and standards that address the seismic qualification of piping systems:

- The International building Code (IBC), which since 2000 has consolidated and replaced a number of other building codes. IBC refers to ASCE 7. By doing so, it avoids overlap and possibly contradictions with ASCE-7.
- ASCE 7 Section 13, which provides the seismic input to be applied in the analysis of piping systems (the demand) and, for process and power piping, refers to ASME B31 for one option for qualification. The exceptions from explicit seismic qualification (systems that do not require seismic bracing) are not consistent with ASME B31 and ASME B31E.
- ASCE 43 applies to seismic design of safety-related structures, systems and components in nuclear facilities (in practice nuclear process facilities, such as U.S. Department of Energy facilities) as opposed to nuclear power plants.
- ASCE 4 and U.S. Nuclear Regulatory Commission Standard Review Plan NUREG 0800 Chapter 3, applies to the analysis and qualification of safety-related piping systems in nuclear power plants.
- ASME B31 applies to power plant piping systems (B31.1), process plant piping systems (B31.3), pipelines (B31.4 and B31.8), utility systems (B31.5 and B31.9), and hydrogen systems (B31.12). The B31 code books do not address the seismic input (the demand), but they address the seismic capacity in the form of stress limits for occasional loads, but between ASME B31 code books, not all the occasional stress limits are the same.
- ASME B31E is meant to apply to all ASME B31 code books for above-ground metallic piping systems. It provides a well-structured overview of the seismic qualification process, and it provides guidance on when to use qualification by analysis and when to use qualification by rule. Qualification by analysis is based on the stress limit of $2.4S_h$, which is larger than current ASME B31 stress limits for occasional loads.
- MSS-SP-127 is a standard for design by rule of piping (spans) and braces (standard bracing details). Its primary value to the designer is in the figures of seismic bracing. The seismic input (demand) is not consistent with ASCE-7, and the spans are based on fire protection standard NFPA-13 and not on the ASME B31 code or the ASME B31E standard.
- NFPA-13 is similar to MSS-SP-127 and applies to sprinkler systems. It uses a design by rule approach, and permits analysis but without explicit analysis requirements, relying instead on the professional engineer.
- FEMA 450 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. This document has a Section 6.4 Mechanical and Electrical Components, which has requirements redundant with ASCE-7, and others, which contradict

ASCE-7. Its "Appendix to Chapter 6 – Alternative Provisions for the Design of Piping Systems" is in many places a copy of ASME B31E, yet it does not reference B31E. This FEMA document is at places redundant and in others contradictory to ASME B31E and ASCE-7.

- The State of California Office of Safety Health Planning and Development (OSHPD) regulates seismic bracing of piping systems in critical facilities, such as hospitals.
- SMACNA "Guidelines for Seismic Restraints of Mechanical Systems and Plumbing Piping Systems" applies to duct piping and plumbing systems.
- Vendor-specific standards include R-0003 the Superstrut "Seismic Restraint System," R-0114 B-Line System, R-0120 Unistrut "Seismic Bracing Systems," Tolco "Seismic Restraint Systems Guidelines," Cooper B-Line Seismic Restraints, Loos & Co Seismic Restraints, etc. Some of these vendor-specific bracing systems are pre-approved by OSHPD.

1.3 How the Interface Should Work

As described in Section 1.2, the interface between standards for the seismic design and qualification of piping systems overlaps and, in some cases is contradictory.

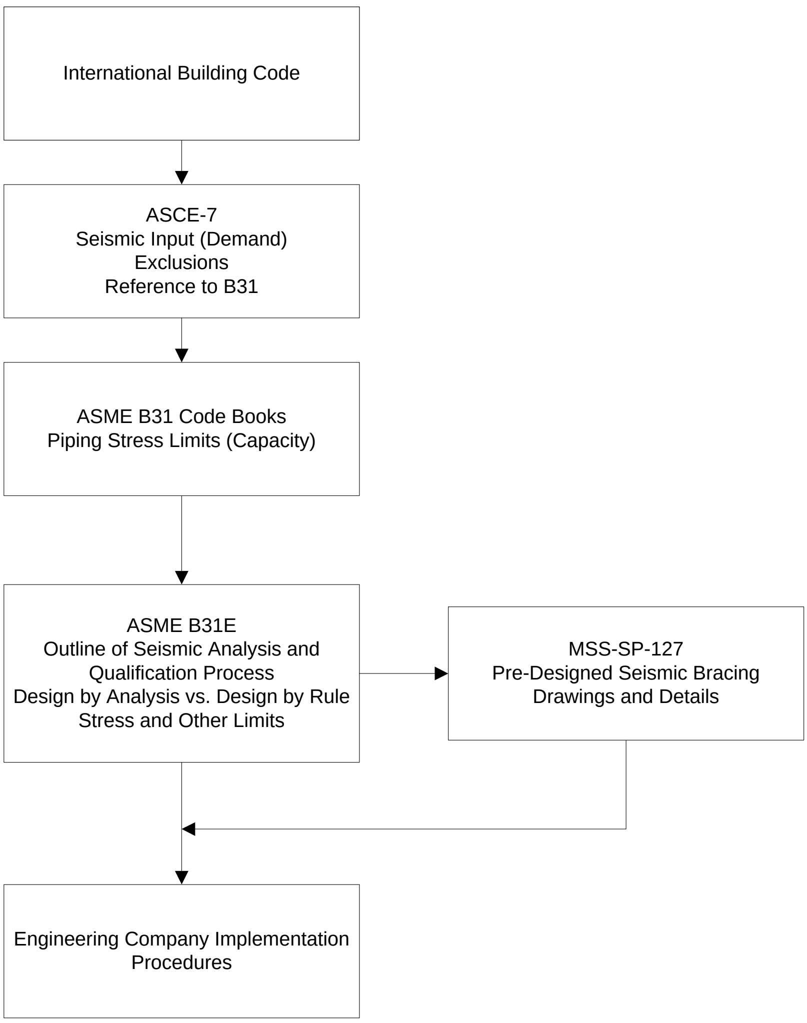

Figure 1 - How the Seismic Analysis and Qualification Process Should Work

Figure 1 outlines one way the interface can work for above-ground metallic piping systems in the scope of ASME B31:

- IBC refers to ASCE-7 for piping systems (and more generally for mechanical and electrical systems).
- ASCE-7 defines the seismic input (demand) in the form of static coefficients or response spectra.
- ASME B31 defines the capacity in the form of seismic stress limits (occasional loads) and how they should be combined (or not combined) with sustained and expansion stresses.
- ASME B31E outlines the seismic qualification process, the choice of qualification by analysis or rules, and stress limits, consistent with ASME B31, and capacity limits other than stress limits.
- MSS-SP-127 provides seismic bracing details, without contradicting the input (demand) of ASCE-7 or the capacities of ASME B31 and B31E.

1.4 Recommendations for MSS-SP-127-2001

There are several good features to MSS-SP-127-2001. But there are also many shortcomings that deserve prompt attention. These shortcomings are addressed here.

Recommendation SP-1. Change the Purpose statement. It states, for purpose:

> "1.1 Piping systems shall be protected to reduce the risk of piping overstress where subject to seismic, wind and other dynamic forces."

This is not a scope statement, instead it is a requirement. It is a requirement that belongs in a building code (IBC), not in a standard on how to achieve seismic adequacy. It is also a requirement that ignores the fact that not all piping systems need to be seismically designed. Many systems need not be seismically designed as their seismic-induced failure would not cause harm to the public, the worker, or the environment. To state that these inconsequential systems "shall be protected to reduce the risk of piping overstress" during an earthquake is unnecessary and cost-prohibitive. It is in fact not the practice in the power, pipeline, or process industries.

Recommendation SP-2. The Scope statement has one paragraph that may well be the most useful aspect of MSS-SP-127. It states:

> "2.3 This Standard Practice is intended for use on piping systems where formal engineered bracing design may not have been performed."

This approach rules for pre-qualified seismic spans and seismic bracing. This approach to seismic design of piping systems is what is commonly referred to as a cook-book approach, as opposed to the stress analysis approach contained in the ASME B31 codes. Seismic spans are addressed in ASME B31E, but pre-qualified pipe supports are not provided elsewhere.

Recommendation SP-3. Exemptions from seismic bracing are addressed in MSS-SP-127 Section 4.1. Of particular interest are the following exceptions:

> "a) Piping in boiler and mechanical equipment rooms 1 inch (25 mm) and less nominal pipe size.
>
> b) All other piping 2 inch (50 mm) and less nominal pipe size, except as noted in 4.1 a."

These two exemptions based on size alone are not in ASCE 7, ASME B31E or in ASME B31. In fact, they cannot be justified as some lines 2 inch and less can contain toxic materials and should be seismically restrained. We have seen small lines fail in large earthquakes, particularly as a result of seismic anchor motion.

Recommendation SP-4. The bracing spacing is stated as:

> "4.5 Lateral bracing shall be spaced at a maximum of 40 ft. (12 m).
>
> 4.6 Longitudinal bracing shall be spaced at a maximum of 80 ft. (24 m) and shall be attached directly to the pipe."

This approach, very similar to NFPA-13, has no technical basis. The spacing should be a function of several parameters, as addressed in ASME B31E: (a) The seismic acceleration level (the higher the acceleration the shorter the spacing), (b) the presence of equipment nozzles (spans near pumps or compressors that have to operate after an earthquake, etc.), (c) the pipe material, (d) the type of pipe joints, etc.

Recommendation SP-5. The following requirement is not realistic, as few projects have a sufficiently detailed building analysis to know when different parts of buildings "respond differently." If they do, they then do have relative anchor motion and should be able to determine if these motions (called seismic anchor motions) are damaging given the pipe layout. The statement in question follows:

> "4.18 A length of pipe shall not be braced to parts of a building (walls, ceilings, floors, etc.) that may respond differently during dynamic loading (seismic, or other)."

Recommendation SP-6. The following requirement needs to be clarified and technically justified, as it can lead to costly bracing:

> "4.20 Each change in direction of the piping system that is greater than 12 feet (3.7 m) in length shall be braced."

This is probably meant to say that each span with a bend, elbow, tee or branch shall not exceed 12 ft. between seismic braces, compared to the 40 ft.-long straight span. This is a tall order.

Recommendation SP-7. The use of U-bolts is indeed useful and common for lateral bracing. However, U-bolt catalogs often do not provide a lateral capacity for the U-bolt. MSS-SP-127, with its strong manufacturers' membership, could address and solve this question better than others. The paragraph in question follows:

> "10.3 Brackets, anchors and guides, which are also being considered as lateral and longitudinal braces shall be checked to ensure that the additional expected loads generated by seismic, wind, or other dynamic loading do not exceed the maximum load ratings for the pipe hanger/support in all directions. Often, providing a U-bolt to a bracket can meet the requirement of a lateral brace. Floor stands must be analyzed for stability."

Recommendation SP-8. Table 2 should be eliminated from MSS-SP-127. It is based on an applied seismic load stated as:

> "To calculate horizontal seismic force, use the following formula: Fs = Cs Wp"

This formula is different than ASCE 7 for piping systems, and should not be used for projects that reference IBC or UBC. The seismic demand (the input load formula) should not be in MSS-SP-127 or ASME B31; it is site-specific and building-specific and it belongs to IBC (and ASCE 7 by reference).

Recommendation SP-9. The bracing figures are quite valuable. However, because the input load does not comply with IBC/ASCE-7, the actual member sizes should not be used without verification by calculations based on the IBC/ASCE-7 input load. Instead of pre-sized members, the standard should provide step-by-step calculation procedures to size braces, with examples.

1.5 Recommendations for ASCE-7-05

Recommendation ASCE7-1. Section 13.2.1 of ASCE 7 (similar in 13.6.5) – "… shall comply with the sections referenced in Table 13.2-1" add "except where exempted in accordance with Section 13.1.4".

Recommendation ASCE7-2. ASCE 7 Sections 2.4.1 and 13.1.7 and 15.1.2 – Should a statement be added along the lines of "Where 0.7E is used for allowable stress design, the design code allowances for an increase in seismic allowable stress shall not be permitted"? In other words, should the ASME B31 occasional load (seismic) allowable stress of 1.3S (30% increase over S the allowable for sustained loads) be used together with 0.7E?

Recommendation ASCE7-3. ASCE 7 Section 13.3 – Add a new section for dynamic analysis along these lines: "13.3.3 Seismic Dynamic Input. Where the designer selects to design using response spectra modal analysis, the seismic design input response spectrum in the horizontal direction shall be in accordance with Section 11.4.5, where the spectrum is multiplied by (1 + 2 z/h) / R_P. Alternatively, building-specific in-structure spectra may be used. The vertical input may be 0.2 S_{DS} unless building-specific in-structure spectra are developed."

Recommendation ASCE7-4. ASCE 7 Section 1.5.2 and Table 1.1 and definition of Hazardous Content in 11.2 – In addition to "public," add "worker and environment".

Recommendation ASCE7-5. ASCE 7 Section 13.1.3 – Table 1.1 refers appropriately to "threshold quantity". The same should be added to 13.1.3 item 2: "The component contains hazardous materials of a quantity that could be dangerous to the public, the worker, or the environment."

Recommendation ASCE7-6. ASCE 7 Table 13.6-1 notes "rigid components and rigidly attached components" – Change to "rigid components that are rigidly attached".

Recommendation ASCE7-7. ASCE 7 Section 13.6.5.3 – The intent seems to be that for Ip = 1.0, the designer needs to check the support and its attachment weld to the vessel; while at Ip = 1.5, the designer needs to also check the vessel shell at the support.

Recommendation ASCE7-8. ASCE 7 Sections 11.7.2 and 15.7.2 – Add that the effects of the lateral force must be combined with the vertical force given in 12.4.2 (i.e. 0.2 S_{DS}).

Recommendation ASCE7-9. ASCE 7 Section 13.2.2 (b) – "maintain containment" should be by analysis or testing, delete "experience data".

Recommendation ASCE7-10. ASCE 7 Section 13.6.2 – (Deleted based on peer review comments)

Recommendation ASCE7-11. ASCE 7 Sections 13.6.8.1 and 13.6.9 – Reword to make clear the division of responsibilities: "13.6.8.1 ASME B31 Pressure Piping Systems. ASME B31 pressure piping systems, including their supports, shall be designed to the design input loads specified in this Standard. Piping systems qualified in accordance with the ASME B31 code stress, displacements and load limits shall be deemed to meet the requirements of this section." Same for vessels.

Recommendation ASCE7-12. ASCE 7 Sections 13.6.8.2 and 13.6.8.3 – Add a statement to flag to the designer that NFPA-13 is based on a constant 0.5g not on the force in Section 13.3.1. Maybe by adding upfront of Sections 13.6.8.2 and 13.6.8.3, "Fire protection systems shall be designed to the seismic force defined in Section 13.3.1."

Recommendation ASCE7-13. ASCE 7 Section 13.6.11 – Add "e. For components joined by mechanical joints and couplings (other than welded, threaded, and flanged connections), the loads and movements applied to the component due to seismic and concurrent operating loads shall not exceed the manufacturer limits. The manufacturer limits shall include a design margin of three against leakage or fracture."

Recommendation ASCE7-14. ASCE 7 Table 13.6-1 – For welded piping, change R_P from 12 down to 6.

1.6 Recommendations Regarding ASCE-7 Factor a_P

The factor a_P in ASCE-7 equation is meant to reflect the dynamic amplification of the seismic input due to the natural frequencies of the pipe spans and multi-mode response. It should be as a minimum 2.5, which would lead to 0.4 S_{DS} x a_p = 0.4 S_{DS} x 2.5 = $S_{DS,}$ which is the peak spectral acceleration. In other words, the seismic input for a piping system is the peak spectral acceleration. This appears to be conservative, but in fact, this question has been studied at length for the seismic design of nuclear power plant piping systems using static methods. It was concluded that for the seismic design of nuclear power plants using static methods, the seismic input should be 1.5 times the peak spectral acceleration, and only if the piping system has a simple geometry with a dominant mode shape (close to a single degree of freedom). This is stated in the US Nuclear Regulatory Commission Standard Review Plan (NUREG 0800) Section 3.7.2. This would make the factor a_P = 2.5 x 1.5 = 3.75.

1.7 Recommendations Regarding ASCE-7 Factor R_p

The factor R_P represents the energy absorption capacity (the ductility) of well-constructed metallic piping systems. Figure 2 is an example of such ductility. The value R_P = 12 is difficult to justify. It has been stated that R_p = 12 should only be used when applied to calculate intensified stresses and should not be used for displacements and for anchorage, or maybe for ductile anchors, but not for non-ductile anchors. This is an area of confusion that needs to be clarified. At best, such an approach (two R_p for the same system) muddies the waters as we now have two analyses: one to obtain stresses (and nozzle loads?), and the other to obtain movements (and nozzle loads?). This needs to be resolved. There should be a single seismic input, used to qualify both loads (stresses) and displacements (strains).

Figure 2 - Classic Example of Ductility of Non-Corroded, Well-Constructed, Welded Steel Pipe

One solution to achieve the objective of a consistent and technically-based factor R_P may be found in the relatively recent standard ASCE-43-05. In this standard, the seismic demand is calculated

$$D_{Seismic} = D_S / F_\mu$$

Where $D_{Seismic}$ is the seismic demand, D_S is the seismic response of the component due to the seismic inertia load, and F_μ is the inelastic energy absorption factor, given in Table 8-1 of ASCE 43-05, and repeated here, for piping systems, as Table 1. The inelastic energy absorption factor F_μ is a function of the "limit state" to be achieved, where four limit states are defined as A = short of collapse, but structurally stable, B = Moderate to permanent deformation, C = Limited permanent deformation, and D = essentially elastic.

The energy absorption factors F_μ and the factor R_P are meant to play the same role, yet their values are very different. They should be reconciled.

Table 1 - ASCE 43 F_μ Inelastic Energy Absorption Factor

Type of Pipe Joint	Limit State			
	A	B	C	D
Butt joined grooved welded pipe [sic]	1.75	1.50	1.25	1.00
Socket welded pipe	1.50	1.25	1.15	1.00
Threaded pipe	1.25	1.15	1.00	1.00

1.8 Recommendation for ASME B31 and ASME III

It is typical for an engineering firm to develop their own procedures for the application of codes and standards for the seismic analysis and qualification of piping systems. This activity is achieved with mixed results. Some procedures are quite good, others are lacking. Annex A lists the key attributes that should be covered in a competent piping analysis and qualification procedure, arranged in logical order. ASME B31 and ASME III should consider developing a guide along the lines of Annex A.

The ASME B31.E stress allowable of 2.4S should be reconciled with ASME B31 code book stress limits for occasional loads.

2 EARTHQUAKE AND SEISMIC TEST PERFORMANCE OF PIPING SYSTEMS EXPERIMENTAL METHODS

2.1 Chronological Bibliography

The following chronological bibliography lists reports that document seismic tests of piping components and piping systems, as well as post-earthquake field investigation reports on the behavior of piping systems. Clearly, most of the experimental work was conducted in the 1980's and early 1990's. Later, some tests were conducted to assess the fracture mechanics aspects of the seismic response of piping systems with cracks.

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1997 WRC Bulletin 423, Evaluation of Seismic Response Data for Piping, Gerry C. Slagis

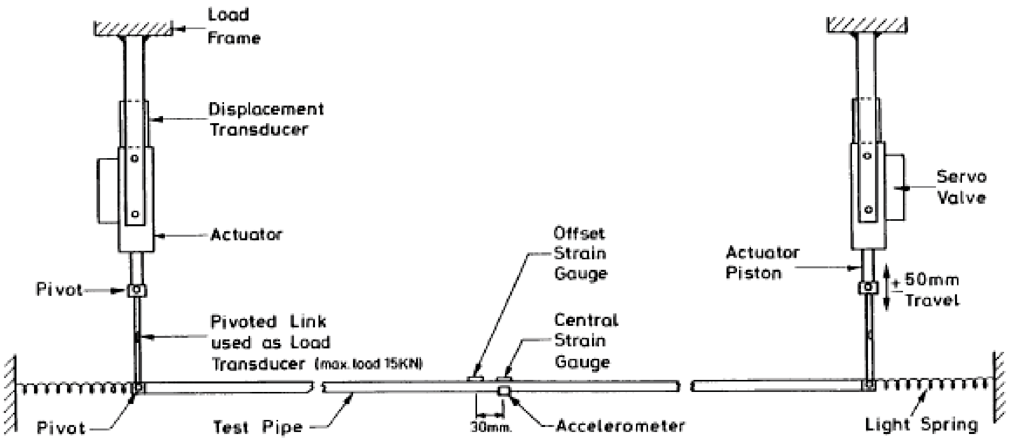


Figure 3 - E.M. Beaney Test, 1985

Vibration Test: ± 2 in, PD/2t = 2/3 S_y to S_y

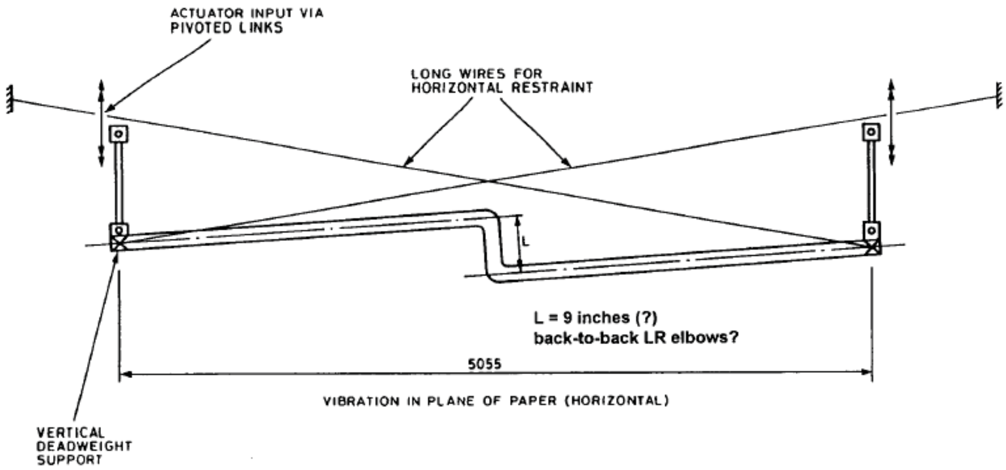


Figure 4 - E.M. Beaney Test, 1991

Displacement-Control Sinusoidal Input

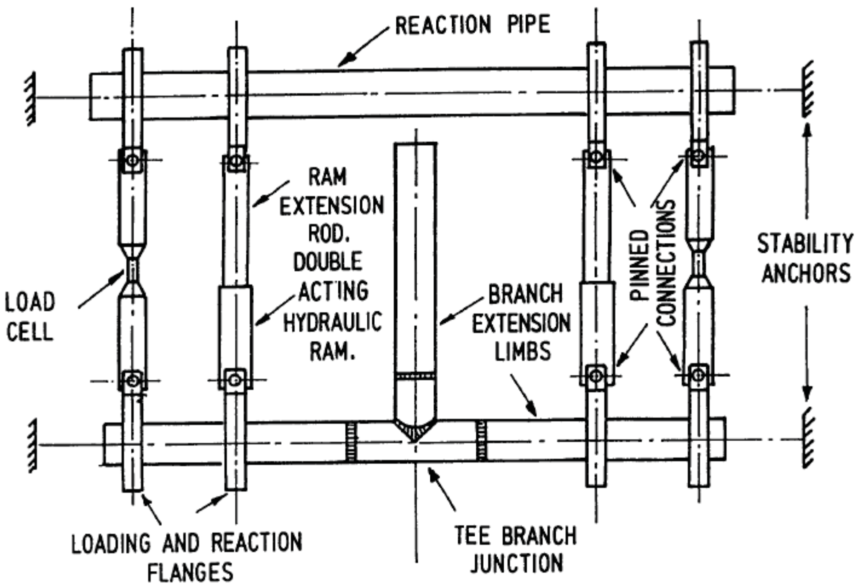


Figure 5 - K. Yahiaoui, et al. Test, 1992

Displacement-Controlled Sinusoidal Input

Displacement-Controlled Sinusoidal Vibration

± 0.2g to ± 5g, 23 Components, ASTM A 106 Grade B, Run to Failure

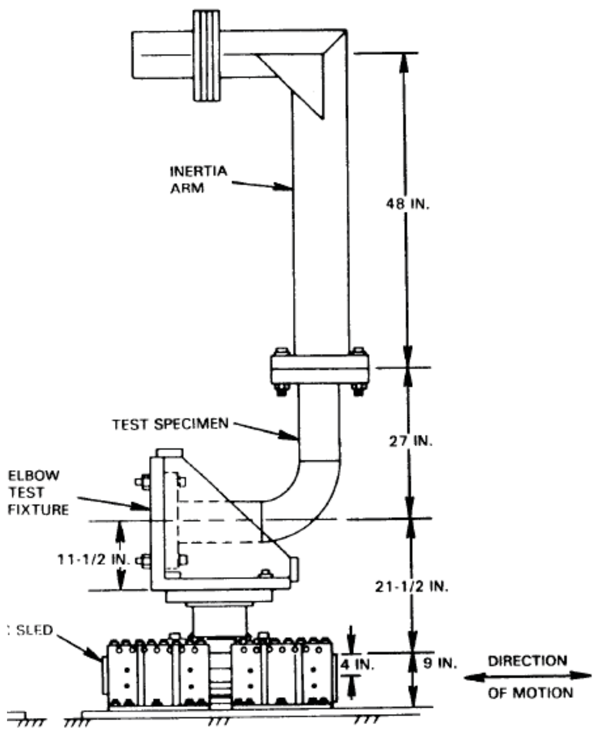
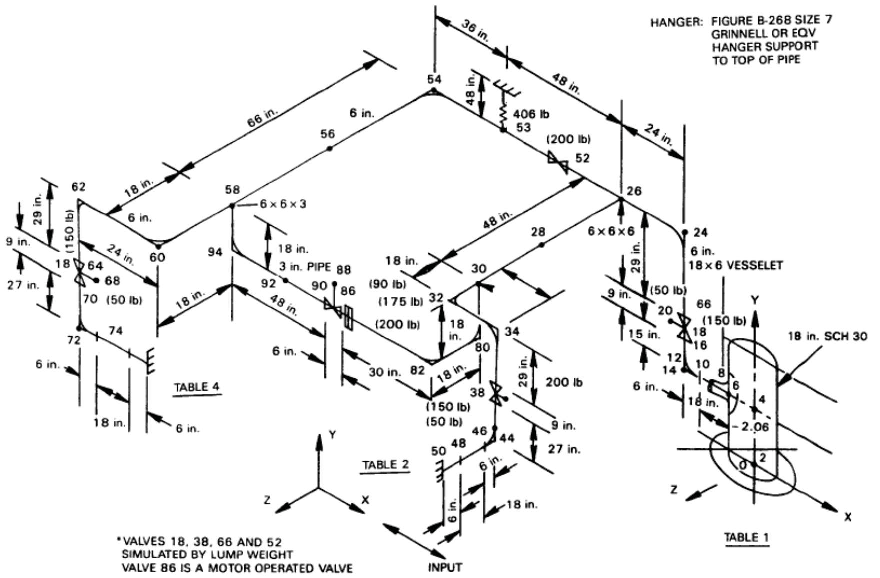


Figure 6 - EPRI, 1994, Component Tests

32 Seismic Tests, Actual Seismic In-Structure Excitation, Repeated Testing to Failure

Failure by Cracking or Ratcheted Opening of the Vertical Leg



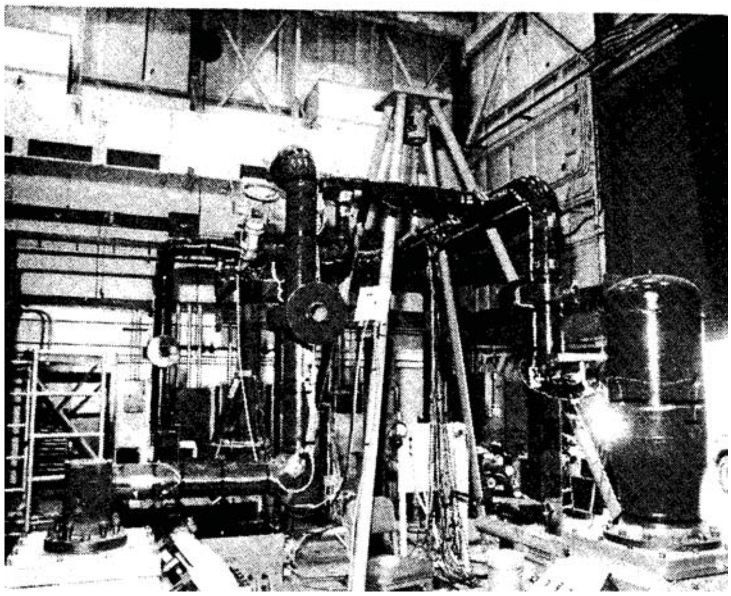


Figure 7 - EPRI, System 1 Test

ASTM A 106 Grade B, 6 in sch. 40, with 3 in. sch. 40 Bypass, and 18 in. Vessel

1000 psi Internal Pressure, Input OBE, SSE, 5 SSE

½ Table (~10g Peak) and Full Table (~20g Peak)

Figure 8 - EPRI Test Elbow Failure

Figure 9 - EPRI Test Vessel-Pipe Nozzle Weld Failure

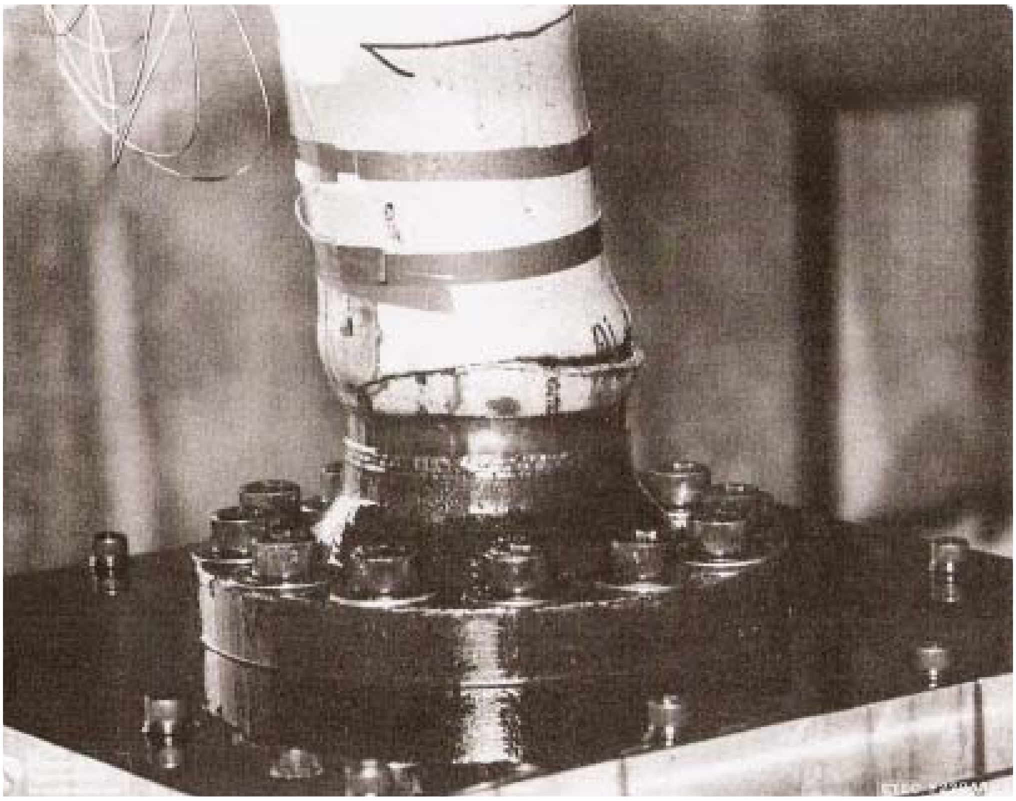
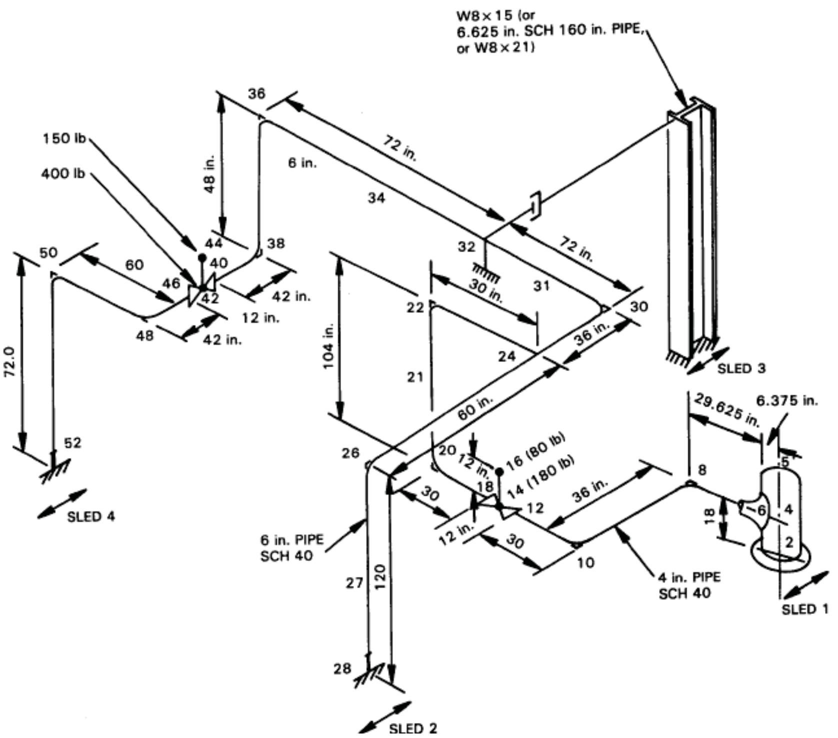


Figure 10 - EPRI Test Fatigue Ratcheting

Combined Hoop And Cyclic Bending Induced Bulging And Cracking



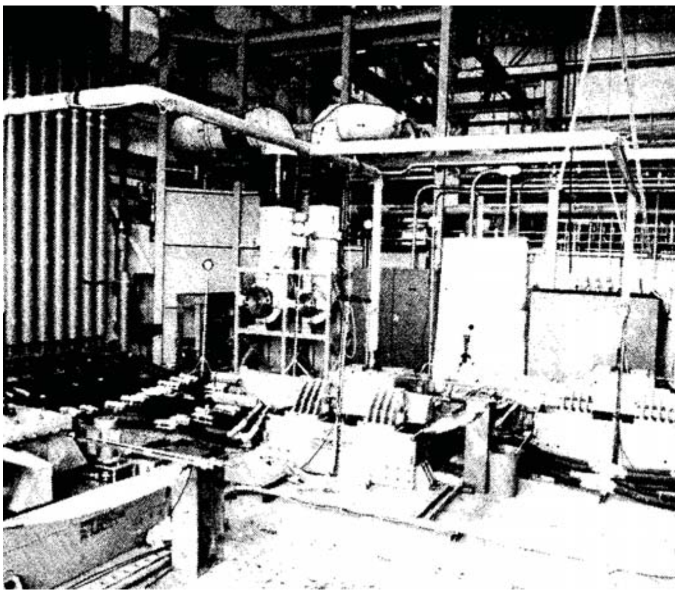


Figure 11 - EPRI, System 2 Test

316L Stainless Steel, 6 in sch.40, with 4 in. sch. 40 Branch, and 12 in. Vessel

1000 psi Internal Pressure, Input OBE, SSE, 5 SSE

½ Table (~10g Peak) and Full Table (~20g Peak)

Figure 12 - EPRI System Test 2 Tee Failure

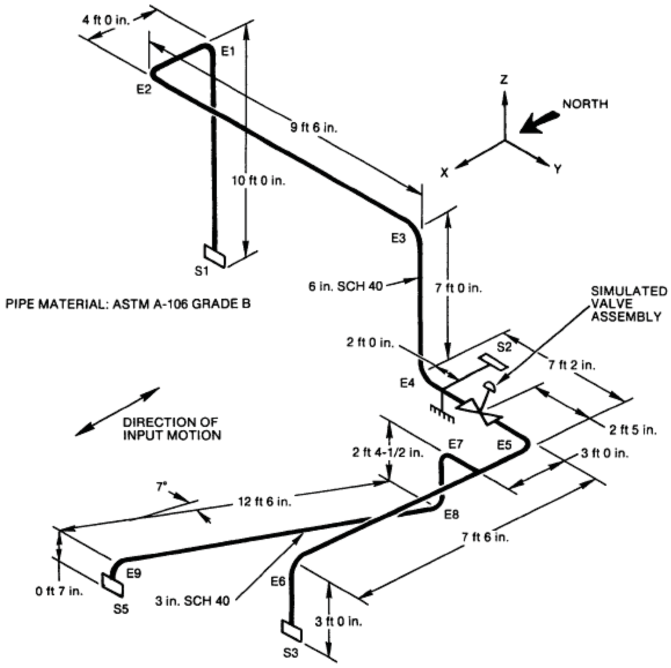


Figure 13 - ETEC System Test

ASTM A 06 Grade B, 3 in. sch. 40, 5g – 14g – 30g Seismic Input

Elastically Calculated Stress Reached 21 Times Level D (21 x 60 ksi)

Tee Failure from Post-Seismic Sinusoidal Testing

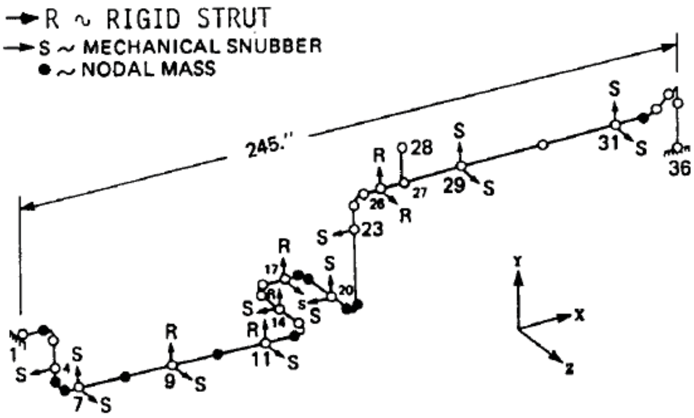


Figure 14 - Westinghouse Hanford Test

1 in Stainless Steel, SSE and 1.3 SSE Loading, No Damage As-Shown

Large Distortion Eventually Occurred After Several Supports Were Removed

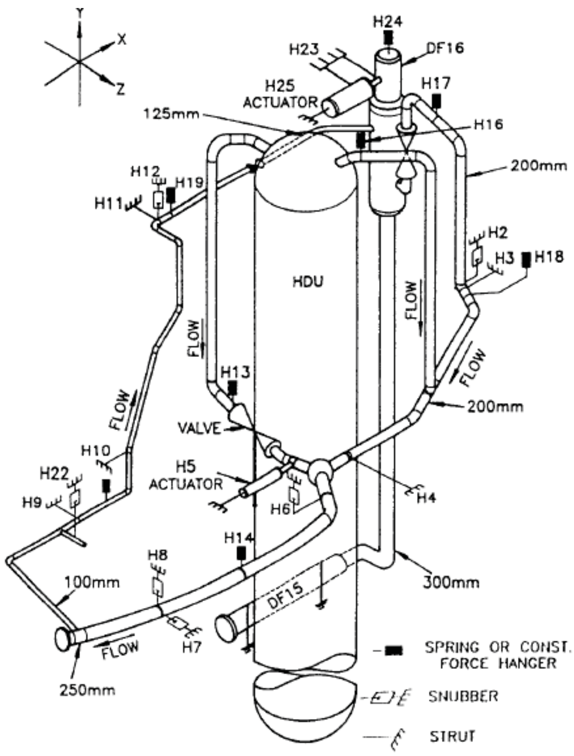


Figure 15 - Heissdampfreactor (Germany) Test

Stainless Steel, 4 to 8 in. Pipe, 1000 psi, Ambient Temperature

Seismic Input SSE 0.6g ZPA Applied to the Containment, Followed by 2 SSE, 6 SSE, 8 SSE

Stress Reached 2.2 Times ASME III Level D

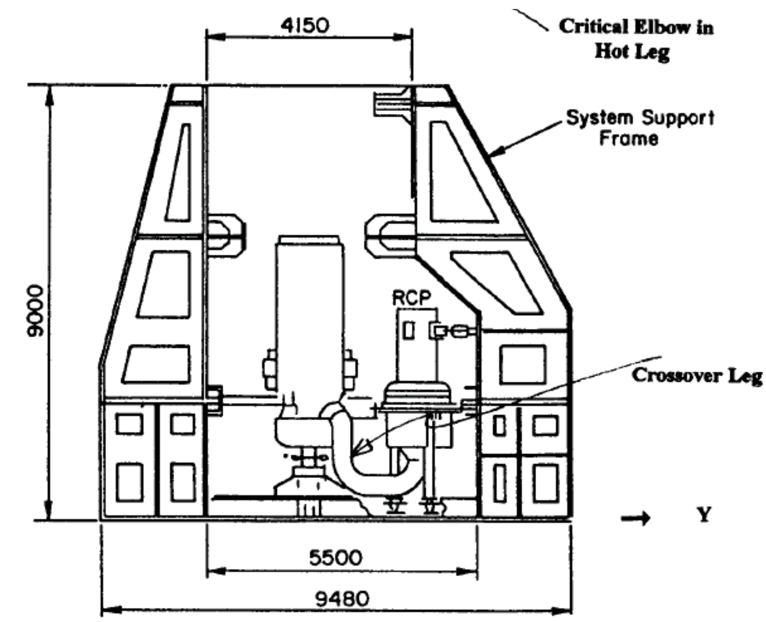


Figure 16 - Tadotsu 1/2.5 Modified Loop Scale Test
13g Peak Spectral Acceleration at 3% Damping, 2230 psi Pressure
Eight Times 3Sm Before Failure,
Failure by Bulging Plus Fatigue Crack

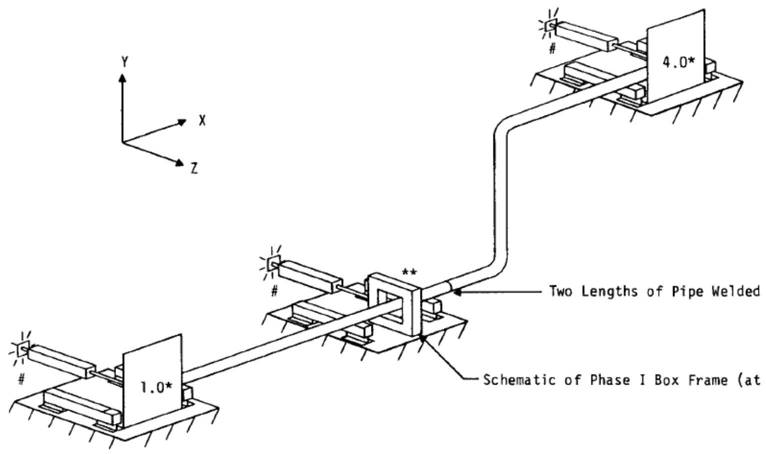


Figure 17 - EPRI Prototype Test
ASTM A 106 Grade B, 4 in. and 6 in. sch.40, 1500 psi Pressure
Stress 3 to 5 Times ASME III Level D of 3 S

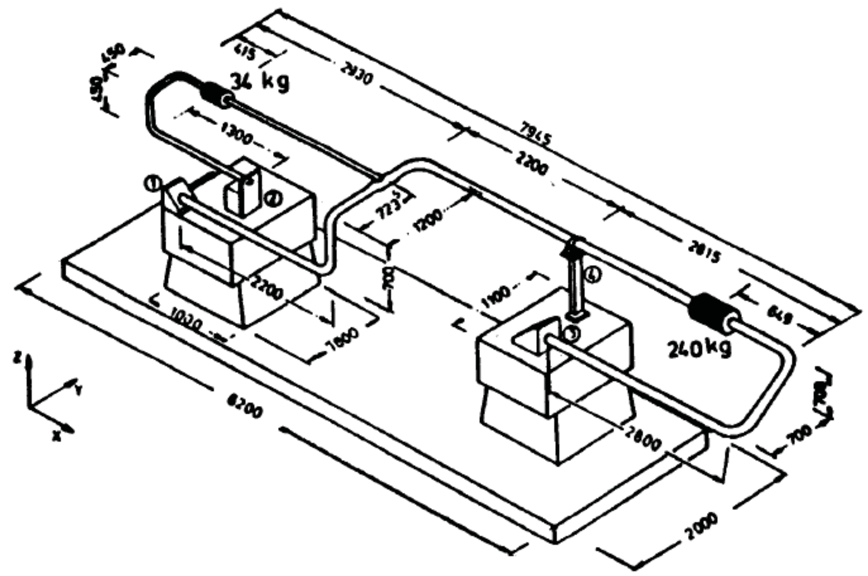


Figure 18 - KWU/TUV System Test

4 in. and 2 in., No Pressure, Stress 2.5 x Level D (2.5 x 3 Sm)

No Failure, Local Distortion

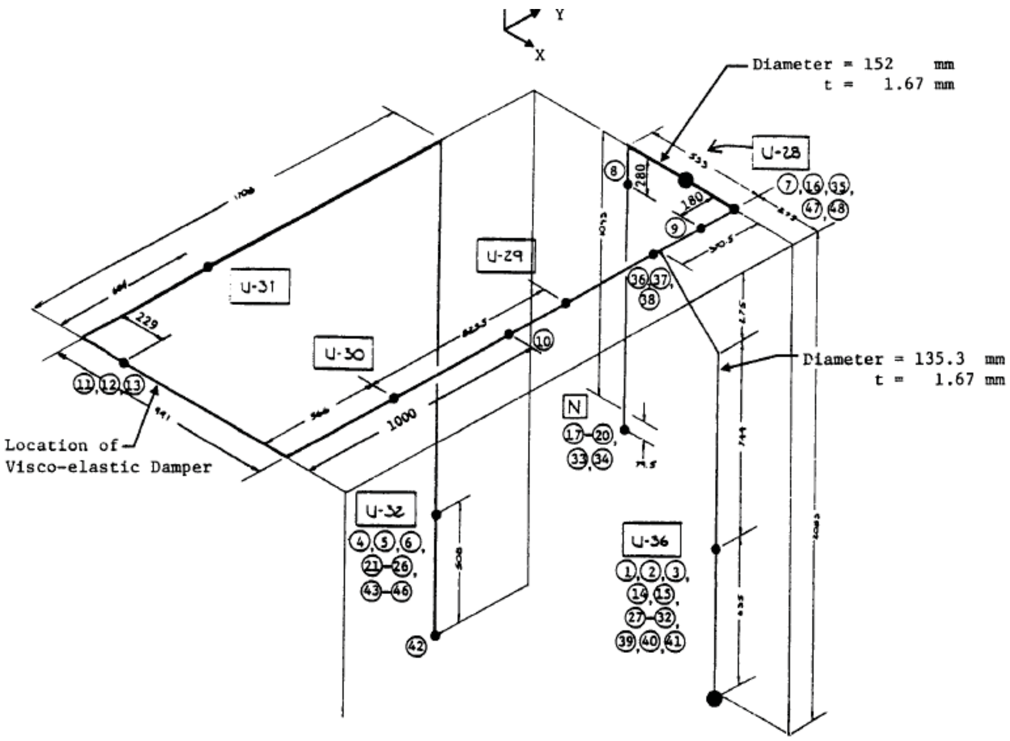


Figure 19 - KWU Loop Test

Internal Pressure 80% Sy, SSE, 2 SSE and 2.5 SSE

Stress was 6 x 3 Sm

2.2 Conclusions from Seismic Tests

The most comprehensive analysis of test results remains to this day WRC 423, 1997, by G. Slagis. The Bulletin lists several conclusions, including the following:

Stress limits for inertial effects: "All of the test programs demonstrate the conservatism of the Level D stress limit (3Sm and 2Sy) for tested dynamic response of piping. As shown by these tests, the dynamic primary bending stress can significantly exceed the 2Sy limit adjusted for actual material properties without a collapse failure. However, the amount of conservatism in the limit for all possible piping configurations has not been established at this time. It also has to be recognized that almost all the tests are on piping with a frequency of a fatigue failure in a single earthquake event is also 4 Hz or greater. Pipe frequency was shown to have a possible significant effect on response--the lower the frequency, the greater the response. Therefore, direct applicability of the test results is limited to piping with a frequency of 4 Hz or greater."

Fatigue failure: Seismic-induced fatigue failure can occur in a single large seismic excitation in joints that do not conform to the ASME code (a very thin tee in a thicker piping system).

Large permanent deformation: Significant permanent deformation is possible for unusual configurations with large deadweight stresses (above 0.5 S).

Hoop ratcheting effects: Large amplitude seismic tests of components pressurized at 1000 psi (hoop stress near 10 ksi) resulted in radial ballooning of the pipe at fixed anchor points due to the combination of large hoop and cyclic bending stresses.

2.3 Conclusions from Post-Earthquake Investigations

Post-earthquake investigation reports point to two important conclusions:

(a) Non-seismically designed piping systems can fail during large earthquakes.

(b) The failure causes are predictable.

The common failure modes are:

- Failure of pipe supports, either at expansion anchors or at undersized welds to the structure (Figure 21 through 25)
- Failure of small stiff pipe attached to an equipment or header that undergoes large seismic anchor movements (Figure 20)
- Failure of mechanical joints (other than flanges) in very flexible pipes subject to large swing (Figure 26 and Figure 27)
- Failure of significantly corroded pipe
- Failure by interaction from a heavy falling structure (like a block wall)
- Sliding of friction supports, such as C-clamp attachments to beams.

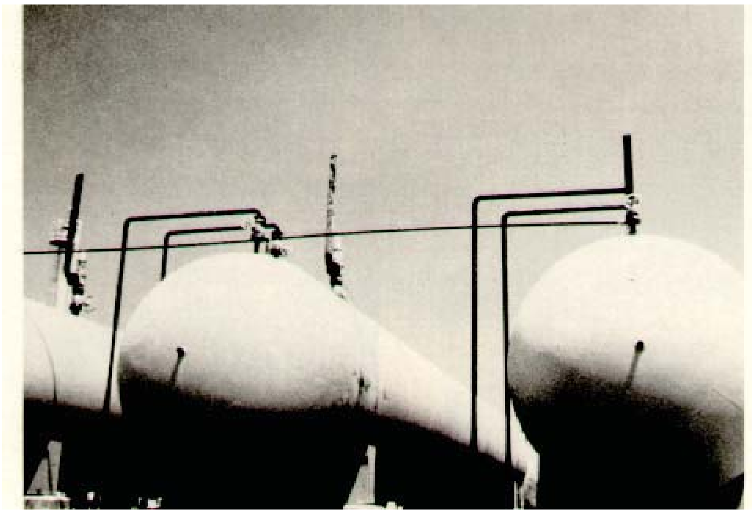


Figure 20 - Seismic Anchor Motion Failure
The Horizontal Vessels Slid on their Supports
Caused Failure of the Small Bore Piping at Top of Tanks

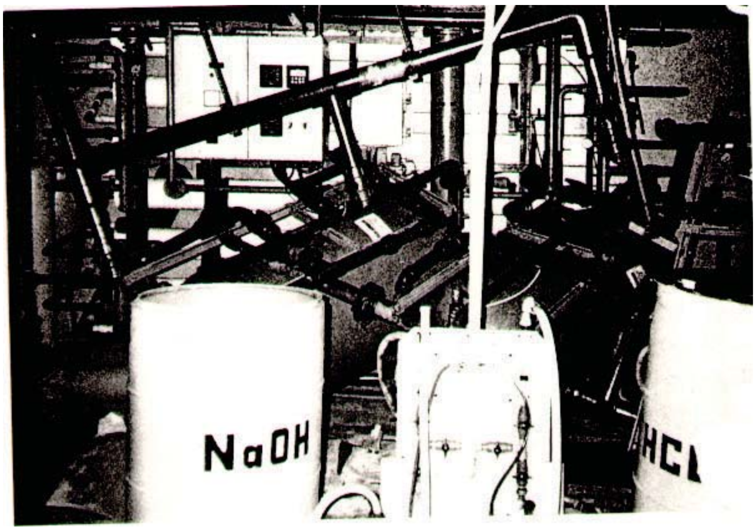


Figure 21 - Failure of Ceiling-Attached Pipe Supports

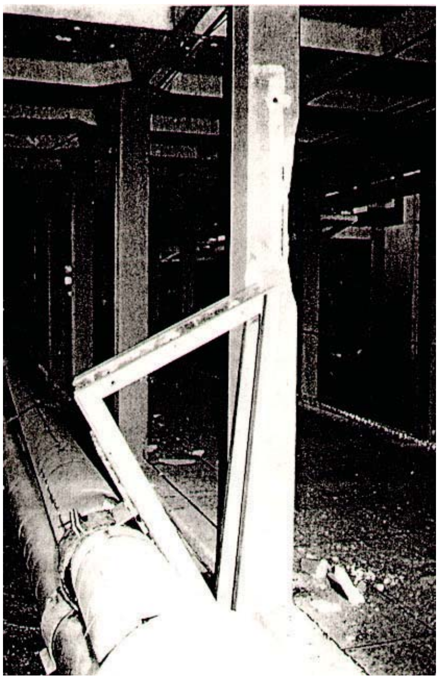


Figure 22 - Failure of Pipe Supports Due to Insufficient Edge Distance

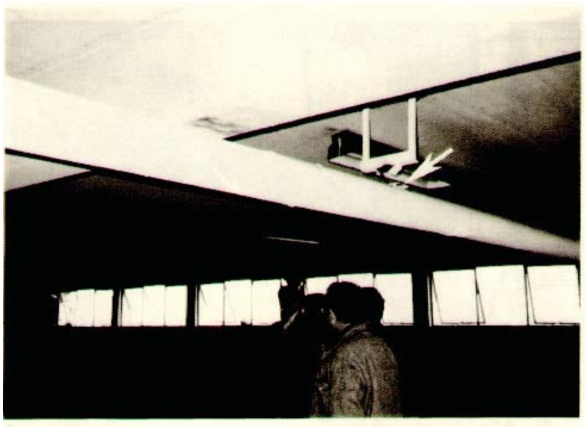


Figure 23 - Failure of Overhead Pipe Sliding Guide

Figure 24 - Failure of Welded Attachment to Backup Structure

Figure 25 - Ground Liquefaction Causes the Saddle Supports to Sag Down, Pipe Did Not Fail

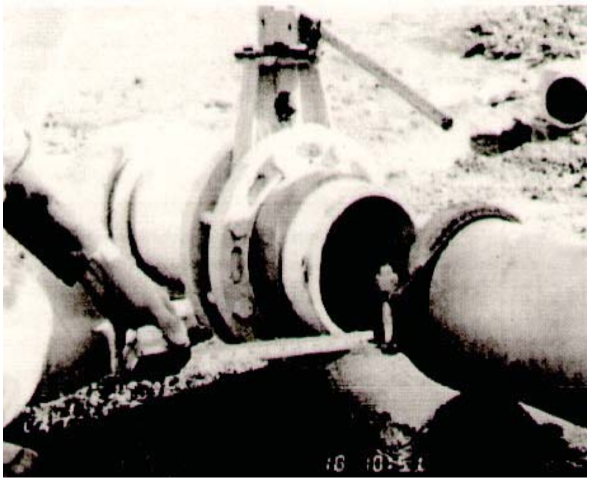


Figure 26 - Failure of Mechanical Pipe Coupling

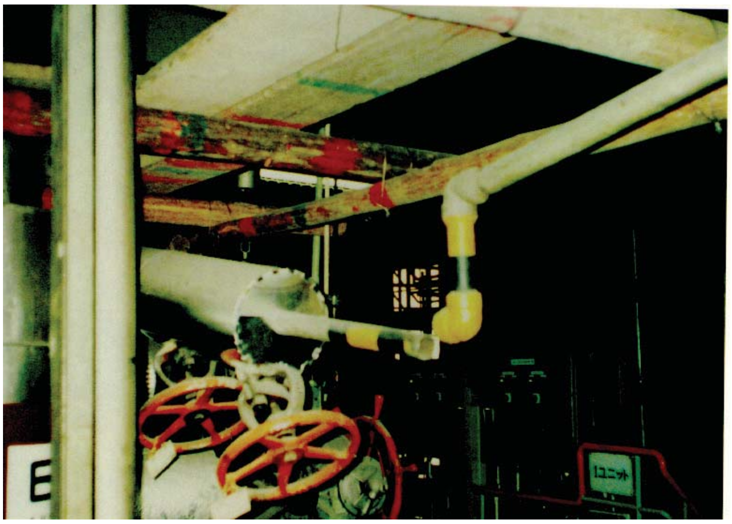


Figure 27 - Instance of Inertial-Induced Failure of Threaded Elbow

3 SEISMIC TESTING OF PIPING SYSTEMS

3.1 Codes and Standards

The qualification of piping systems is typically achieved through analysis. Seismic shake table testing is used primarily for:

(a) The qualification of active piping components (valve operators, instruments and controls, etc.)

(b) Research and development.

In the U.S., when seismic shake table testing is performed, it follows one of the following standards:

- IEEE-344 (1975, 1987) Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Power Plant Generating Stations, Institute of Electrical and Electronics Engineers, New York. (nuclear)
- ASME QME-1 Qualification of Active Mechanical equipment Used in Nuclear Power Plants (nuclear)
- ICBO AC156 Acceptance Criteria for the Seismic Qualification Testing of Nonstructural Components, International Conference of Building Officials, Whittier, CA. (non-nuclear)

3.2 Test Plan

Because testing of piping non-active components or piping systems is primarily performed for research and development, there is no standard test plan. However, based on the above codes and standards, the following considerations apply to testing:

- Select the testing method: (a) Proof testing to a test response spectrum (TRS), (b) Generic testing to a spectrum larger than the design spectrum, (c) Fragility testing to failure or table capacity
- Decide whether to test a system or a component: If testing a component, account for the in-system amplification of the seismic input.
- Specify the test input: Single frequency, sine sweep or response spectrum test.
- Choose whether the test will be single-axis or multi-axis.
- Specify interface requirements: Mounting and hold-down details.
- Specify Inspections: Attributes to be inspected prior, during and/or after testing.
- Specify instrumentation and records: Typically, the test instrumentation includes accelerometers on the table, to record the table input and confirm that the required input (RRS) is enveloped by the test response spectra (TRS), over a certain frequency range (such as 1 Hz to 100 Hz).
- Specify the contents of the test report: The applicable standard will normally specify the contents of the test report.

3.3 U.S. Test Facilities

Table 2 compiles most U.S.-based seismic shake table test facilities, and key attributes of the tables.

Table 2 - Seismic Shake Tables in the U.S.

State	Location	Size (m)	Payload (metric tonnes)	Degrees of Freedom	X Horiz Disp (mm)	Y Horiz Disp (mm)	Z Vert Disp (mm)	X Horiz accel (m/s2)	Y Horiz accel (m/s2)	Z Vert accel (m/s2)	Max Freq (Hz)
Ohio	Trentec	3.3 x 3.3	13	6	±200	±200	±200	±70	±70	±70	100
North Carolina	Duke University	1.2 x 1.2	5	1	±75	n/a	n/a	±50	n/a	n/a	60
New York	University at Buffalo (State University of New York) (2 identical tables of 3)	3.6 x 3.6	50	6	±150	±150	±75	±12	±12	±12	100
New York	University at Buffalo (State University of New York) (3 of 3)	3.7 x 3.7	50	5	±150	n/a	±75	±12	n/a	±23	50
California	University of California at Berkley	6.1 x 6.1	45	6	±127	±127	±51	±15	±15	±20	20
California	California State University, Fresno	2.4 x 2.0	?	1	±125	n/a	n/a	?	n/a	n/a	?
California	University of California at San Diego	12.2 x 7.6	2000	1	±750	n/a	n/a	±10	n/a	n/a	20
Connecticut	University of Connecticut	1.5 x 1.5	1	1	±150	n/a	n/a	±20	n/a	n/a	50
Illinois	University of Illinois at Urbana/Champaign	3.7 x 3.7	5	1	±50	?	?	±30	?	?	50
Nevada	University of Nevada at Reno (3 identical biaxial tables)	4.3 x 4.5	45	2	±300	±300	n/a	±20	±20	n/a	50
Nevada	University of Nevada at Reno (6 axis table)	2.75 x 2.75	50	6	±75	±300	±100	±20	±40	±10	50
Texas	Rice University	0.465m^2	7	1	±75	n/a	n/a	±20	n/a	n/a	50
New York	Rensselaer Polytechnic Institute	1.7 x 2.6	5	1	±130	n/a	n/a	±20	n/a	n/a	50
Alabama	Wyle Laboratories	6.1 x 5.5	27	2	±152	?	?	±60	?	?	100
Alabama	Wyle Laboratories	2.7 x 2.7	4.5	3	±250	±250	±250	±45	±45	±45	100
Alabama	Wyle Laboratories	2.4 x 2.4	4.5	2	±305	n/a	±228	±70	n/a	±80	70

ANNEX A - STRESS ANALYSIS OUTLINE

Annex A outlines the topics and contents that need to be addressed in developing a procedure for the seismic analysis and qualification of piping systems.

A.1 Scope

1.1 Purpose

To outline the attributes to be addressed for the qualification by analysis of above-ground ASME B31.1, B31.3, B31.4, B31.5, B31.8, and B31.9 metallic piping systems.

1.2 Interfaces

Client – Design contractor – Professional engineer – System engineer – Layout – Materials engineer – Civil-structural

A.2 Codes and Regulatory Requirements

2.1. Codes and Standards

2.1.1 Code Edition and Addenda

2.1.2 Code Cases

2.2 Regulatory Requirements

A.3 Interfaces

A.4 Analysis Specification

4.1 The functions and boundaries of the items covered

4.2 The design requirements including all required overpressure protection requirements

4.3 The environmental conditions and corrosion allowances

4.4 The Code classification of the items covered

4.5 Mechanical requirements including impact test requirements

4.6 When operability of a component is a requirement, the Design Specification shall make reference to other appropriate documents that specify the operating requirements

4.7 The effective Code Edition, Addenda, and Code Cases to be used for construction

A.5 Modeling

5.1 Isometric

5.2 Coordinates

5.3 Modeling Tolerances

5.4 Corrosion Allowance

5.4 Node Numbering

5.5 Number of Node Points

5.6 Line Identification

5.7 Support Labels

5.8 Mechanical Properties

5.9 Physical Properties

5.10 Restraints and Anchor Stiffness

5.11 Wall Penetrations

5.12 Tributary Weight of Supports

5.13 Overlap

5.14 Decoupling of Branch Lines

5.15 Decoupling of Equipment Nozzles

5.16 Valves and In-Line Components

5.17 Pipe Fittings

5.18 Equipment Nozzles

5.19 Special Stress Intensification Factors and Stress Indices

5.20 Vents and Drains

5.21 Welded Attachments

5.22 One-way Supports

5.23 Friction

A.6 Input Loads

6.1 Deadweight

6.2 Pressure

6.3 Temperature

6.3.1 Thermal Expansion

6.3.2 Exemption from Flexibility Analysis

6.3.3 Thermal Fatigue and Local Effects

6.3.4 Thermal Anchor Movements

6.3.5 Stagnant Lines

6.4 Test Cases

6.5 Seismic Analysis Input

6.5.1 Methods of Seismic Analysis

6.5.1.1 Small Bore Qualification by Rules

6.5.1.2 Seismic Modal Analysis

6.5.1.3 Static Seismic Inertia Analysis

6.5.1.4 Time-history Seismic Analysis

6.5.1.5 Inelastic Analysis

6.5.2 Seismic Input

6.5.2.1 Seismic Response Spectra

6.5.2.2 Nozzle and In-Equipment Spectra

6.5.2.3 Seismic Anchor Motions

6.5.2.4 Combination of Inertia and SAM Response

6.6 Fluid Transient Analysis Input

6.7 Pipe Break Input Loads

6.8 Wind, Tornado, Snow and Ice Loads

A.7 Load Combinations

A.8 Qualification Requirements

8.1 Pipe Stress Limits

8.2 Pipe Movement Limits

8.3 Valve Qualification

8.4 Equipment Nozzle Loads

8.5 Pipe Flanges

8.6 Expansion Joints

8.7 Supports and Anchors

8.8 Sealed Penetrations

8.9 Welded Attachments

8.10 Break Exclusion Zone

A.9 Documentation

9.1 Pipe Stress Analysis Calculation Package

9.2 Models

9.3 Design Report

A.10 As-Built Reconciliation

A.11 References

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