PB90184409

JBA 109-060-001

SEISMIC RESTRAINT OF HAZARDOUS PIPING SYSTEMS IN INDUSTRIAL BUILDINGS

(PHASE I)

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APRIL 30, 1987

This material is based upon work supported by the National Science Foundation under Grant No ISI 85-60754.

Any opinions, findings and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REPRODUCED BY:
NTIS
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

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444 Castro Street, Mountain View, California 94041

EXECUTIVE SUMMARY

This project, funded under a grant from the National Science Foundation, has been undertaken to develop a design methodology, including practical guidelines, which will provide industry and others with the guidance necessary to seismically protect hazardous piping systems. The project is a multi-phase effort, with the results of Phase I research reported herein.

Phase I has developed design requirements for industrial piping systems containing hazardous materials. This effort began with the identification and review of existing documents applicable to seismic design, piping systems, and hazardous materials classification. Subsequently, specific design criteria were delineated. The design criteria includes categorization of piping system importance (based on pipe contents), quantification of earthquake hazard and vibratory environment (considering both building and piping system dynamics), and specification of allowable stresses (based on piping material and importance). These criteria were used to develop tentative design requirements which specify acceptable methods for determining seismic restraint of hazardous piping. Finally, analytical models of polyvinyl chloride (PVC) and steel piping systems, typical of systems found in industrial facilities, were analyzed to evaluate the tentative design requirements for various seismic bracing schemes. Included in the bracing schemes evaluated, was an energy-dissipative scheme which uses flexible, damped restraints, rather than conventional rigid bracing, to mitigate excessive piping response.

The results of Phase I research has established and evaluated design requirements for seismic restraint of hazardous piping systems. These requirements will be used in subsequent Phase II and Phase III work to develop specific guidelines for selecting and positioning braces, and to develop a new method of seismic bracing (i.e., energy-dissipative restraints).

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CHAPTER 1

INTRODUCTION

1.1 Background

Lack of appropriate guidance for seismic design and installation of process piping containing hazardous materials at industrial facilities has created a potentially dangerous situation. In the electronics industry, for example, toxic, flammable, and reactive liquids are commonly used to manufacture semiconductors and electronic parts. Process piping containing these hazardous fluids is routinely installed without special consideration of the potentially catastrophic effects of a strong earthquake. This is due, in part, to a specific lack of guidance regarding seismic design and installation of systems containing hazardous materials. At the present time, no single design guide or building code fully addresses seismic protection of hazardous piping systems in industrial facilities.

Traditionally, building codes have focused on the seismic adequacy of the structural system and have placed less importance on the building's subsystems. This is quite understandable, since building codes have evolved from a time when building subsystems were less extensive and of minimal importance to life safety. The complex and potentially hazardous process systems, found in some manufacturing facilities today, were not common to facilities built twenty-five or fifty years ago.

The ever increasing use of hazardous materials in manufacturing has, likewise, increased the risk of exposure. For example, the recent disaster at the Union Carbide facility in Bhopal, India demonstrated the devastating consequences that an accidental release of toxic chemicals can have on the facility and surrounding community. While this disaster was not initiated by an earthquake, the potential for an earthquake to cause similar accidents is very real for any facility which uses appreciable quantities of hazardous materials.

As a result of the 1906 San Francisco Earthquake, fires started throughout the city which caused as much, or more, damage as the earthquake itself. The lesson in this case is that earthquakes can initiate loss indirectly which may be even more significant than that due directly to the shaking of structures. For industrial facilities, which use appreciable quantities of flammable or toxic materials, risk to life safety due to an earthquake may very well be dominated by the consequences resulting from release of such materials, rather than by collapse of the structure.

While emergency preparedness measures are being taken to cope with isolated releases of hazardous materials, such measures may not be fully adequate to deal with such releases following a large earthquake. This is particularly true since a large earthquake affects all facilities, structures, lifelines, etc. over a vast area. Consequently, multiple releases of hazardous materials can occur at an individual facility, multiple facilities can be affected and lifelines such as water, power, and transportation, which are necessary to mitigate consequences, may be temporarily unavailable.

Fortunately, relatively simple preventive measures can be taken to mitigate the potential for disaster at facilities using hazardous materials. One relatively simple measure is to install equipment, such as piping, with seismic restraints, flexible couplings, etc., which ensure that such equipment will have an acceptably low probability of failure during an earthquake. In the design and installation of seismic restraints, a balance must be reached between the type and extent of restraint used and the level of protection considered acceptable. In the case of complex equipment, such as a piping system, a number of design attributes should be considered, including site seismicity, dynamic response and piping system importance. For a specified level of protection, these attributes will govern design and installation of seismic restraints, which will, in general, be different for different facility locations (e.g., California vs. Texas), different categories of piping importance (e.g., piping containing kerosene vs. water), different vibration environments (e.g., flexible vs. rigid piping), and different types of piping (e.g., PVC vs. steel piping).

This project, funded under a grant from the National Science Foundation, has been undertaken to develop a design methodology, including practical guidelines, which will provide industry and others with the guidance necessary to seismically protect hazardous piping systems.

The project is a multi-phase effort, with the results of Phase I research reported herein. Phase II and Phase III work will be undertaken after Phase I results are reviewed and approval to proceed is given.

1.2 Scope of Phase I Research

The scope of Phase I includes development of a general design methodology for industrial piping containing hazardous materials. This effort begins with the identification and review of existing documents applicable to design of piping systems and classification of hazardous materials. Subsequently, specific design criteria are delineated. The design criteria includes categorization of piping system importance (based on pipe contents), quantification of earthquake hazard and vibratory environment (considering both building and piping system dynamics), and specification of allowable stresses based (on piping material and importance). These criteria are used to develop tentative design requirements which specify acceptable methods for determining seismic restraint of hazardous piping. Finally, analytical models of polyvinyl chloride (PVC) and steel piping systems, typical of systems found in industrial facilities, are analyzed to evaluate the tentative design requirements for various seismic bracing schemes. Included in the bracing schemes evaluated, is an energy-dissipative restraint scheme which uses flexible, damped bracing, rather than conventional rigid bracing, to mitigate excessive piping response.

The results of Phase I research are intended to establish and evaluate design requirements for seismic restraint of piping systems. These requirements will be used in subsequent Phase II and Phase III work to develop specific guidelines for selecting and positioning braces, and to develop new seismic restraint mechanisms (i.e., energy-dissipative braces).

1.3 Report Organization

This report is organized into seven main chapters and five appendices.

Following the Introduction, Chapter 2 summarizes an extensive survey of available documents related to seismic design, piping systems, and hazardous materials. The intent of the literature survey is to pull together pertinent information from a number of different sources.

Chapter 3 delineates seismic criteria and Chapter 4 develops and presents tentative design requirements. Supporting studies are documented in Appendices A and B.

Chapter 5 summarizes results of example analyses of various piping systems/bracing schemes. Details of the analyses are provided in Appendices C, D, and E.

Chapter 6, Conclusion, summarizes the findings of Phase I and recommends actions for Phase II study. Chapter 7 is a list of references.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The literature survey is divided into the following four sections:

- General Seismic Criteria
- Piping-Specific Seismic Criteria
- Piping System Performance Requirements
- Hazardous Materials Classification

In the first section, various design documents found in the literature are surveyed to identify general seismic criteria (i.e., specification of ground motion and earthquake loads used in design of ground-supported structures). In the second section, the same design documents are surveyed to identify design criteria specific to piping systems (i.e., specification of seismic load on systems within a building and other design criteria applicable to piping). In the third section, the design documents are again surveyed to identify the allowable stresses and forces, and other design requirements applicable to piping systems.

The design documents surveyed include existing building codes (e.g., Uniform Building Code [Ref. 1]), model building codes (e.g., ATC-3 [Ref. 7]), the new SEAOC Blue Book [Ref. 10], the Tri-Services Manual and Essential Building Supplement [Refs. 11, 12], nuclear-related design documents (e.g., U.S. Nuclear Regulatory Standard Review Plan [Ref. 17]), piping codes (e.g., ASME B31.9 [Ref. 20]) and design guides (e.g., SMACNA [Ref. 23]). The intent of the first three sections of the literature survey is to identify sources of seismic criteria and piping system requirements specified or implied by existing design documents.

The final section of the literature survey investigates various sources which identify and classify hazardous materials. Literature surveyed includes documents from the Environmental Protection Agency, the Occupational Safety and Health Administration, the National Fire Protection Association, and others.

2.2 General Seismic Criteria

In this section, design documents are reviewed, which prescribe, or otherwise define, general seismic criteria.

Existing Building Codes

There are presently four primary building codes in use in the United States:

- Uniform Building Code (UBC) [Ref. 1]. Issued by the International Conference of Building Officials, Whittier, California.
- Basic Building Code (BOCA) [Ref. 2]. Issued by the Building Officials and Code Administrators International, Homewood, Illinois.
- National Building Code (NBC) [Ref. 3]. Issued by the American Insurance Association, New York, New York.
- Standard Building Code (SBC) [Ref. 4]. Issued by the Southern Building Code Congress, Birmingham, Alabama.

The use of these codes is regional [Ref. 5]. For example, the UBC is used throughout the Western United States, while the BOCA is used in the Midwest, the SBC in the Southern portion of the United States, and the NBC in the Northeastern portion. The choice of code for a particular area is up to local building authorities. Common practice is to include the selected code with city ordinances. The role of the city ordinances are to make the code responsive to local needs.

These four building codes are basically the same, but in each, emphasis is placed on various regional phenomena. In this section, seismic load requirements of the UBC will be discussed.

The UBC requires that every structure be designed and constructed to resist lateral forces acting in the direction of the main axes of the building, noncurrently. The calculation of the lateral force to be applied to the building is given by the following equation:

$$V = Z\ I\ K\ C\ S\ W \qquad (2\text{-}1)$$

This equation represents a static-load analysis with each coefficient in the equation accounting for some significant aspect of the seismic problem.

The coefficients in the order in which they appear in the above equation, are defined as follows:

V = the total lateral force or base shear,

Z = a numerical coefficient dependent upon the seismicity of the region,

I = the occupancy importance factor,

K = a numerical factor dependent on building type,

C = a numerical factor dependent on the lateral stiffness of the structure,

S = a factor accounting for soil-structure interaction, and

W = the weight of the structure.

The numerical coefficient Z, is defined by a Seismic Zone map. The continental United States, Hawaii and Alaska have been divided into zones ranging from Zone 0, corresponding to very low seismic risk, to Zone 4, corresponding to extreme seismic risk. The values for the coefficient Z are as follows:

Zone	Coefficient
1	3/16
2	3/8
3	3/4
4	1

Essential buildings should be designed with special consideration of seismic effects. The UBC recognizes this fact by introducing the occupancy importance Factor I. In Table 23K of the UBC this factor is defined as follows,

Type of Occupancy	Factor I
Essential Buildings	1.5
Buildings where occupancy could exceed 300 persons	1.25
All other buildings	1.0

Different types of buildings respond quite differently to seismic forces. For example, ductile moment resistant steel frames are known to efficiently resist lateral forces, while buildings without a vertical load-carrying frame are known to be less efficient. Hence, in the UBC Table 23I, a K coefficient of 0.67 is used in the former, and 1.33 in the latter type of building. In addition, other types of buildings and structures are listed in Table 23I and the corresponding values of the coefficient K specified.

The coefficient C is a modification to the magnitude of the total shear, which takes into account the effect of the period for the structure. The coefficient C is given by the following equation,

$$C = \frac{1}{15\sqrt{T}} \tag{2-2}$$

where:

T = the natural period of the building, in seconds.

In order to account for the soil conditions at the building site, the UBC has introduced a soil factor, S. This factor may be evaluated by one of two methods. The first method requires that the building's period, T, and the natural period of the soil, T_S, underlying the structure be known. Without intensive analysis, neither of these two quantities is known precisely. As an alternative method numerical values of S may be obtained based on the soil type, as defined below,

Soil Type	Numerical Value
S_1	1.0
S_2	1.2
S_3	1.5

where:

S_1 is a hard rock material,
S_2 is a deep cohesionless or stiff clay, and
S_3 is a soft to medium stiff clay or sand.

The UBC requires the total lateral load V, to be distributed using a triangular shape with a portion of V acting as a concentrated load at the top of the building.

The document used by some building codes as the basis for defining loads and load combinations is entitled; "<u>The American National Standard Building Code Requirements for Minimum Design Loads in Buildings and Other Structures</u>," [Ref. 6]. The analytical provisions contained in this document are very similar to those found in the UBC. Static analysis is required for seismic analysis, and the base shear formula is the same as that found in the UBC.

Model Building Codes

In an attempt to develop uniformity in seismic requirements, as well as to advance the state-of-the-art, model seismic design codes have been developed. The most significant of these efforts was the work performed by the Applied Technology Council in the mid-1970's, which resulted in the ATC-3 document; "Tentative Provisions for the Development of Seismic Regulations for Buildings," [Ref. 7]. More recently, the Federal Emergency Management Agency has expanded upon ATC-3 as part of the National Earthquake Hazards Reduction Program (NEHRP). The result of this effort is a recent document; "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings," [Ref. 9], which is virtually identical to ATC-3 for most seismic provisions.

One of the primary contributions of ATC-3 is the rationalization of seismic load criteria on the basis of the probability of reaching, or exceeding, various levels of ground acceleration. ATC-3 introduces the concept of prescribing loads by a design-basis event which has approximately a 500-year return period (e.g., an event which has a 0.10 probability of being exceeded one or more times in the next fifty years). Ground response spectra are provided in ATC-3 for various seismic zones and soil profiles. ATC-3 soil profiles are specified below.

> **Soil Profile Type S_1:** Rock of any characteristic, either shale-like or crystalline in nature (such material may be characterized by a shear wave velocity greater than 2500 feet per second); or stiff soil conditions where the soil depth is less than 200 feet and the soil types overlying rock are stable deposits of sands, gravels, or stiffer clays.

Soil Profile Type S_2: Deep cohesionless or stiff clay soil conditions, including sites where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

Soil Profile Type S_3: Soft-to-medium stiff clays and sands, characterized by 30 feet or more of soft-to-medium stiff clay with, or without, intervening layers of sand or other cohesionless soils.

For establishing minimum design requirements, the ATC-3 document prescribes seismic loads as follows,

$$V = \frac{1.2\ A_v\ S}{R\ T^{2/3}}\ W \qquad (2\text{-}3)$$

where:

V = the total lateral force of base shear,

A_v = the coefficient representing effective peak velocity-related acceleration,

S = the coefficient for the soil profile characteristics of the site,

R = the response modification factor,

T = the fundamental period of the building, and

W = the weight of the structure.

Several limitations on various factors of this equation are also specified. The essence of this formula is to represent design-basis accelerations by the A_v, S, and T coefficients and to reduce these accelerations by the response modification factor, R, for the purpose of designing building components.

The ATC-3 document also provides methods for performing response spectrum analysis, again basing the loads on the 500-year design basis event.

New SEAOC Blue Book

The most recent revision of the Structural Engineers Association of California (SEAOC) Blue Book [Ref. 10] permits either static or dynamic analysis based on the ATC-3 approach. Both methods take into account four aspects of the seismic problem which are assumed significant by SEAOC:

1. Zoning and site characteristics
2. Configuration and type of structural system
3. Type of occupancy
4. Period of Structure

For the static analysis a total base shear, V, must be calculated from the following formula,

$$V = \frac{Z\ I\ C}{R_W} W \qquad (2\text{-}4)$$

Each of the variables in this formula accounts for one of the four items listed above. The definition of each variable is given below,

V = the total lateral force or base shear,

Z = the seismic zone factor,

I = the importance factor which is 1.25 for essential and hazardous facilities, and 1.0 for all other structures,

R_W = the response modification factor (working-stress design),

W = the total weight of the structure, and

C = a numerical coefficient dependant on the sites soil characteristics and the fundamental period of vibration for the building.

$$C = \frac{1.25\ S}{T^{2/3}} \qquad (2\text{-}5)$$

where:

S = the soil coefficient at the site, and

T = the fundamental period of vibration for the structure.

The essence of the above formulas is to simulate the requirements of ATC-3 using working-stress design, rather than strength-design allowables.

As a result of the 1986 Mexico City Earthquake, the new SEAOC Blue Book has added a fourth soil coefficient to the three defined by ATC-3. This soil coefficient which applies to long-period response would be required for sites with extremely soft underlying soil.

Dynamic analysis is permitted (and in some cases required) by the new SEAOC Blue Book and can be either a response spectrum or a time-history analysis. For response spectrum analysis, spectra are defined which are similar to those recommended by ATC-3.

Tri-Services Manual and Supplement

The military standards for seismic design (i.e., Tri-Services Manual and Essential Building Supplement) [Ref. 11] and [Ref. 12] have been prepared by the Army, Navy, and Air Force to ensure seismic adequacy of their facilities. As seismic design documents, the Tri-Services Manual and Supplement are intended only for use at military installations.

The seismic design methodology of the Tri-Services Manual has been taken from existing documents. It is based on the seismic requirements of the UBC which, in turn, is based on the Recommended Lateral Force Requirements and Commentary published by the Structural Engineers Association of California (SEAOC), 1975.

The Tri-Services Manual Supplement [Ref. 12] has developed a seismic design methodology for essential buildings which is based on dual-level criteria. The two earthquakes described below, are defined for use in design:

1. EQ-I having a 50% chance of exceedance in 50 years.
2. EQ-II having a 10% chance of exceedance in 100 years.

Both earthquakes are required by Reference 12, and procedures are presented for developing a response spectrum for each earthquake considering; earthquake occurrence, attenuation relations between the source and site, and other pertinent information concerning the seismicity of the region. Either response spectrum or time-history analysis is permitted.

The design requirements for the earthquake defined as EQ-I specify that the structure will remain within elastic limits. Consequently, the building should be designed, in this case, for the stress allowables of the applicable code.

The second earthquake, EQ-II, has design requirements which permit a post-yield condition. In this case, the overstress beyond the elastic limit must be estimated by either one of two methods given in the document. To determine whether the structure is acceptable for loads determined from earthquake EQ-II, an inelastic-demand procedure has been developed and limits on inelastic demand ratios are specified.

Nuclear-Related Design Criteria

The expected damage resulting from a nuclear power plant accident far exceeds the potential for damage or injury from the failure of a commercial building. It is necessary, therefore, to accurately understand the performance of nuclear-related structures when exposed to such natural phenomena as earthquakes. As a result, a great deal of effort has gone into nuclear-related research and development of nuclear design methods.

In Reference 14, the Nuclear Regulatory Commission (NRC) is granted the power to define the "Design Bases" for a nuclear power plant, and in References 15 and 16, criteria are prescribed for evaluation of the suitability of a proposed site for a nuclear reactor. The "Design Bases" include information which identifies the specific functions to be performed by a structure, system, or component of a nuclear facility and requires that structures, systems, and components important to safety be designed for earthquakes and other natural phenomena. During exposure to natural phenomena nuclear structures, systems, and components are not to lose their capability to perform their intended safety-related function.

The Nuclear Regulatory Commission has defined two earthquakes: the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake (OBE). These two earthquakes are defined as follows:

a) **Safe Shutdown Earthquake (SSE)**

The maximum credible earthquake for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure control of the reactor and the capacity to safely shut it down.

b) **Operating Basis Earthquake (OBE)**

This earthquake is generally assumed to have half the magnitude of the Safe Shutdown earthquake. During this earthquake, those systems of the nuclear plant necessary for continued operations without undue risk to the health and safety of the public are designed to remain functional.

The Standard Review Plan [Ref. 17] of the NRC is intended to provide guidance for reviewers (and preparers) of documents submitted by utilities seeking a construction permit for a nuclear power plant. Quality and uniformity of the review is provided by this plan. The Standard Review Plan, and referenced NRC regulatory guides, specify detailed requirements to be used to seismically analyze and design nuclear structures, systems, and components.

For seismic loads, the ground motion used in dynamic analyses of nuclear power plant structures and subsystems is based on a site-specific hazard analysis and is characterized by a response spectrum which has a shape defined by the NRC Regulatory Guide 1.60 [Ref. 28].

Piping Codes

In general, piping codes do not prescribe seismic criteria, but require earthquake loads to be considered in design.

Seismic Bracing Guides

Seismic bracing guides such as Superstrut [Ref. 22] and SMACNA [Ref. 23] do not specify seismic criteria but do describe some measure of earthquake force to which the guide conforms (e.g., UBC Seismic Zone 4 loads).

2.3 Piping-Specific Design Criteria

In this section design documents are reviewed which prescribe, or otherwise define, seismic criteria applicable specifically to piping systems.

Existing Building Codes

The Uniform Building Code (UBC) requires that the design of piping, and other nonstructural components, include the effects of lateral load due to earthquakes. This methodology inherently disregards the effect of frequency interaction between the piping system and the building. Design force is described as follows,

$$F_p = Z\ I\ C_p\ W_p \tag{2-6}$$

where:

F_p = the seismic force applied to a component of a building or equipment at its center of gravity,

I = the occupancy importance factor for the building,

Z = the seismic zone factor,

C_p = the horizontal force factor based on location in building, and

W_p = the weight of the piping and contents.

The approach prescribed by the UBC is suitable for the design of piping systems which are very stiff and do not dynamically amplify response. For piping systems which are flexible or flexibly mounted, the UBC requires the horizontal force factor, Cp, to be determined with consideration given to both the dynamic properties of the piping and to the building in which it is located. Unfortunately, the UBC does not specify how this is to be done and dynamic considerations are usually ignored.

Model Building Codes

Chapter 8 of ATC-3 [Ref. 7] provides requirements for the seismic design of nonstructural components, including piping systems. These requirements recognize the occupancy hazard and specify design forces based on dynamic amplification and location in the building.

Lateral design forces are prescribed by the following formula,

$$F_p = A_v C_c P a_c a_x W_c \tag{2-7}$$

where:

F_p = the seismic force applied to a component of a building or equipment at its center of gravity,

C_c = the specified seismic coefficient for components of mechanical or electrical systems,

W_c = the weight of a component of a building or equipment including contents,

A_v = the seismic coefficient representing the effective peak velocity-related acceleration,

P = the specified performance criteria factor,

a_c = the amplification factor related to the response of a system or component as affected by the type of attachment, and

a_x = the amplification factor at level x related to the variation of the response in height of the building.

The following piping systems have been deleted from consideration:

> "Seismic restraints may be omitted from the following installations:
>
> a. Gas piping less than 1-inch inside diameter.
> b. Piping in boiler and mechanical rooms less than 1-1/4 inches inside diameter.
> c. All other piping less 2-1/2 inches inside diameter....

d. All piping suspended by individual hangers 12 inches or less in length from the top of the pipe to the bottom of the support for the hanger."

The NEHRP Provisions [Ref. 9] specify seismic load for piping systems in a manner similar to ATC-3.

New SEAOC Blue Book

The new SEAOC Blue Book [Ref. 10] requires that the design of piping, and other nonstructural components, include the effects of lateral loads due to earthquakes, and prescribes design forces using essentially the same equation as the UBC [Ref. 1].

In contrast to the UBC, however, the new SEAOC Blue Book specifies the upper limit on dynamic response of flexible or flexibly-mounted equipment. In lieu of detailed analysis, equipment which is flexible or flexibly-mounted is required to be designed for two (2) times the force required for design of rigid equipment of like type.

Tri-Services Manual and Supplement

The Tri-Services Manual [Ref. 11] prescribes loads in a manner similar to the UBC for piping systems which are rigid and rigidly attached to the building. Flexible piping systems are required to be designed for forces considering dynamic effects. In lieu of detailed analysis, forces on flexible or flexibly-mounted piping systems may be taken as five (5) times the force required for rigid piping systems. Tables of allowable spans are provided for steel, copper, and brass piping of various diameters.

The Tri-Services Manual also provides design requirements for piping systems, other than fire protection systems which are governed by NFPA-13 [Ref. 18].

According to the Tri-Services Manual, all piping with an inside diameter of 2-1/2 inches or larger must be braced. Fuel gas lines, acid waste pipes, and pipes within boiler and equipment rooms are exceptions. They must be braced regardless of pipe diameter.

The manual recognizes that seismic deflections are greater in a building as elevation increases. It also recognizes that at expansion joints or at a common boundary between dissimilar buildings, relative displacements may be large and "piping should cross building seismic or expansion joints only in the lower levels of the facility."

The Tri-Services Manual Supplement [Ref. 12] recognizes the increase in acceleration with a height above ground level for essential buildings, and describes an approximate method for calculating floor response spectra (i.e., seismic load as a function of equipment frequency and location in the building).

Nuclear-Related Design Documents

The Standard Review Plan [Ref. 17] and referenced NRC regulatory guides provide detailed requirements for seismic analysis and design of nuclear subsystems, such as piping systems.

The effects of pressure within the pipe, temperature of the operating fluid, and other operating loads, in conjunction with earthquake and other abnormal loads, are required to be rigorously evaluated. In all cases, seismic input is described by floor response spectra which are based on building and site-specific dynamic analyses. Damping requirements are governed by NRC Regulatory Guide 1.61 [Ref. 25], spectral peak broadening/enveloping requirements by NRC Regulatory Guide 1.122 [Ref. 26], and modal response combination requirements by NRC Regulatory Guide 1.92 [Ref. 27].

Piping Codes

Applicable piping codes include products of the American Society of Mechanical Engineers (ASME), or special-purpose codes such as that produced by the National Fire Protection Association (NFPA) for fire protection systems.

The American Society of Mechanical Engineers (ASME), with accreditation of the American National Standards Institute (ANSI), has organized the ANSI B31.1 Code for Pressure Piping into the ASME Boiler and Pressure Code [Ref. 19]. ASME B31.1 is the primary document governing nuclear piping design.

This document requires that each piping system be fully evaluated using detailed stress analysis for normal loads such as pressure and temperature, and abnormal loads such as earthquake. This document is also applicable to non-nuclear pressure piping (e.g., steam lines).

The ASME also has a piping code for building services piping, ASME B31.9, [Ref. 20]. This code provides design requirements for pressure, temperature, and gravity-load design of metal and plastic piping commonly found in commercial and industrial buildings. Seismic loads are required in the design of pipe for longitudinal stress, but seismic loads and design methods are not prescribed.

The NFPA is aware of the effect of earthquakes on fire sprinkler systems installed in commercial buildings. In NFPA-13 [Ref. 18], guidance is provided on installation of sprinkler systems in buildings where earthquakes pose a hazard. The following sections are taken directly from NFPA-13.

"3-10.3 **Protection of Piping Against Damage Where Subject to Earthquakes.**

3-10.3.1 The basic criteria for protecting piping from earthquake damage is as follows:

(a) Piping shall be made flexible where necessary.

(b) Piping shall be tied to the structure for minimum relative movement, but allowing for expansion, and differential movement within and between structures."

Lateral bracing is required by NFPA-13 as follows:

"3-10.3.5 **Sway Bracing of Piping Where Subject to Earthquakes.**

3-10.3.5.1 Feed and cross mains shall be braced with a two-way sway brace. Tops of risers shall be secured against drifting in any direction, utilizing a four-way sway brace. Sway bracing shall be designed to withstand a force in tension or compression equivalent to not less than half the weight of water-filled piping.

3-10.3.5.2 Where "U" hook hangers are used on branch lines, the pipe shall be secured to the end hanger by a wrap-around-type "U" hook.

3-10.3.5.3 U-type hangers used to support a system will satisfy most of the requirements for sway bracing except that, in general, the longitudinal brace referred to as No.1 in Figure A-3-10.3.5(b) shall also be required for 2 1/2 in. and large diameter piping. U-type hangers used as lateral braces shall have legs bent out 10 degrees from the vertical.

3-10.3.5.4 When feed and cross mains are hung with single rods sway bracing shall be provided.

Exception: Sway bracing may be omitted when hanger rods less than 6 in. (152 mm) long are used.

3-10.3.5.5 Bracing shall be attached directly to feed and cross mains."

In the following paragraphs, the NFPA code recognizes that between walls of diverse stiffness, one must provide for relative displacement as well as between walls and roofs.

"3-10.3.5.6 A length of pipe shall not be fastened to sections which will move differently, such as a wall and a roof.

3-10.3.5.7 The last length of pipe at the end of a feed or cross main shall be provided with a transverse brace. Transverse braces may also act as longitudinal braces if they are within 24 in. (610 mm) of the center line of the piping braced longitudinally.

3-10.3.5.8 When additional flexible couplings are used in horizontal piping for purposes other than the requirements for earthquake protection (usually for each of installation), a sway brace shall be provided within 24 in. (610 mm) of each such coupling."

Recognition of the relative displacement which exists between floors of a building is given in the following NFPA-13 paragraphs:

"3-10.3.4 **Clearance.** Sleeves shall be provided around all piping extending through walls, floors, platforms, and foundations, including drains, fire department connections and other auxiliary piping.

(a) Minimum clearance between the pipe and sleeve shall be not less than 1 in. (25 mm) for pipes 1 in. through 3 1/2 in. and 2 in. (51 mm) for pipe sizes 4 in. and larger.

(b) When required the clearance between pipe and sleeve shall be filled with a flexible material such as mastic.

Exception: When piping enters a building through a basement wall and ground water conditions make providing clearance a problem, the end of the pipe may be attached firmly to the wall, with provisions to allow flexing to take place outside the building. The pipe shall be connected to the riser with fittings with flexible joints.

(c) Floor sleeves shall extend at least 3 in. (76 mm) above the top of the wearing surface."

To minimize or prevent pipe breakage where subject to earthquakes, NFPA-13 requires sprinkler systems to be protected as follows:

"3-10.3.2 **Couplings.** Listed flexible pipe couplings joining grooved end pipe shall be provided as flexure joints to allow individual sections of piping 3 1/2 in. or larger to move differentially with the individual sections of the buildings to which it is attached. Couplings shall be arranged to coincide with structural separations within a building. They shall be installed:

(a) Within 24 in. (610 mm) of the top and bottom of all risers.

Exception No. 1: In risers less than 3 ft (0.9 m) in length flexible couplings may be omitted.

Exception No. 2: In risers 3 to 7 feet (0.9 to 2.1 m) in length, one flexible coupling is adequate.

(b) At the ceiling of each intermediate floor in multi-story buildings.

(c) At each side of concrete or masonry walls 2 to 3 feet (0.6 to 0.9 m) from wall surface.

(d) On one side of building expansion joints.

3-10.3.3 **Fittings.** Additional fittings and devices with flexible joints shall be installed where necessary.

3-10.3.3.1 Fittings with flexible joints shall be installed at the top of drops to hose lines regardless of piping size.

3-10.3.3.2 Drops to sprinklers in racks shall be equipped with swing joints assembled with flexible fittings between the rack and the overhead sprinkler system.

Exception: Flexible fittings are not required in the swing joints on drops 3 in. or less in size."

Seismic Bracing Guides

The Sheet Metal and Air Conditioning Contractors National Association (SMACNA) [Ref. 23] has published a guide to the installation of seismic restraints for mechanical and piping systems. This guideline appears to be applicable to steel or cast iron pipes only.

Basically, SMACNA provides general bracing guidelines with specific details for fabrication of braces. The document is directed towards usage by field engineers and contractors by providing generic brace drawings and spacing guidelines.

For most pipes, transverse braces are required at intervals of no more than 40′. The engineer can, of course, install them more often but no information is provided upon which to base the analysis. For longitudinal braces SMACNA recommends a maximum spacing of 80′. The remainder of the guidelines is concerned with the details and fabrication of the braces needed to support the piping. Various configurations for different piping installations are provided.

In general, SMACNA guidelines appear to be adequate for the installation of steel piping systems containing nonhazardous materials. Dynamic considerations do not enter into the selection of transverse spacing intervals, and the importance of the piping is not considered.

There are several suppliers of strut material commonly used to brace piping. Using strut components eliminates much of the cutting, drilling and fabrication associated with pipe supports and braces. The catalog of one supplier, Superstrut [Ref. 21], describes strut and fittings typically offered and Superstrut's seismic brace guide [Ref. 22] provides details for laterally restraining piping systems.

To assist in selecting the type and number of piping system supports, tables for the spacing of vertical, transverse and longitudinal braces is provided by Superstrut [Ref. 22]. Although the tables are helpful, it appears that they are intended only for steel piping and do not address either pipe dynamics or importance.

2.4 Piping System Performance Requirements

In this section, design documents are reviewed to identify the allowable stresses and forces permitted for process piping systems. These parameters generally govern piping system performance.

Existing Building Codes

The Uniform Building Code (UBC) [Ref. 1] has incorporated the requirements of the American Institute for Steel Construction (AISC) Specification in Chapter 27, and the requirements of the Specification of the American Iron and Steel Institute (AISI) in Standard 27-9. These requirements are useful to engineers for design of mild steel piping and all types of structural framing. They provide tensile, shear, and bending allowable stresses as well as interaction formulas for combined states of stress.

The AISC Specification is intended to govern design of structural steel systems, rather than piping elements. In this sense, the AISC (and AISI) Specification is applicable for design of piping system supports and bracing, but is not, in general, appropriate for design of pipe elements.

Proposed Building Codes

The ATC-3 [Ref. 7] includes restrictions on the design allowables for steel components based on AISC Specification allowables, factored upward to correspond to strength, rather than working-stress design. NEHRP [Ref. 9] has followed the same approach as the ATC.

New SEAOC Blue Book

The SEAOC Blue Book [Ref. 10] provides material requirements for framing of the buildings. For steel framing, SEAOC requires that the materials meet the stress limits of the AISC (and AISI) Specifications.

Tri-Services Manual and Supplement

The Tri-Services Manual and Essential Building Supplement, [Ref. 11] and [Ref. 12], developed by the Army, Navy, and Air Force for seismic protection of military buildings are basically concerned with the seismic design of structural systems. For material allowables the Tri-Services Manual refers to applicable codes such as the AISC for steel.

Nuclear Related Design Documents

Generally, the nuclear industry has used existing codes for the specification of performance allowables in nuclear structures. For example, the AISC Specification is generally used for defining stress allowables for steel, and the American Concrete Institute (ACI) Code for concrete allowables.

For nuclear piping, ASME B31.1 [Ref. 19] is used. ASME B31.1 provides material allowables and detailed design requirements for both normal operation conditions and abnormal (upset, emergency, and faulted) conditions. Upset conditions require analysis for the OBE using basic allowable stresses. Emergency conditions require analysis for the SSE using basic allowable stresses factored upward to about the elastic limit. Faulted conditions permit inelastic analysis for the SSE combined with postulated accident condition loads such as those which might result from a rupture of a main steam line.

Piping Codes

The ASME's Building Services Piping B31.9 [Ref. 20] provides the most appropriate allowables for process piping. ASME B31.9 provides the allowable stresses for a large number of materials commonly used in the fabrication and construction of piping systems, including polyvinyl chloride (PVC) and other plastic materials. For materials not explicitly included in allowable stress tables of ASME B31.9, rules are specified for determining material allowable stress, based on the ultimate tensile and minimum yield strength of metals, and the hydrostatic design basis strength of plastics.

In addition to specifying allowable stress, ASME B31.9 provides detailed requirements for pressure, temperature, and gravity-load design of piping systems including, components, fittings, and supports. ASME B31.9 does not provide requirements specific to seismic design other than allowing a 33% increase in axial allowable stress for combined pressure and earthquake loads.

Seismic Bracing Guides

SMACNA and SUPERSTRUT bracing guidelines do not provide information on allowable stresses for either metal or plastic piping. However, these documents do provide a number of design requirements similar to NFPA-13 and the Tri-Services Manual.

2.5 Hazardous Materials Classification

In this section, various documents which identify and classify hazardous materials are reviewed.

The increase in the use of hazardous materials at industrial facilities has generated revisions to fire codes and standards [Ref. 50]. Likewise, the use of hazardous materials also requires consideration in the structural design of systems containing or transporting hazardous materials. This is particularly true for earthquake design, since an earthquake has the potential to initiate multiple releases of hazardous materials.

Earthquakes are not only a concern as an initiator of hazardous material release, but also have the potential to affect the emergency preparedness response to such releases [Ref. 51]. A hazardous material release can initiate secondary fires which are of danger to the occupants of a facility as well as to the facility itself. The response to fire can, in turn, be impeded by the effects of the earthquake throughout the community.

Definition of Hazardous Material

Each year thousands of new chemicals are produced in the United States and abroad. The hazards which they present to the environment and workplace are only moderately understood. Information on the toxic effects of chemicals is compiled by the U.S. Department of Health, Education and Welfare [Ref. 54]. Other, commercially available publications include the MERCK Index [Ref. 55], and sources which provide practical information on hazardous materials. With these publications, it is possible to establish the health hazard of a particular chemical.

The National Fire Protection Association (NFPA) has developed a number of publications which establish the risk posed by flammability of hazardous materials. General information on fire protection for hazardous materials is provided in References 57 and 58. The NFPA has also developed a rating system for hazardous materials, NFPA-704 [Ref. 59]. In addition, the National Fire Protection Association (NFPA) continuously compiles information on hazardous chemicals. The latest compilation is NFPA-49 [Ref. 60] which was issued in 1975. Since then some twenty chemicals a year have been added to the list.

Although the primary purpose of NFPA-704 is to promote the efficiency of fire fighting and prevention associated with hazardous materials, it also provides a system for determining the degree of hazard posed by each chemical. This system identifies the hazards of material in terms of three principal categories: health, flammability, and reactivity of the material. For each category materials are rated from a scale of 0 to 4 to delineate their degree of health, flammability, or reactivity hazard.

Control of Hazardous Substances by the Federal Government

The number of hazardous materials used in the United States is constantly increasing [Ref. 54]. Recognizing the danger posed by these chemicals, the Federal government has undertaken the responsibility of regulating their use. In the United States there are three major programs under which hazardous materials are regulated:

1. Environmental Protection Agency (EPA) [Ref. 61].

   The regulation of hazardous waste is the responsibility of this agency. Hazardous wastes are enumerated by this agency in one of four lists:

   a. F list (40 CFR 261.31)
   b. K list (40 CFR 261.32)
   c. P list (40 CFR 261.33)
   d. U list (40 CFR 261.34)

2. Occupational Safety and Health Administration (OSHA) [Ref. 62].

   This agency is responsible for regulating an employee's access to information about hazardous materials in the workplace. A Hazard Communication Standard (29 CFR 1910.1200) has been formulated for this purpose.

3. Department of Transportation (DOT) [Ref. 63 and Ref. 64].

Under this program, safety criteria for the transport of hazardous materials has been formulated. Hazardous materials are defined in the Hazardous Materials Table (49 CFR 172.101) along with the proper hazard class and required identification.

At the Federal level there are two organizations: the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA), which deal with different aspects of this problem. For hazardous materials outside of the workplace, the regulations of the EPA must be observed, while in the workplace it is the requirements of OSHA. Their efforts at this point have been mainly in the storage and handling of hazardous chemicals. Engineering of piping systems or storage facilities has not been investigated at this time. Explanations of EPA and OSHA requirements are presented in References 65 and 66. Additional information, clarifying further Federal regulations, is provided in References 67 and 68.

The EPA and OSHA requirements are intended to control hazardous materials and to insure that they are handled safely. A third organization of the Federal Government is charged with the control of the transportation of hazardous materials. This responsibility has been delegated to the Department of Transportation (DOT) [Ref. 63]. Under this program, safety criteria for the transport of hazardous materials have been developed. Furthermore, a list of materials considered hazardous by DOT is given in the Hazardous Materials Table (49 CFR 172.101) along with the proper hazard class and required identification. In case of an accident in the transport of hazardous materials, a guide to handling the situation has been prepared for selected materials [Ref. 64].

Control of Hazardous Substances by State and Local Government

Only certain states have attempted to regulate hazardous materials. For example, in the State of California two laws have been proposed which deal with hazardous chemicals: AB2185 [Ref. 52] and AB2187 [Ref. 53]. Both laws deal with the potential effects of hazardous material releases in the community.

It is instructive to study the requirements of these bills. Initially, these bills require that an inventory of hazardous materials within each county be made. The goal is to determine what resources are needed for emergency planning in case of an accident involving hazardous materials.

No engineering requirements above those existing in local building codes are required. Thus, it is left to the manufacturer or the installer of the piping system to determine what makes a good design and installation. This requires a broad knowledge of the entire problem, which is normally not found among piping manufacturers and installers.

AB2185 requires that a response plan be formulated to treat the release of hazardous materials. The following quote is taken directly from this bill:

> "The bill would require any business, as defined, which handles a hazardous material, as defined, and is located within an implementing county or city, to establish a specified business plan by September 1, 1986, in accordance with standards adopted by the Office of Emergency Services, for emergency response to a release or threatened release of the hazardous material. A handler would be required to report certain releases or threatened releases, as specified."

This bill places at this time, the emphasis on obtaining an inventory of hazardous materials:

> "The Legislature declares that, in order to protect the public health and safety and the environment, it is necessary to establish business and area plans relating to the handling and release or threatened release of hazardous materials. The establishment of minimum statewide standards for these plans is a statewide concern. Basic information on the location, type, quantity, and the health risks of hazardous materials handled, used, stored, or disposed of in the state, which could be accidentally released into the environment, is not now available to fire fighters, health officials, planners, public safety officers, health care provides, regulatory agencies, and other interested persons. The information provided by business and area plans is necessary in order to prevent or mitigate the damage to the health and safety of persons and the environment from the release or threatened release of hazardous materials into the workplace and environment."

The definition of a hazardous material is broad and basically leaves it up to the organization using hazardous chemicals to know what a hazardous material is:

> "'Hazardous material' means any material that, because of its quantity, concentration, or physical or chemical characteristics, poses a significant present or potential hazard to human health and safety or to the environment if released into the workplace or the environment. 'Hazardous materials' include but are not limited to, hazardous substances, hazardous waste, and any material which a handler or the administering agency has a reasonable basis for believing that it would be injurious to the health and safety of persons or harmful to the environment if released into the workplace or the environment."

Some guidance is provided by the next paragraph in the bill:

> "'Hazardous substance' means any substance or chemical product for which one of the following applies:
>
> (1) The manufacturer or producer is required to prepare a MSDS for the substance or produce pursuant to the Hazardous Substances Information and Training Act (Chapter 2.5 [commencing with Section 6360] of Part 1 of Division 5 of the Labor Code) or pursuant to any applicable federal law or regulation.

(2) The substance is listed as a radioactive material in Appendix B of Chapter 1 of Title 10 of the Code of Federal Regulations, maintained and updated by the Nuclear Regulatory Commission.

(3) The substances listed pursuant to Title 49 of the Code of Federal Regulations.

(4) The materials listed in subdivision (b) of Section 6382 of the Labor Code."

The remainder of the bill deals with the inventory procedures for hazardous materials, emergency response to the release of these materials, and the penalties for failure to comply with its provisions.

Summary

The number of hazardous materials in the United States is continually increasing. These materials pose a hazard to the health and welfare of those individuals who are working in, or living close to, facilities which use these materials.

The Federal Government has undertaken to regulate hazardous materials nationally. State and local governments are trying to comply with Federal requirements and at the same time develop ordinances to regulate local hazards.

Each agency or organization evaluates hazards from its own perspective, based on its own responsibilities. After investigating available criteria for identifying and classifying hazardous materials, it appears that NFPA-704 is most suitable document for rating hazardous materials contained in industrial piping systems.

CHAPTER 3

DESIGN CRITERIA

3.1 Introduction

This chapter presents and delineates criteria for seismic design of hazardous process piping. These design criteria will be used as the basis for subsequent development of design procedures in Chapter 4 and analysis of example piping models in Chapter 5.

The design criteria have been synthesized from the pertinent sections of a number of diverse sources. The intent of Chapter 3 is to pull together as much information as possible from existing design documents.

3.2 Basic Approach

Criteria for seismic design of hazardous piping includes the following topics:

1. Importance of Piping (i.e., piping contents)
2. Analysis Methods
3. Seismic Load Criteria
    a. Ground Floor Elevations
    b. Upper-Floor Elevations
4. Pipe and Support (Brace) Allowables
5. Design and Construction Requirements

Since there is no single source document available which provides input for all of the above areas, the applicable sections of documents reviewed as part of the literature survey were used to form the design criteria. For this purpose the following documents were summarized and compared:

1. 1985 Uniform Building Code [Ref. 1]
2. NEHRP/ATC-3 [Refs. 7/9]
3. New SEAOC Blue Book [Ref. 10]
4. Tri-Services Manual and Supplement [Refs. 11-12]
5. Nuclear-Related Documents [Refs. 14-17]
6. ASME B31.9 [Ref. 20], and
7. SMACNA [Ref. 23].

The comparisons of the above documents are presented in Table 3-1, in terms of the prescription of seismic load, and in Table 3-2, in terms of piping system allowables and other design/construction requirements.

As Table 3-1 indicates, piping loads are prescribed in most building codes by simple formulas (i.e., static analysis method). For model seismic codes (i.e., NEHRP/ATC-3 and the new SEAOC Blue Book) ground response spectra are also included, permitting (and sometimes requiring) more rigorous dynamic analysis methods. In these cases a single-level of earthquake is specified (i.e., a 500-year return period event). For the more sophisticated or important designs (i.e., nuclear-related for "essential" military facilities) dual-level design criteria are specified with peak ground acceleration return periods ranging from less than 100 years to over 1000 years.

The effects of piping elevation in the building are considered for building codes by factoring ground criteria (e.g., by a factor of 1.5, per the new SEAOC Blue Book) to account for amplified motion of upper-floors. Only nuclear-related documents and the Tri-Services Supplement for essential facilities provide methods for calculating upper-floor spectra. Likewise, with the exception of the nuclear-related documents, the effects of piping flexibility on dynamic response are either ignored or approximated by factoring load criteria (e.g., by a factor of 2.0 per the new SEAOC Blue Book). The difficulty in applying these factors lies in determining when the piping system is "flexible" and when it is "rigid."

Table 3-2 provides a summary of piping system allowables (i.e., allowable forces and stresses) and other design and construction requirements. In general, building code documents do not thoroughly cover piping system design. Details for combining seismic load with pressure and temperature loads, material allowables (for materials other than common steel pipe), and design requirements are generally not provided. Clearly, the evolution of these documents has focused on seismic design of the building's structural system and has not treated nonstructural components, such as piping, in an equally rigorous manner.

For allowables and loads other than seismic, the ASME Code provides comprehensive coverage of most piping materials and components. ASME B31.9 is a relatively new addition to the ASME Code, and provides detailed requirements for pressure design of building services piping, including piping made of polyvinyl chloride (PVC), reinforced thermosetting resins (RTR), and other polymeric materials now commonly used in industrial facilities.

In terms of design and construction do's and don'ts (e.g., use of flexible couplings at building joints, etc.) requirements are found in the Tri-Services Manual [Ref. 11], NFPA-13 [Ref. 18]; in design guides such as SMACNA [Ref. 23], and in brace manufacturer's catalogs such as Superstrut [Ref. 22]. In addition, SMACNA and brace manufacturer's catalogs provide details of acceptable seismic brace construction.

As a result of the comparisons of documents summarized in Tables 3-1 and 3-2, the following basic approach was adopted for developing design criteria.

1. Define piping importance on the basis of the hazardous nature of the contents. Since none of the documents reviewed in Tables 3-1 and 3-2 adequately define "hazardous" materials, an additional source will be used (e.g., NFPA-704 [Ref. 59]).

2. Use a "streamlined" analysis method for positioning braces in accordance with design spectrum loads and pipe/brace allowables. Since none of the documents reviewed have such a method, design procedures embodying such an approach will be developed (i.e., Chapter 4).

3a. Use a single-level of design seismic load corresponding to NEHRP/ATC-3 to determine 500-year return period ground response spectra for design of piping systems supported from, or attached to, the ground floor or other horizontally rigid portions of a building.

3b. Use techniques similar to these specified in the Tri-Services Supplement to develop upper-floor response spectra from ground motion spectra for design of piping systems supported from, or attached to, upper-floors or other horizontally flexible portions of a building.

4. Use ASME B31.9 to define pipe and vertical support allowables. Use 1985 UBC to define seismic brace allowables.

5. Extract design and construction requirements pertinent to piping from Tri-Services Manual, NFPA-13, SMACNA, and brace manufacturers' catalogs.

3.3 Importance Categorization of Piping

The determination of the level of importance for piping requires a great deal of judgement and broad knowledge of a number of fields. For the purpose of this work contained herein, importance will be based entirely on the hazardous nature of the piping system contents (i.e., potential health, flammability or reactivity hazard should the pipe rupture or leak occur). It is recognized that other considerations, such as the threat of extended business interruption, may also make certain piping systems "important." However, determination of importance of piping to facility operation cannot be made generically and rests largely with the owner or facility manager.

After review of the available documentation on hazardous materials, it was found that the rating system for potential health, flammability, and reactivity hazards given in NFPA 704 [Ref. 59] was the best means for categorizing hazardous substances. This document rates substances by a number from 0 to 4, for each of the three types of hazard. Short definitions of the type and level of hazard for each rating are given in Table 3-3.

Three levels of importance have been selected for the categorization of piping systems, which are defined below:

Category	Description
A	Extreme Importance - This category recognizes that failure of the piping system would release hazardous chemicals which would endanger the health of those individuals in the vicinity of the accident, or pose an extreme threat from fire and reactivity.
B	Moderate Importance - This category considers those situations where the hazardous chemical is only a moderate threat to the health of those individuals in the vicinity of the accident, or poses only a moderate threat due to fire or reactivity. It also could be the design level selected if there is no human factor to consider; but some additional protection is necessary.
C	Low Importance - No special precautions are needed for seismic considerations. (No lateral braces.)

Although arbitrary, it was concluded based on the definitions given in Table 3-3, that piping with contents rated as 3 or 4 in terms of health, flammability, or reactivity hazard should be considered to be of extreme importance and be grouped in Category A. In certain specific cases, (e.g., small diameter lines, piping located in areas away from building personnel, etc.) piping with materials rated as 3 would be more correctly considered to be of moderate, rather than extreme importance. Piping with contents rated as 2 were, in general, considered to be of moderate importance and piping with contents rated as 0 or 1 were, in general, considered to be of low importance. The above descriptions are summarized in Table 3-4.

A list of some hazardous substances commonly used in industrial facilities, their rating in terms of health, flammability, and reactivity hazard and their importance category are given in Table 3-5.

3.4 Analysis Methods

Rigorous evaluation of seismic stresses in piping system components requires dynamic analysis using detailed models of the piping system. Largely as a result of work in the nuclear industry, dynamic analysis of piping systems has been developed fully. However, use of dynamic analysis in routine design of seismic braces for conventional non-nuclear piping systems is not practical. Consequently, a "streamlined" approach was developed for selecting pipe brace locations. This approach is described in full in Chapter 4, and is summarized below.

Rather than analyzing the entire piping system, spacing of lateral braces is selected on the basis of generic design curves which describe peak pipe bending stress and peak brace force as a function of unbraced span length. The generic curves of peak response are calculated using equivalent static analysis with a peak seismic acceleration corresponding to the factored design spectrum ordinate at the fundamental-mode frequency of the pipe. The amount by which the ordinate is factored was "benchmarked" by comparisons with multi-mode dynamic analyses.

Thus, the streamlined approach uses equivalent static analysis to develop generic design curves, avoiding the need to rigorously analyze the piping system. In this sense, equivalent static analysis is the method inherently used for piping design.

3.5 Seismic Load Criteria

Seismic load criteria were selected to be represented by a single-level (in contrast to dual-level) criterion earthquake defined as an event having a 10% probability of exceedance in the next fifty years (i.e., approximate 500-year return period event). This selection of seismic criteria was influenced by NEHRP/ATC-3 and the new SEAOC Blue Book both of which are based on this criterion earthquake and which provide ground response spectra corresponding to this event. Although the NEHRP/ATC-3 spectra may not be as precise as spectra developed by site-specific hazard analysis, they are sufficiently accurate for the purpose of designing piping seismic bracing and have been accepted for seismic design of buildings (e.g., the new SEAOC Blue Book has been recently adopted, with minor changes, by the International Congress of Building Officials as Chapter 23 of the 1988 UBC).

The following sections provide additional descriptions of damping levels, and development of ground and upper-floor design spectra.

3.5.1 Damping

The damping levels for piping system design were selected with consideration of the level of vibratory motion and the type of pipe material. Damping values of 4% for ground motion accelerations of 0.2g EPGA, and 7% for ground motion accelerations of 0.4g EPGA were chosen for both steel and PVC piping. Damping levels for other materials and levels of vibration were not required for Phase 1 work.

The damping levels selected are considerably higher than those often found in literature for piping systems. For instance, Table 3 of Newmark and Hall [Ref. 8] lists vital piping damping at 2% to 3% for stresses at, or just below, yield point. The basis for selecting the higher criteria damping levels is that industrial facility piping systems are typically supported, clamped, and braced with slightly sloppy or nonlinear hardware, which tends to dissipate a substantial amount of energy (in addition to the energy dissipated by internal friction of the pipe's material).

3.5.2 Ground-Level Design Spectra

Ground level design spectra were taken as smoothed versions of the NEHRP/ATC-3 spectra and adjusted to account for damping levels other than the 5% damping inherent in the NEHRP/ATC-3 spectra. Adjustments were made to the spectra by ratioing the median spectra amplification factors given in Table 1 of Newmark and Hall [Ref. 8]. For instance, in the velocity domain (i.e., approximately 0.25 Hz to 2.0 Hz) 7%-damped spectra were created from the NEHRP/ATC-3 spectra by decreasing each ordinate by:

$$\frac{1.51\ (7\%)}{1.65\ (5\%)} = 0.915$$

where the 1.51 and 1.65 factors were taken from Table 1 at the 7% and 5% damping levels, respectively.

Plots of 4%, 7%, and 20%-damped ground-level design spectra are shown in Figure 3-1 for NEHRP/ATC-3 Map Area. No. 7 (i.e., 0.4g EPGA) and Soil Type S_2.

3.5.3 Upper-Floor Design Spectra

Upper-floor design spectra were directly generated from ground-spectra using an existing JBA Program "FLRSPEC" [Ref. 79]. This approach was selected in lieu of applying the methodology prescribed in the Tri-Services Supplement for "essential" buildings, since it was readily available and produced approximately the same type of results. Other programs which directly generate upper-floor spectra are also available.

The approach used by "FLRSPEC" to generate upper-floor spectra is summarized below.

- The linearly-elastic ground spectrum (i.e., as defined in Section 3.5.2) is modified in accordance with the procedures given in Newmark and Hall [Ref. 8] for development of inelastic design spectra. A ductility factor of 2 was used for the degree of inelastic response anticipated at 0.4g.

- For each mode of the building which has significant participation, amplified response is determined over a frequency range centered on about the frequency of the mode of interest. The degree of amplification and the width of the frequency range is based on the degree of degradation in frequency due to inelastic response (e.g., one dominant mode at about 2.5 Hz - 5.0 Hz was used in this study to simulate one-story industrial building roof response).

- The resulting spectrum is broadened and smoothed slightly to account for uncertainty in the calculation of building and piping frequency.

Plots of 4%, 7%, and 20%-damped upper-floor level design spectra are shown in Figure 3-2 for ground motion corresponding to NEHRP/ATC-3 Map Area No. 7 (i.e., 0.4g EPGA) and Soil Type S_2.

3.6 Allowable Stresses and Load Combinations

The ASME B31.9 Code was selected as the governing document for allowable stresses in piping elements and gravity supports, and the 1985 UBC was selected as the governing document for allowable stresses in seismic braces.

3.6.1 Piping Elements

Section 902.3.1 of ASME B31.9 requires piping systems to meet the following load combination and allowable stress requirements for axial loads.

$$P \leq 1.0\ S\ E \quad \text{(axial only)} \qquad (3\text{-}1)$$

$$P + DL + LL + EQ + \leq 1.33\ S \quad \text{(axial only)} \qquad (3\text{-}2)$$

where:

P = design basis pressure,
DL = dead load,
LL = live load,
EQ = earthquake load,
S = allowable material stress as specified in ASME B31.9, and
E = joint efficiency factor.

The basic allowable stress, S, specified by Section 902.3 of ASME B31.9 for various materials is summarized below:

Cast Iron -	1/10 of specified minimum yield strength,
Malleable Iron -	1/5 of specified minimum tensile strength,
Other Metals -	1/4 of specified minimum tensile strength, not to exceed 2/3 of yield strength (e.g., ASTM A53, Grade A steel pipe has a minimum tensile strength of 48 ksi, a minimum yield of 30 ksi and a basic allowable stress of 12 ksi), and
Thermoplastics -	1/2 of the hydrostatic design basis (HDB) strength (e.g., ASTM D1785 PVC pipe has a HDB strength of 2.0 ksi and an allowable stress of 1.0 ksi).

The joint efficiency factor, E, is used to account for reduced strength of certain types of pipe due to longitudinal or spiral welding.

ASME B31.9 does not stipulate specific limits on bending stresses other than those due to expansion and construction loads. In this case reference is made to ASME B31.1 [Ref. 19] for determining the allowable stress range. For the purposes of checking bending in pipe elements the following limits were selected:

Category A Piping Systems

$$P + DL + LL + EQ + \leq 1.5\ S\ E \quad \text{(axial and bending)} \qquad (3\text{-}3)$$

Category B Piping Systems

$$P + DL + LL + EQ + \leq 3.0\ S\ E \quad \text{(axial and bending)} \qquad (3\text{-}4)$$

Category C Systems

No limits on bending

The 1.5 factor used for Category A systems is consistent with the axial plus bending limits required by the ASME Code for nuclear piping. The 3.0 factor used for Category B systems is consistent with the secondary stress range limits required by ASME for certain operating conditions.

In summary, all systems must meet the basic requirements of ASME B31.9 in terms of limits on axial stresses (i.e., Equations 3-1 and 3-2), the additional axial plus bending limits specified in Equation 3-3 for Category A systems, and in Equation 3-4 for Category B systems. Limits on shear, which seldom govern, would be appropriately taken from ASME B31.9 as 0.8 times the allowable stress for all external loads, including earthquake.

The above limits on axial and bending stresses involve pressure loads. For the purpose of seismic analyses it is desirable to remove the pressure load from the load combination and specify limits for external forces only. This is appropriate for most industrial piping systems since axial stresses due to pressure are usually much less than 1.0 S.

For commonly used industrial pressures up to about 150 psi in most types of PVC pipe or up to 600 psi in steel pipe, the axial stress due to pressure will not exceed 0.5 S.

Thus, the following load combinations are developed by differencing Equations 3-1 and 3-3, and Equations 3-2 and 3-4:

Category A Piping System Limits on Axial + Bending Stress

$DL + LL + EQ + \leq 0.5\ S\ E$ (extreme pressure) (3-5a)
$DL + LL + EQ + \leq 1.5\ S\ E$ (no pressure) (3-5b)
$DL + LL + EQ + \leq 1.0\ S\ E$ ("normal" pressure) (3-5c)

Category B Piping System Limits on Axial + Bending Stress

$DL + LL + EQ + \leq 2.0\ S\ E$ (extreme pressure) (3-6a)
$DL + LL + EQ + \leq 3.0\ S\ E$ (no pressure) (3-6b)
$DL + LL + EQ + \leq 2.5\ S\ E$ ("normal" pressure) (3-6c)

In closing, it is of importance to note that ASME B31.9, in specifying the stress limits described above, requires all couplings and fittings to be at least as strong as the pipe under pressure load. This must also be true for vibratory earthquake loads. Allowable stresses for couplings or fittings not as strong as the attached pipe should be reduced accordingly.

3.6.2 Supports and Braces

Allowable stresses for gravity supports and hangers were selected to be defined by the limits of Section 921.1 of ASME B31.1 (i.e., 1/5 of ultimate tensile strength).

Allowable stresses for seismic braces, not essential for vertical load stability, were selected to be equal to those permitted by the 1985 UBC.

TABLE 3-1

SUMMARY OF PIPING SYSTEM SEISMIC LOADS PRESCRIBED BY VARIOUS DESIGN DOCUMENTS

Design Document(s)	Piping System Seismic Loads are Prescribed on the Basis of:				
	Simple Formula?	Ground Spectra?	Importance of Piping?	Elevation of Piping in Building?	Flexibility of Piping System?
1985 UBC (Ref. 1)	**Yes** $F_p = ZIC_pW_p$	**No** Level of hazard is not explicitly defined.	**Partially** I = 1.5, if hazardous; however "hazardous" contents are undefined.	**Yes** Upper-floor load = 1.5 x ground-level load.	**No** Footnote 3 of Table 23-J does not provide adequate description.
ATC-3/NEHRP (Refs. 7/9)	**Yes** $F_p = A_vC_cPa_ca_xW_c$	**Yes** 500-year spectrum recommended for "building" design.	**No** Performance Factor, P, does not consider hazardous materials.	**Yes** Amplification factor, a_x, is based on building height.	**Partially** Amplification factor, a_c, is based on building period, but not fully defined.
New SEAOC Blue Book (Ref.10)	**Yes** $F_p = ZIC_pW_p$	**Yes** 500-year spectrum recommended for "building" design.	**Partially** I = 1.5, if hazardous; however "hazardous" contents are undefined.	**Yes** Upper-floor load = 1.5 x ground-level load.	**Partially** Horizontal force factor, C_p, increased by 2.0, if piping flexible.
Tri-Services Manual and Supplement (Refs. 11/12)	**Yes** $F_p = ZIC_pW_p$	**Yes** Dual level design used for "essential" facilities: EQ-I=72-year spectrum EQ-II=949-year spectrum	**No** I = 1.0, for all piping (except fire protection).	**Yes** For "essential" facilities upper-floor spectra are defined.	**Partially** Pipe flexibility between supports is considered.
Nuclear-Related Documents (Refs. 14-17)	**No** Nuclear design is based on site-specific spectra only.	**Yes** Dual level design used: OBE=200-500 year spectrum SSE=1000-5000 year spectrum	**No** However, piping importance is considered in determ. allwble. stresses	**Yes** Upper-floor spectra are defined.	**Yes** Equivalent static and dynamic analyses are based on piping frequency.
ASME B31.9 (Ref. 20)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
SMACNA (Ref. 23)	**N/A** However, bracing guidelines comply with $C_p = 0.5$.	**N/A**	**N/A** Bracing guidelines ignore piping importance, unless enveloped by $C_p = 0.5$.	**N/A** Bracing guidelines ignore piping elevation, unless enveloped by $C_p = 0.5$.	**N/A** Bracing guidelines ignore piping flexibility, unless enveloped by $C_p = 0.5$.

TABLE 3-2

SUMMARY OF PIPING SYSTEM ALLOWABLES, AND OTHER REQUIREMENTS, PRESCRIBED BY VARIOUS DESIGN DOCUMENTS

Design Document(s)	Piping System Allowables (or Other Requirements) Prescribed on the Basis of:				
	Importance of Piping?	Combination of Seismic with Other Loads?	Type of Piping Material?	Type of Brace Material?	Special Design/Construction Considerations?
1985 UBC (Ref. 1)	**No** Allowables are not based on piping importance.	**Partially** Gravity loads, but not temperature or pressure.	**No** Except for very common types of steel pipe.	**Indirectly** For steel brace components.	**No** Nothing provided specifically for piping.
ATC-3/NEHRP (Refs. 7/9)	**No** Allowables are not based on piping importance.	**Partially** Gravity loads, but not temperature or pressure.	**No** Except for essential components require "manufacturer certification".	**Indirectly** For steel brace components.	**No** Except, periodic inspection of large-bore piping with combustible material.
New SEAOC Blue Book (Ref. 10)	**No** Allowables are not based on piping importance.	**Partially** Gravity loads, but not temperature or pressure.	**No** Except for very common types of steel pipe.	**Indirectly** For steel brace components.	**No** Nothing provided specifically for piping.
Tri-Services Manual and Supplement (Refs. 11/12)	**No** Except, "essential" piping is required to remain functional.	**Partially** Gravity loads, but not temperature or pressure.	**Partially** Spacing guidelines provided for steel and copper piping.	**Indirectly** For steel brace components.	**Yes** Specific seismic design/ construction requirements are provided.
Nuclear-Related Documents (Refs. 14-17)	**Yes** Allowables are based on piping importance.	**Yes** Temperature and pressure are explicitly included in load combinations.	**Yes** Per ASME code requirements for various types of steel piping.	**Yes** Per ASME or AISC code requirements.	**Partially** General design/construction requirements are specified (no specific details).
ASME B31.9 (Ref. 20)	**No** B31.9 does not consider piping importance.	**Partially** Pressure is included; however, bending allowables are undefined.	**Yes** Including plastic and materials other than steel.	**Partially** For pipe supports (hangers) only.	**Partially** Non-seismic design/ construction requirements are specified.
SMACNA (Ref. 23)	**No** Bracing guidelines ignore piping importance.	**Partially** Bracing guidelines consider gravity load, but not temperature and pressure.	**No** Spacing requirements are appropriate for only one pipe material (steel).	**Yes** Brace details are explicitly shown.	**Yes** Specific seismic design/ construction requirements are provided.

TABLE 3-3

IDENTIFICATION OF THE FIRE HAZARDS OF MATERIALS (from Ref. 59)

Health Hazard		Flammability Hazard		Reactivity (Stability) Hazard	
Rating	Type of Possible Injury	Rating	Susceptibility of Materials to Burning	Rating	Susceptibility to Release of Energy
4	Materials which on very short exposure could cause death or major residual injury even through prompt medical treatment were given.	4	Materials which will rapidly or completely vaporize at atmospheric pressure and normal ambient temperature, or which readily dispersed in air and which will burn readily.	4	Materials which in themselves are readily capable of detonation or of explosive decomposition or reaction at normal temperatures and pressures.
3	Materials which on short exposure could cause serious temporary or residual injury even though prompt medical treatment were given.	3	Liquids and solids that can be ignited under almost all ambient temperature conditions.	3	Materials which in themselves are capable of detonation or explosive reaction but require a strong initiating source or which must be heated under confinement before initiating or which react explosively with water.
2	Materials which on intense or continued exposure could cause temporary incapacitation or possible residual injury unless prompt medical treatment is given.	2	Materials that must be moderately heated or exposed to relatively high ambient temperatures before ignition can occur.	2	Materials which in themselves are normally unstable and readily undergo violent chemical change but do not detonate. Also materials which may react violently with water or which may form potentially explosive mixtures with water.
1	Materials which on exposure would cause irritation but only minor residual injury even if no treatment is given.	1	Materials that must be preheated before ignition can occur.	1	Materials which in themselves are normally stable, but which can become unstable at elevated temperatures and pressures or which may react with water with some release of energy but not violently.
0	Materials which on exposure under fire conditions would offer no hazard beyond that of ordinary combustible material.	0	Materials that will not burn.	0	Materials which in themselves are normally stable, even under fire exposure conditions, and which are not reactive with water.

TABLE 3-4

Importance Categorization for Hazard Piping

Importance Category	Hazardous Rating of Piping Contents		
	Health	Flammability	Reactivity
A	4,3	4,3	4,3
B	2,3[1]	2,3[1]	2,3[1]
C	0	0	0

1. For certain special conditions contents with a hazard rating of 3 may be classified as Category B, rather than Category A. Examples of such special conditions include very small diameter lines or piping used in areas of low or occasional piping.

TABLE 3-5

Importance and Hazard Ratings of Various Substances Found at Industrial Facilities

Substance	Hazard Rating			Importance Rating
	Health	Flammability	Reactivity	
Acetone	1	3	0	A
Acetylene	1	4	2	A
Ammonia (liquid)	3	1	0	A
Butyl Acetate	1	3	0	A
Chilled Water	0	0	0	C
Chloroethane VG	2	4	0	A
Compressed Air	0	0	0	C
Deionized Water	0	0	0	C
Dichlorobenzene	2	2	0	B
Distilled Water	0	0	0	C
Ethanol	0	3	0	A
Fluorine (gas)	4	0	3	A
Fuel Oil	0	2	0	B

TABLE 3-5 (continued)

Importance and Hazard Ratings of Various Substances Found at Industrial Facilities

Substance	Hazard Rating			Importance Rating
	Health	Flammability	Reactivity	
Hexane	1	3	0	A
Hydrogen (liquid)	3	4	0	A
Hydrogen Fluoride	4	0	0	A
Hydrogen Peroxide	2	0	1	B
Isopropyl Alcohol	1	3	0	A
Isophorone	2	2	0	B
Kerosene	0	2	0	B
Methyl Ethyl Ketone	1	3	0	A
Methyl Iso-Butyl Ketone	1	3	0	A
Natural Gas (liquid)	3	4	1	A
Nitrogen (liquid)	3	0	0	A
Normal Butyl Acetate	1	3	0	A

TABLE 3-5 (continued)

Importance and Hazard Ratings of Various Substances Found at Industrial Facilities

Substance	Hazard Rating			Importance
	Health	Flammability	Reactivity	Rating
Oxygen (liquid)	3	0	0	A
Phosgene (gas)	4	0	0	A
Potassium Hydroxide	3	0	1	A
Propane (gas)	1	4	0	A
Sodium Hydroxide	3	0	1	A
Sulfuric Acid	3	0	2	A
Trichloroethylene	2	1	0	B
Xylene	2	3	0	A

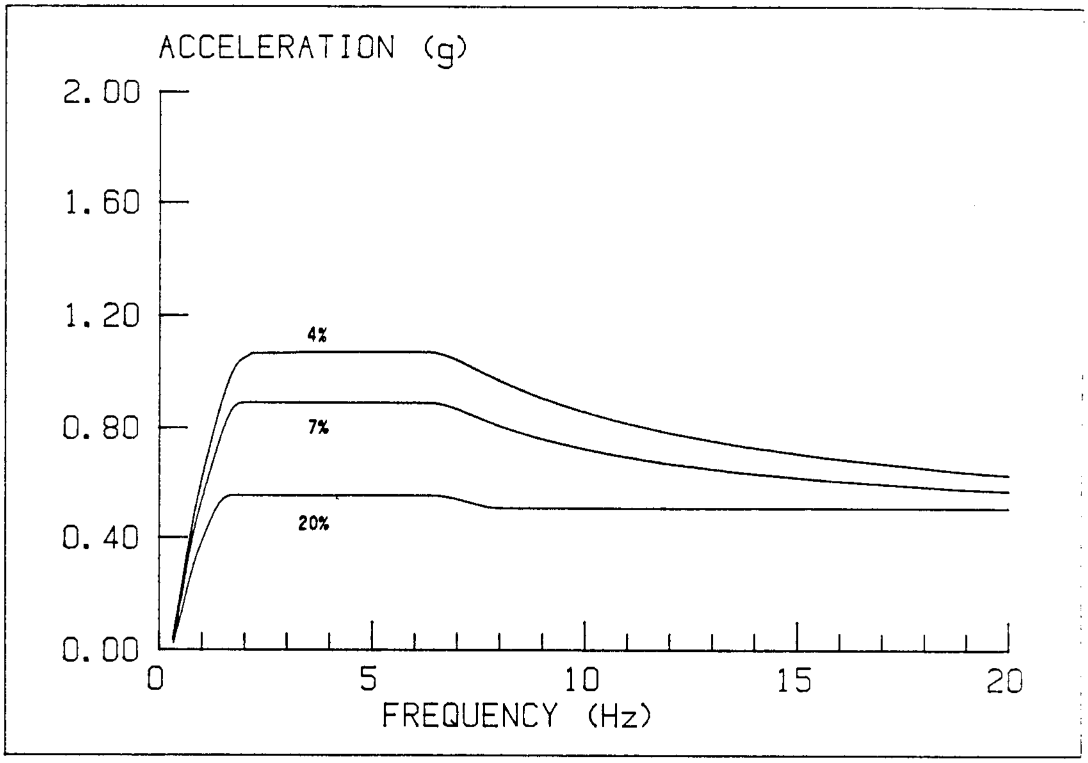


FIGURE 3-1 GROUND LEVEL 4%, 7% AND 20%-DAMPED DESIGN SPECTRA, NEHRP/ATC-3 MAP AREA NO. 7, SOIL TYPE S_2.

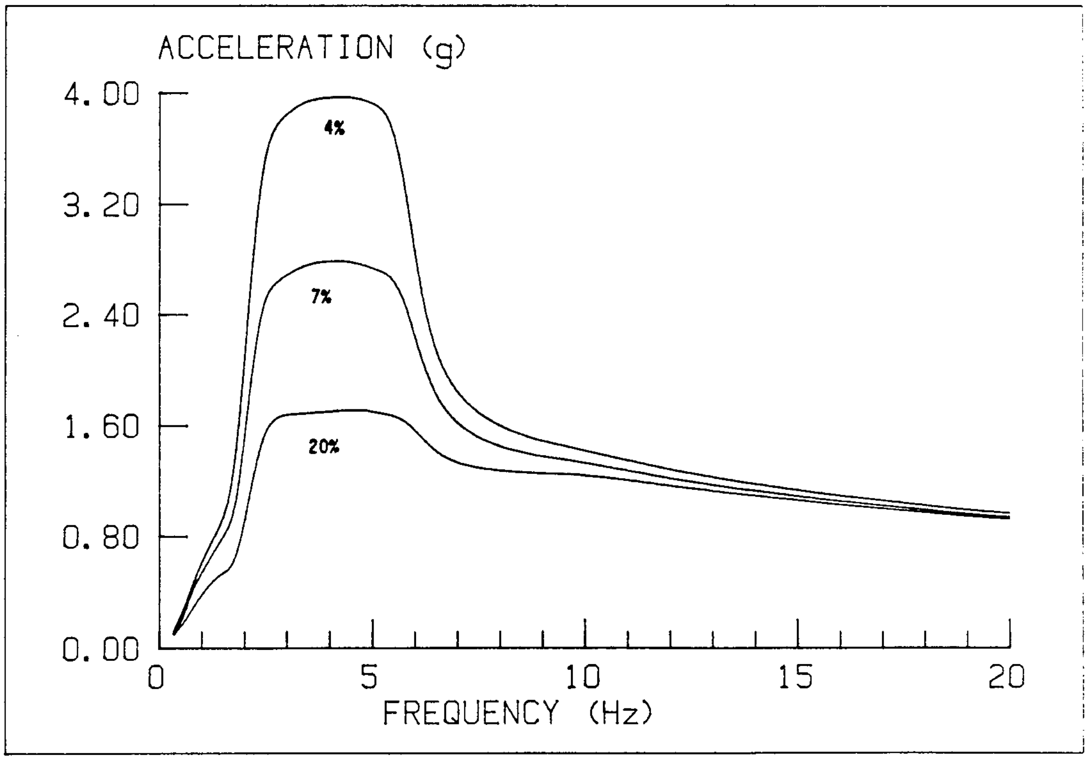


FIGURE 3-2 UPPER-FLOOR 4%, 7% AND 20%-DAMPED DESIGN SPECTRA, NEHRP/ATC-3 MAP AREA NO. 7 SOIL TYPE S_2.

CHAPTER 4

TENTATIVE DESIGN PROCEDURES

4.1 Introduction

Existing seismic codes and piping-related design documents provide a broad choice of methods for design of seismic bracing. At one extreme the engineer can choose to perform dynamic analyses for design of piping and verification of seismic brace adequacy (e.g., the nuclear industry approach). At the other extreme the engineer can ignore all analysis and select brace types and locations in accordance with generic designs and spacing guidelines (e.g., SMACNA [Ref. 23]). The first approach can be used to directly address all pertinent concerns such as piping importance, dynamic amplification of seismic load, type of pipe material, and piping system flexibility. However, the time and expense of such an effort is not practical for piping systems in conventional industrial facilities. In the later approach (e.g., bracing guidelines) brace type and location can be efficiently determined, but pipe importance, flexibility and strength, and the seismic environment are either ignored or based on assumptions which are not valid in all cases.

To bridge the gap between the extremes described above a "streamlined" design methodology has been developed which avoids complex dynamic analysis and yet considers piping importance, pipe flexibility and strength, and seismic environment.

4.2 Methodology

Before developing a methodology it was necessary to first decide if the approach would involve "flexible" or "rigid" restraint of the piping system. By "flexible" it is implied that all, or a portion of, the piping system is essentially free to move relative to the building or supporting structure. A pipe run on long hanger rods is an example of such a system. While the concept of "isolating" the piping system from the supporting structure is appealing, it is also not practical for most piping systems which are, in general, rigidly anchored at certain locations (e.g., to fixed equipment, walls, etc). Full isolation of a piping system would require use of expansion joints and other special hardware not commonly installed with most piping systems. For this reason the more traditional "rigid" bracing approach was adopted as the method of restraint for which design procedures would be developed.

"Rigid" restraint implies that the pipe is essentially fixed to the building or supporting structure at each brace location. In reality the braces are not completely rigid, however the amount of displacement between the pipe and the supporting structure is relatively small (e.g., 0.25 inch or less). For long spans between transverse braces the primary source of lateral seismic displacement will be due to pipe flexure. Consequently, "rigid" restraint of a piping system requires spacing of transverse braces as necessary to limit excessive bending of pipe segments between braces.

The approach of the "streamlined" design methodology is outlined by the following steps:

- Identify the contents of piping system and determine the appropriate importance categorization (i.e., A, B or C).

- Determine allowable bending stress on the basis of the piping system's importance, and the allowable stress values specified by ASME B31.9 for the type of pipe material used.

- Identify the seismic environment; i.e., determine the NEHRP/ATC-3 [Refs. 7/9] seismic acceleration coefficient (A_v), the soil type (S_1, S_2 or S_3), and identify the location of the piping system in the building (i.e., determine if the pipe is hung or supported from an upper-floor (roof), which can amplify horizontal vibration, or hung or supported from the ground floor (basement) which moves essentially with the ground.

- Select and position longitudinal braces to restrain longitudinal movement of each run of the piping system. Tentative procedures and guidelines for spacing and positioning longitudinal braces on long runs are presented in Section 4.3.2.

- Select and position transverse braces to restrain excessive transverse vibration of piping system segments. Space transverse braces at intervals such that peak pipe stresses, peak brace forces, as given by generic design-aid curves, are less than allowables. Tentative procedures, generic design-aid curves, and guidelines for their usage are presented in Section 4.3.3.

4.3 Selection of Seismic Braces

This section describes tentative procedures for positioning transverse and longitudinal seismic bracing preceded by a discussion of spacing requirements for gravity-load supports and vertical seismic bracing.

4.3.1 Gravity-Load Supports and Vertical Seismic Bracing

As a matter of installation convenience, as well as economy, seismic braces are usually positioned at vertical support locations. In this manner, contractor personnel can attach braces to existing pipe clamps or trapeze beams and avoid the additional time and expense of duplicating pipe support hardware. It is prudent, therefore, for seismic brace design procedures to specify brace location and spacing in terms of multiples of vertical support spacing and location.

Allowable spans for vertical loads are governed by ASME B31.9, which specifies that:

> "Stresses in the piping due to support spacing shall not exceed the basic allowable stress S when computed on the basis of a support span twice as the actual span."

ASME B31.9 also places limits on deflection, particularly pertinent to plastic piping, as follows:

> "The allowable deflection of the pipe between supports shall not exceed the smaller of 0.2 in. or 10% of the nominal diameter D_n of the pipe, based on the weight of the empty pipe, insulation, and other dead loads."

Figures 4-1 and 4-2 are graphs of ASME B31.9 [Ref. 20] support spacing requirements for steel pipe (e.g., ASTM A53, Grade A) and for pipe made of other materials (e.g., PVC), respectively. These figures are valid provided there are no concentrated loads such as valves, between supports. An example of ASME B31.9 requirements follows: 6-inch diameter Schedule 40 steel pipe (ASTM A53, Grade A) at 300 psig, or less, is required to be supported for vertical loads at intervals not to exceed 20 feet. In contrast, 6-inch diameter Schedule 80 PVC pipe is required to be supported at intervals not to exceed 7.5 feet. In general, PVC spacing is about 1/2 to 1/3 of that required for steel.

The effect of spacing supports in accordance with ASME B31.9 is to create piping systems which are quite rigid in the vertical direction (i.e., natural frequencies greater than about 20 Hz). This degree of rigidity ensures that horizontal segments of pipe will not exceed the stress limitations of Chapter 3 for vertical seismic motion. Consequently, design for the vertical direction of earthquake motion is implicitly covered by the support spacing requirements of ASME B31.9.

While vertical supports are, in general, sufficient to restrain the pipe against purely vertical seismic vibration, they may not be entirely adequate for horizontal-load effects at points where the pipe is braced laterally. When the pipe is restrained laterally with diagonal bracing in the vertical plane, vertical uplift of the pipe and/or buckling of hanger rods can occur. In such cases, the pipe should be secured against uplift, particularly if uplift could cause the pipe to become disengaged from the vertical support and, if necessary, hanger and trapeze rods should be stiffened. The need to stiffen rods for transient dynamic load is debatable. However, most standard pipe bracing details require stiffening of rods when lateral seismic loads are large.

Examples of typical vertical supports with seismic brace assemblies are shown in Figure 4-3 for single-pipe hangers, and in Figure 4-4 for multiple-pipe trapezes. In both figures, examples are shown of transverse-only seismic bracing and multi-directional (transverse plus longitudinal) seismic bracing.

4.3.2 Longitudinal Seismic Bracing

Longitudinally, brace spacing is primarily a function of brace capacity, rather than allowable axial stress for the pipe. Some brace manufacturers (e.g., Superstrut [Ref. 22]) provide tables of longitudinal spacings which should be used to avoid brace overloading for a specific seismic load level (e.g., 0.5g). The procedures for design of longitudinal bracing, given below, will generalize this concept to be applicable for any type of hardware and seismic load level.

The intent of placing longitudinal seismic restraints on piping runs is to eliminate longitudinal displacement which would otherwise damage attached equipment or other connecting lines, which are not free to displace. Longitudinally the pipe is very stiff and bracing in the longitudinal direction will make the piping run essentially rigid. Consequently, dynamic amplification of the longitudinally-braced segments of the piping system need not be explicitly considered.

The general limitations governing spacing of longitudinally braces are summarized below:

1. limit seismically-induced axial stresses in the pipe to 0.33 S (i.e., the difference between the maximum axial stress

permitted for pressure plus seismic, 1.33, less the maximum axial stress, S, permitted by ASME B31.9 for pressure alone, and

2. limit seismic-induced force in longitudinal braces in accordance with allowable brace capacity.

The first requirement is easily met as long as the length of pipe between longitudinal supports does not become excessive. As a prudent limit on longitudinal spacing, four times the vertical hanger spacing is recommended for Category A piping when the seismic acceleration coefficient, A_V, is 0.3 or 0.4, and eight times the vertical spacing when the seismic acceleration coefficient is 0.2, or less. In general, these limitations on length of pipe between longitudinal braces ensures that axial stresses will not exceed 0.33 S, even for the most severe seismic environment.

There are some piping system geometries however, where the addition of longitudinal braces could develop high axial stress. For instance, if a line which is braced longitudinally intersects a heavier mainline which is not braced transversely, then transverse vibration of the mainline will apply axial load to the branch line. In such cases where longitudinal bracing restrains more than just the longitudinal pipe segment to which it is attached, either axial stresses must be checked (requiring analysis to determine load distribution), or braces added as necessary to carry the load. In the common case of intersecting lines, described above, potential axial overstress of the smaller diameter line may be avoided simply by adding transverse bracing to the larger diameter line at, or near, the intersection.

The second limitation on the maximum length between longitudinal supports, l_L, may be expressed by the following formula,

$$l_L \leq \frac{B_c}{F\,A_v\,w} \qquad (4\text{-}1)$$

where:

l_L = maximum length, in feet, between longitudinal supports,

B_C = allowable brace load (lbs),

F = elevation factor (i.e., 1.0 for ground elevation and 1.5 for upper-floor elevations),

A_V = seismic coefficient, as defined by NEHRP/ATC-3, and

w = effective weight per foot of pipe (and contents), including weight of supports and all equipment attached to supports (lbs/ft).

The above equation will govern the spacing of longitudinal braces for large diameter lines (e.g., 6-inch diameter) on individual hangers and virtually all systems on trapeze hangers.

The intent of longitudinal bracing is to protect other lines or equipment which would be overstressed due to potential longitudinal movement. Thus, in a piping system of mainlines, branch lines, and feed lines, smaller diameter lines need not be braced longitudinally provided the weight from these lines can be adequately carried by transverse bracing on connecting lines of equal or greater diameter and strength. Examples of typical geometries for which longitudinal bracing could be excluded are shown in Figure 4-5.

4.3.3 Transverse Bracing

As the survey of the literature found, existing procedures and guidelines for transverse bracing of systems are either too complex to be practical or are too simple to fully address all pertinent attributes (e.g., pipe strength and flexibility). Consequently, a new approach for selecting transverse bracing was developed.

The intent of placing transverse bracing restraints on piping segments is to control excessive lateral deflection and bending stress in the pipe. Even with transverse braces, piping systems can still be quite flexible laterally and experience significant dynamic response. Consequently, it is necessary to consider the seismic vibration environment (i.e., design spectrum) when selecting brace locations.

The general limitations governing spacing of braces are summarized below:

1. limit seismic-induced bending stress in Category A pipe to about 1.0 S E (for normal pressure environments), and limit seismically-induced stress in Category B piping to about 2.5 S E (for normal pressure environments), and

2. limit seismically-induced force in transverse braces in accordance with allowable brace capacity.

In contrast to longitudinal bracing, pipe stress limitations generally control transverse bracing selections, except for very large diameter pipes.

To facilitate a rapid means of determining peak bending stress response in a piping system (and thus determine brace spacing acceptability) generic design-aid curves were developed which plot peak bending stress as a function of unbraced span length. The first step in developing these curves was to idealize the piping system as a collection of pipe segments between lateral restraints. For each segment a fundamental-mode frequency was determined based on the pipe's weight, material, span length, and boundary conditions.

Plots of the fundamental-mode frequency as a function of unbraced span length, considering various boundary conditions and gaps at braces, are shown in Figure 4-6 for a six-inch diameter Schedule 40 steel pipe, and in Figure 4-7 for a six-inch diameter Schedule 80 PVC pipe. Frequencies range from about 10 Hz for the shorter spans to less than 1 Hz for the longer spans. Thus, the lateral response of a piping system could occur at a natural frequency either on the "soft-side" or on the "stiff-side" (or at the peak) of the design spectrum, depending on the spacing of transverse braces.

Using the relationship illustrated by the bold lines in Figures 4-6 and 4-7 (i.e., 0.1 inch gaps at braces and fixed-fixed boundary conditions), peak spectral accelerations were obtained from the design spectra specified in Chapter 3, and used to compute peak bending stress as a function of unbraced span length. Plots of these curves have been developed in Appendix B for various diameters of Schedule 40 steel and Schedule 80 PVC pipe. To verify the validity of this approach which bases peak response on a single mode, multi-mode dynamic analyses of a three-span model were performed (Appendix A) and compared to Appendix B results. The comparisons indicate that the simple methodology accurately predicts peak response.

Example plots of peak bending stress versus unbraced length are shown in Figure 4-8 for 2-inch and 6-inch diameter Schedule 40 steel pipe subjected to upper-floor and ground floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 7 (i.e., EPGA of 0.4g). For the six-inch diameter pipe this curve illustrates that for short span lengths (i.e., less than about 30 feet) the pipe is quite rigid and stresses are low. However, for span lengths from just over 30 feet to about 70 feet, stresses increase appreciably. In this range of brace spacings the pipe would be significantly more excited at upper-floors due to building amplification of seismic load. At brace spacing of about 70 feet, or greater, the pipe is quite flexible and stresses are controlled by the low-frequency content of the ground motion, which in this case produces peak bending stress in the pipe of about 20 ksi.

From this curve it is seen that a 6-inch diameter Category A steel pipe should not have transverse braces at spacings greater than about 30 to 35 feet to meet the 1.0 S criteria. In contrast, Category B steel pipe could space transverse braces at very long spans (i.e., greater than 70 feet) to meet the 2.5 S criterion, although the peak bending stress would be close to the limit. For either Category A or Category B pipe, attached to an upper-floor or roof, it would not be desirable to brace in the 35 to 70-foot spacing range.

The same general trend is shown in the Figures for the 2-inch diameter Schedule 40 steel pipe although the curves are shifted toward shorter span lengths due to the inherent greater flexibility per length of span in a 2-inch diameter line. For example, at a brace spacing of 40 feet, a 2 inch diameter line is on the soft side of the design spectrum peak while the 6-inch diameter pipe is on the rigid-side of the spectral peak. It is worth noting that the commonly used guidelines of SMACNA [Ref. 23] require 40 foot transverse spacing, regardless of pipe diameter.

In a manner similar to that used to develop peak bending stress, peak brace force was also calculated as a function of unbraced span length in Appendix B. As mentioned earlier, peak brace force will only be a consideration for very large diameter lines or for multiple pipes on trapezes.

4.4 Design and Construction Requirements

This section presents a collection of design and construction requirements which represent general good practice for seismic bracing of piping systems. These requirements have been extracted from a variety of documents and augmented or embellished in certain cases. A summary of the requirements is given below and the source identified (i.e., SMACNA [Ref. 23], NFPA-13 [Ref. 18], or the Tri-Services Manual [Ref. 11]). In cases where the requirement is new or has been modified the source is identified as "JBA." All of the requirements given below, are in addition to the requirements for supporting piping specified in ASME B31.9.

Flexible Couplings, Expansion Loops and Gaps

Flexible pipe couplings, expansion loops, and gaps should be provided to allow individual sections of piping to move differently with individual sections of the building or equipment. They should be provided as specified below:

1. For threaded piping the flexibility may be provided by the installation of swing joints. In welded or solder joint piping, the flexibility should be provided by expansion loops or by flexible connections. [SMACNA]

2. Flexible couplings should be provided at all locations where rigidly-restrained piping systems connect to flexible or flexibly-mounted equipment (e.g., vibration-isolated equipment). [SMACNA]

3. Flexible couplings should be provided at the top and bottom of all risers and at the ceiling of each intermediate floor in multi-story buildings for piping larger than 3-1/2 inches inside diameter. [Tri-Services and NFPA-13]

4. Flexible couplings or expansions loops should be provided to create pipe flexibility across structural separations. [SMACNA]

5. Flexible couplings should be provided at each side of concrete or masonry walls 2 to 3 feet from wall surface. [NFPA-13]

6. Sufficient clearance for anticipated differential movements should be provided by pipe sleeves (i.e., nominal sleeve diameter 3 inches greater than nominal pipe diameter) at walls or floors. [SMACNA]

Seismic Brace Location

Braces should be spaced in accordance with the procedures described in Sections 4.3.2 and 4.3.3 and located in accordance with the following requirements:

1. In general, pipe corners and turns should be restrained using seismic braces in both transverse directions located not greater than two (2) pipe diameters from the elbow or tee. [SMACNA & JBA]

2. Branch lines should not be used to brace main lines (i.e., lines of larger diameter). [SMACNA]

3. Transverse bracing for one pipe section may act as partial longitudinal bracing for the pipe section connected perpendicular to it; if the brace is located not greater than two (2) pipe diameters from the elbow or tee. [SMACNA & JBA]

4. Seismic braces should not be located in positions which pose a threat to adjacent equipment and piping systems. [JBA]

5. Adequate clearance should be provided between seismic braces and adjacent equipment or piping systems. [JBA]

6. Piping systems should not be rigidly anchored to structurally separate segments of a building. [SMACNA]

7. Pipe risers should be supported, whenever possible, at a point or points above the center of gravity of the riser. Lateral guides should be provided at the top and bottom of tall risers and at intermediate points as required to restrain horizontal seismic displacement. [SMACNA & JBA]

8. Seismic braces should not be installed on or near thermal expansion loops in a manner which would restrict thermal growth or contraction of the expansion loop. Only one longitudinal brace (e.g., at the mid-point between thermal expansion loops) should be provided on straight runs of thermal piping. [JBA]

9. Near reducer seismic transverse braces should be located on the larger-diameter pipe. [JBA]

Seismic Braces and Connections

1. The adequacy of the seismic braces should be verified by the design engineer. [JBA]

2. Set screw c-clamps without restrainer straps or other non-positive connectors should not be used to attach seismic braces or pipe supports to building members. [NFPA-13 and JBA]

3. Piping should be secured to the support, hanger or clamp, and as necessary to avoid gross uplift or relative displacement if such movement could cause the pipe to become disengaged or otherwise lose vertical support. [JBA]

4. Longitudinal bracing should not be used with pipe supports or hangers which do not hold the pipe securely in the longitudinal direction. [JBA]

Structural Support

The adequacy of the structure to carry brace loads should be verified by the design engineer. [JBA]

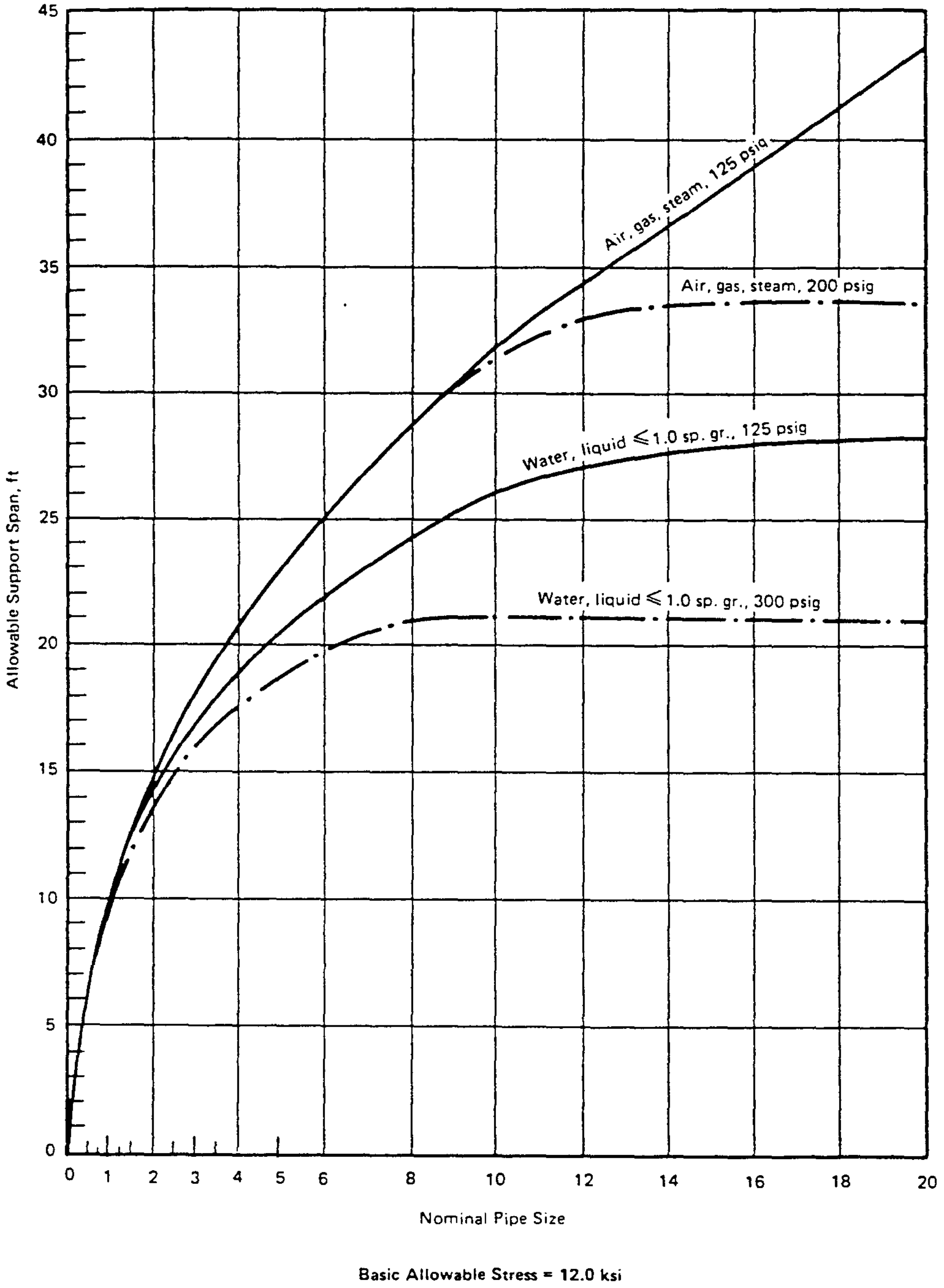
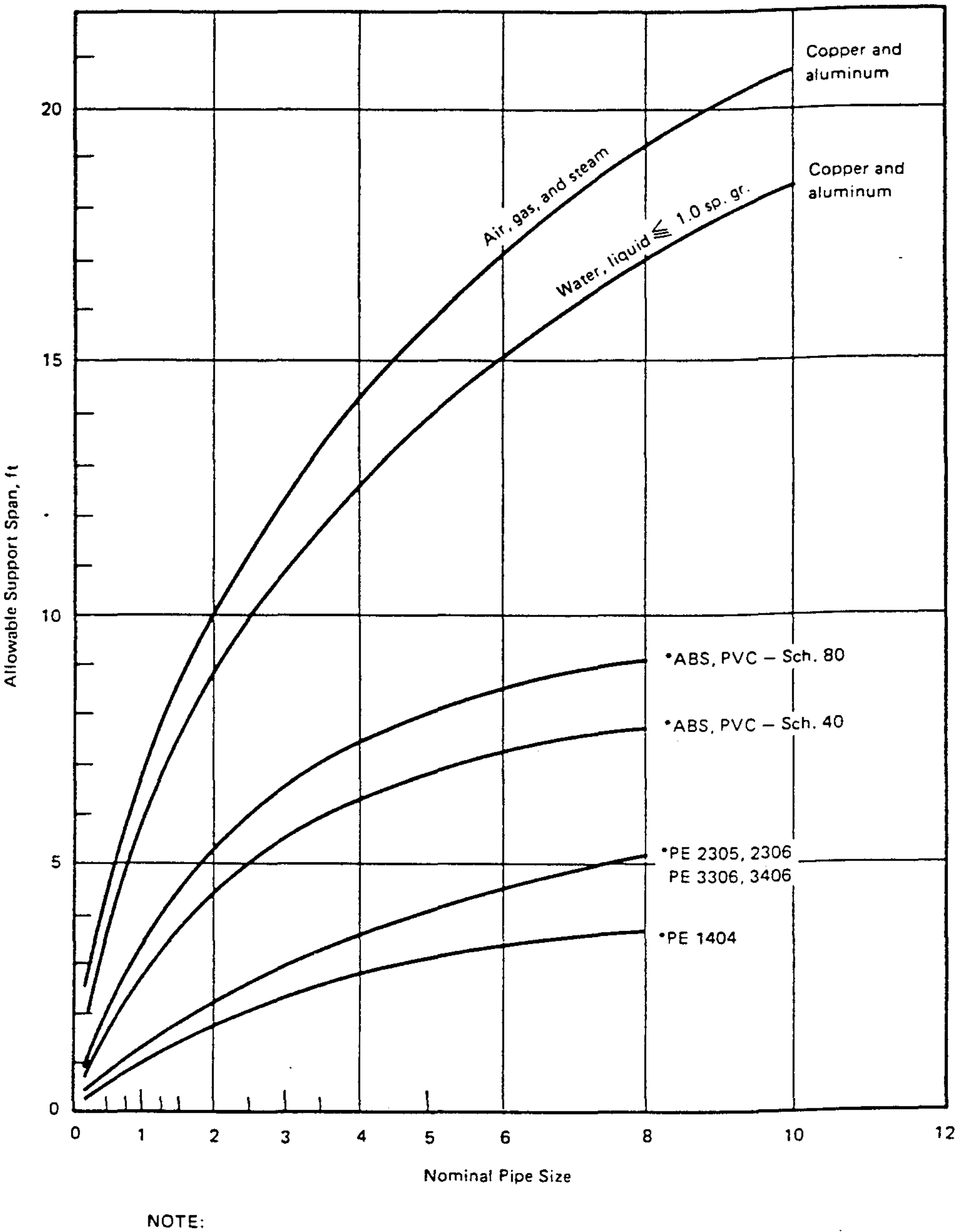


FIGURE 4-1 SUPPORT SPAN FOR STANDARD WALL STEEL PIPE (FROM ASME B31.9 [Ref. 20]).



NOTE:
•Thermoplastics data are for water at 70° F max. Closer support spacing is required at higher temperature, continuous support at 100° F and higher.

FIGURE 4-2 ALLOWABLE SPAN OF SUPPORTS FOR COPPER, ALUMINUM, AND PLASTIC PIPE (from ASME B31.9 [Ref. 20]).

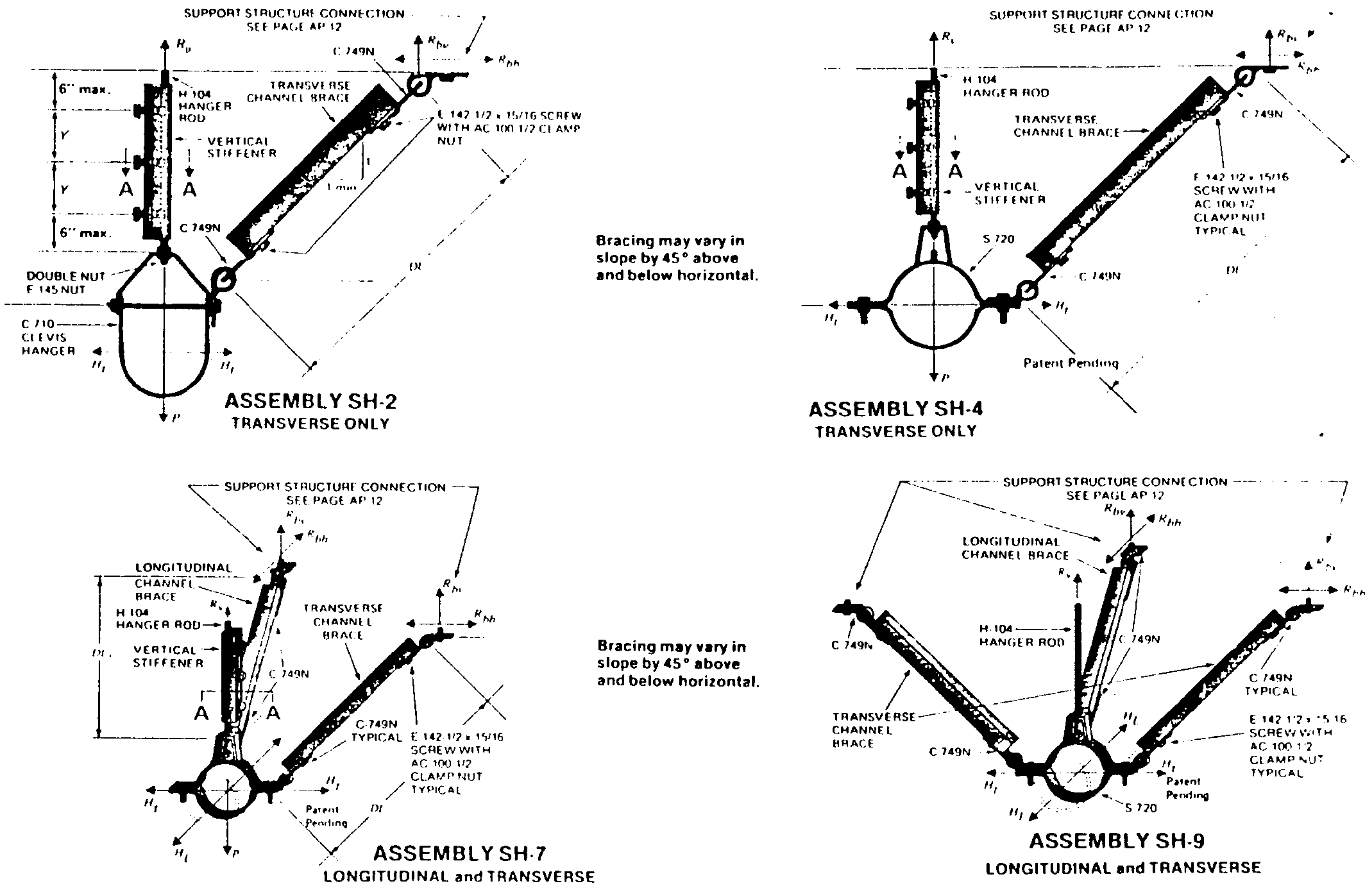
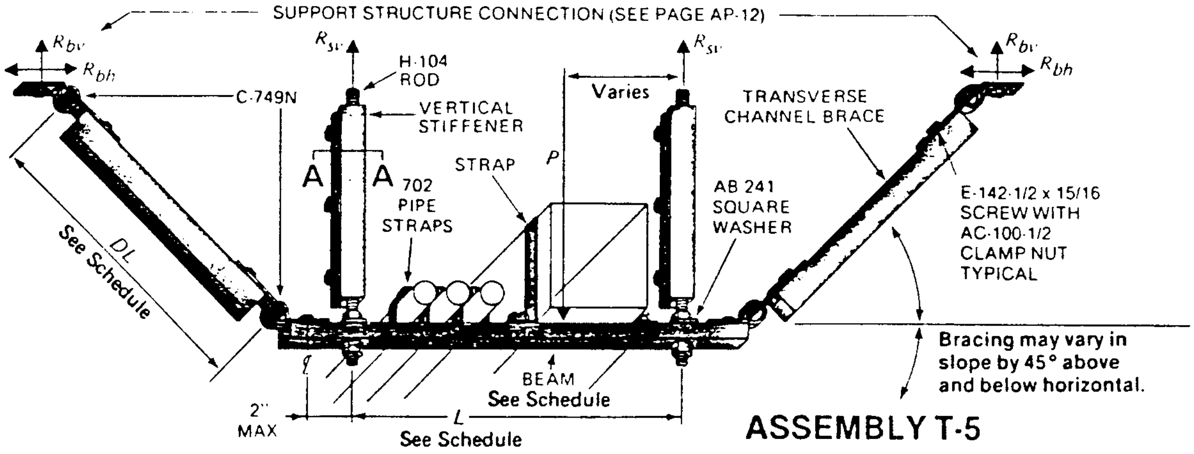
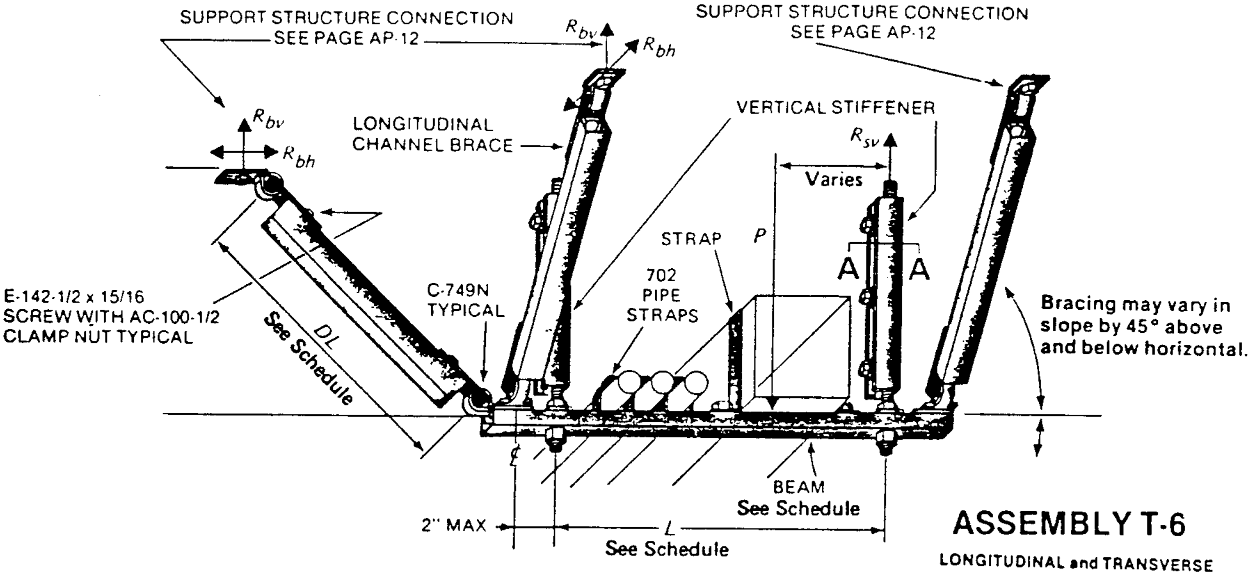


FIGURE 4-3 TYPICAL SEISMIC BRACE ASSEMBLIES FOR SINGLE-PIPE HANGERS (from Superstrut [Ref. 22]).



ASSEMBLY T-5

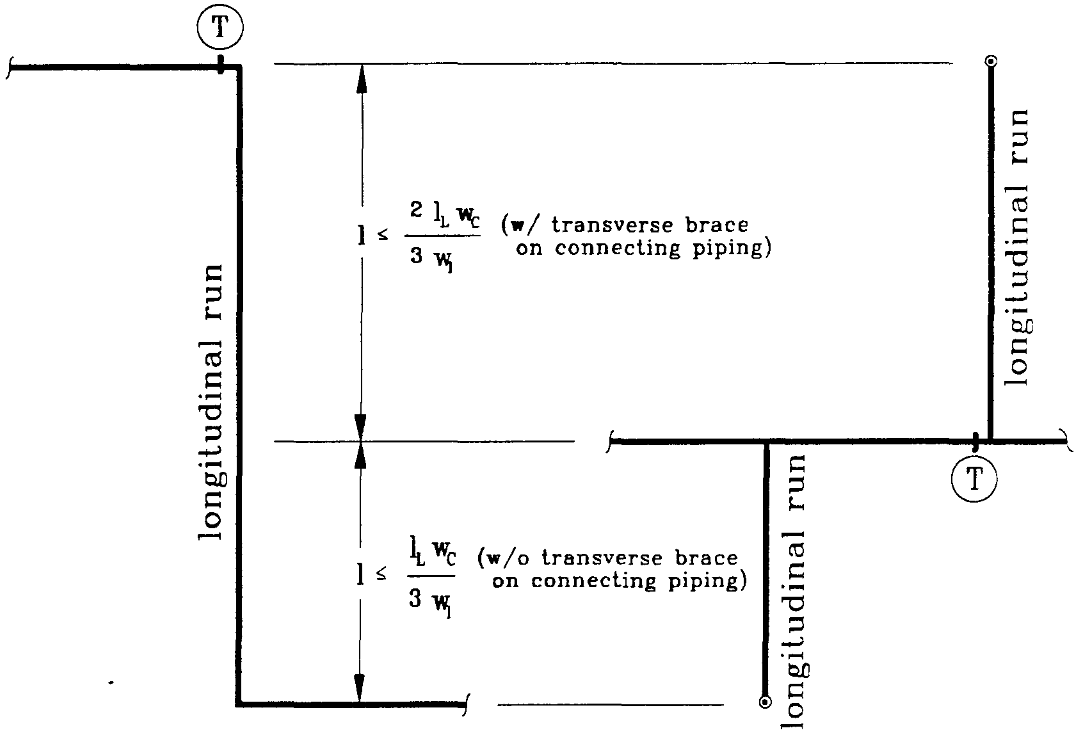
TRANSVERSE ONLY



ASSEMBLY T-6

LONGITUDINAL and TRANSVERSE

FIGURE 4-4 TYPICAL SEISMIC BRACE ASSEMBLIES FOR MULTIPLE-PIPE TRAPEZE SUPPORTS (from Superstrut [Ref. 22]).



l = length of unbraced longitudinal run tributary to connecting piping.

l_L = maximum spacing permitted between longitudinal supports, not to exceed $4\, l_v$ for Category A piping or $8\, l_v$ for Category B piping.

l_v = maximum spacing permitted between vertical (gravity) supports.

Ⓣ = transverse brace of comparable, or greater, capacity to omitted longitudinal brace, located on connecting piping within two (2) diameters of bend or tee fitting.

w_l = weight per unit length of unbraced longitudinal run ($w_l \le w_c$).

w_c = weight per unit length of connecting tee lines.

FIGURE 4-5 EXAMPLES OF PIPING RUNS FOR WHICH LONGITUDINAL BRACING MAY BE EXCLUDED.

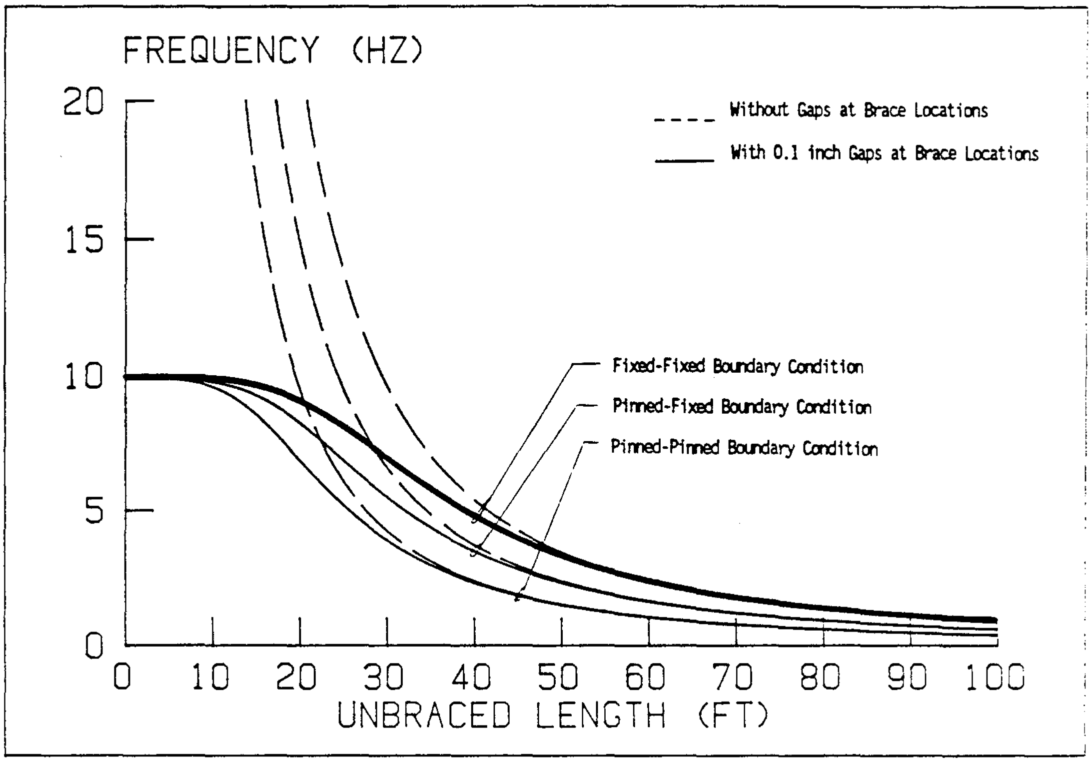


FIGURE 4-6 APPROXIMATE FUNDAMENTAL-MODE FREQUENCY OF TRANSVERSE VIBRATION OF 6"Ø SCHEDULE 40 STEEL PIPE FOR VARIOUS BOUNDARY CONDITIONS.

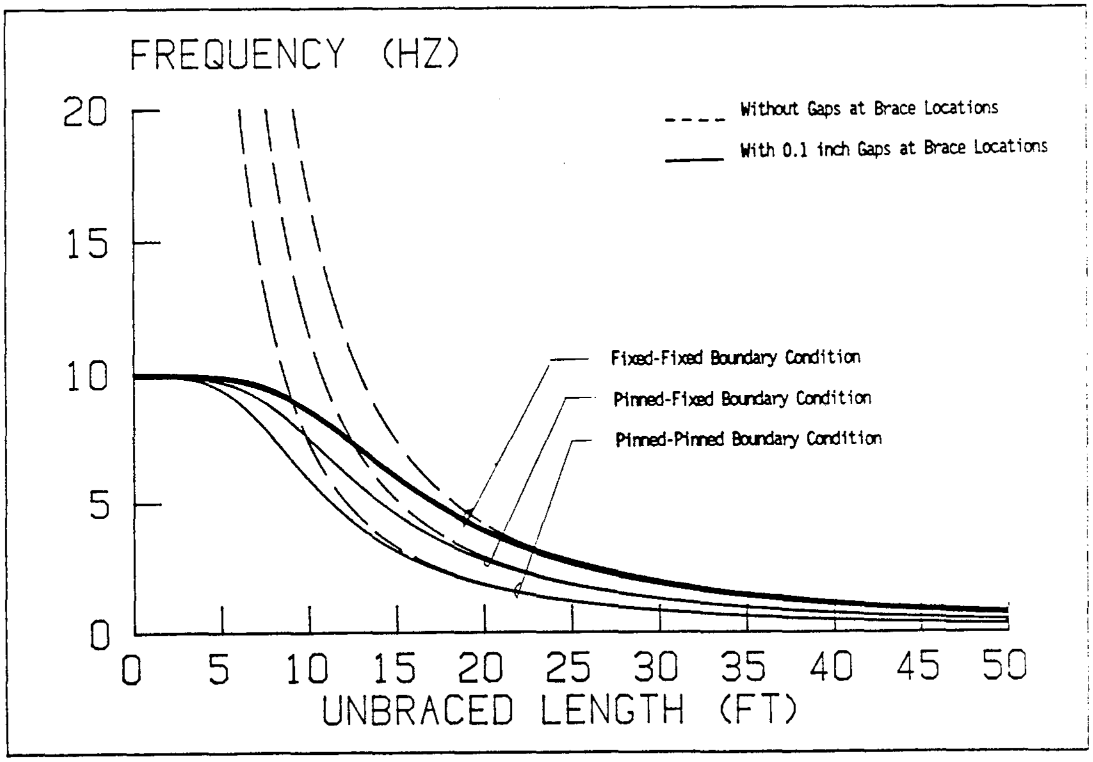


FIGURE 4-7 APPROXIMATE FUNDAMENTAL-MODE FREQUENCY OF TRANSVERSE VIBRATION OF 6"Ø SCHEDULE 80 PVC PIPE FOR VARIOUS BOUNDARY CONDITIONS.

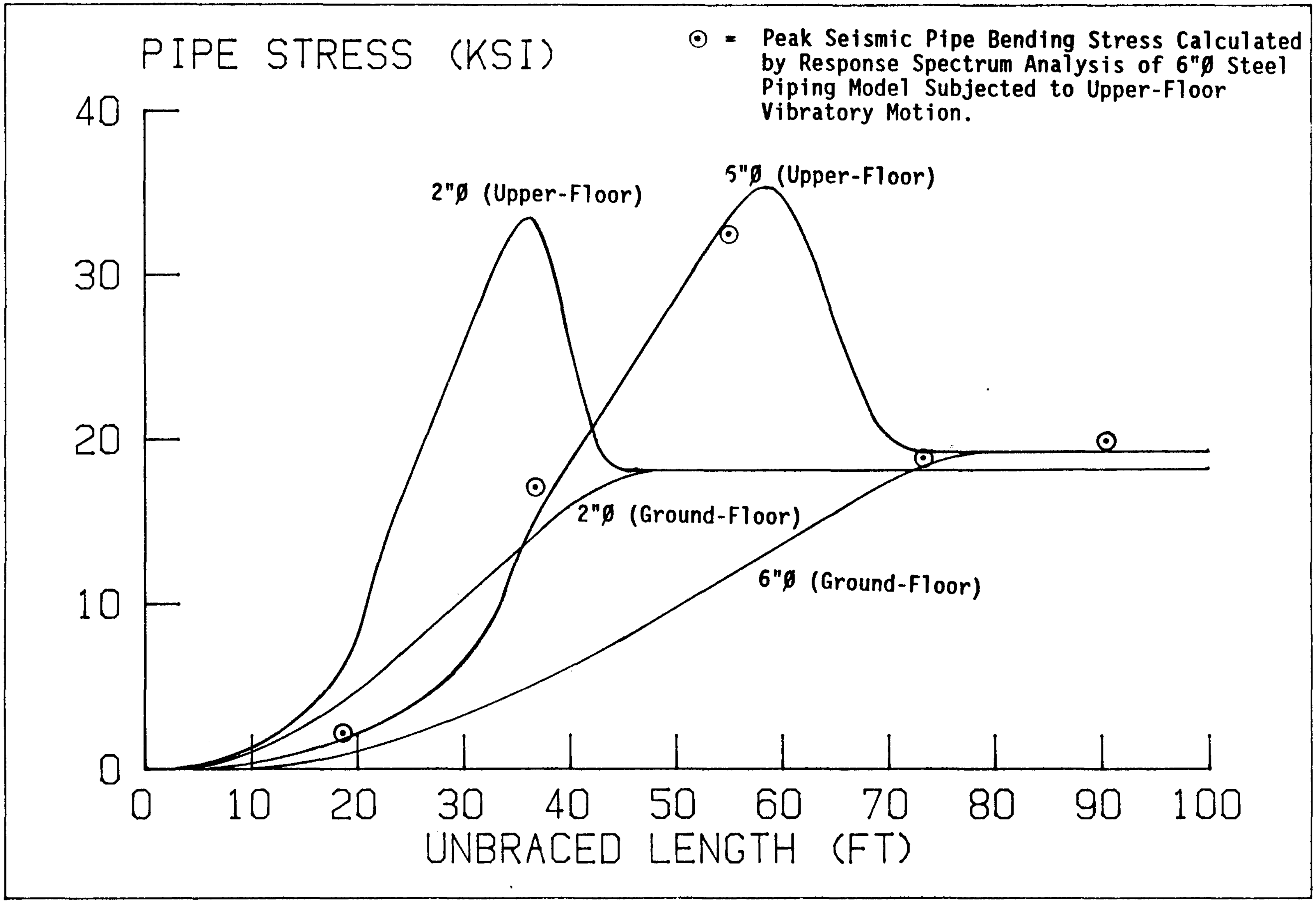


FIGURE 4-8 PEAK SEISMIC BENDING STRESS IN 2"Ø AND 6"Ø SCHEDULE 40 STEEL PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, GROUND-FLOOR AND UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

CHAPTER 5

COMPARISON OF VARIOUS SEISMIC BRACING SCHEMES

5.1 Introduction

This chapter presents the results of detailed seismic response spectrum analyses of a typical steel piping system and a typical PVC piping system. The steel and PVC piping systems were analyzed for several different vibratory environments and several different lateral-force bracing schemes to evaluate the sensitivity of piping response to earthquake level, and brace configuration and type. The purpose of this work is to qualitatively assess the merits of the tentative design procedures (i.e., Chapter 4) and to identify situations for which use of these procedures would be of greatest value. In addition, this work is also intended to assess the merits of using energy-dissipative braces (i.e., flexible, highly-damped restraints) to seismically restrain piping containing hazardous materials.

5.2 Basic Approach

A model of a typical piping system was developed for both steel and PVC pipe materials and analyzed for several different seismic bracing schemes and vibratory environments. The geometry of the piping is complex and has several different pipe diameters (i.e., diameter ranging from six inches to one inch), several different types of gravity supports (i.e., rod hangers, trapeze hangers and wall-mounted supports), and a number of interconnected runs. A complex model was used to realistically represent the type of piping configurations which are typically found at industrial facilities and which have attributes susceptible to seismically-induced damage.

The same basic configuration of piping was used for the steel and the PVC systems except that the spacing of gravity supports was halved for the PVC system in accordance with the need to support the more flexible PVC pipe at a greater number of points. Support spacing for both steel and PVC piping systems conform, approximately, with the requirements of ASME B31.9 [Ref. 20]. The details of the steel and PVC piping system configurations may be found in Appendices C and D, respectively, and Figure 5-1 shows a plan view of the Schedule 80 PVC piping system. The Schedule 40 steel system has an identical configuration, except that vertical supports are spaced twice as far apart.

Five different seismic bracing schemes were examined for restraint of the steel and PVC piping systems. The five schemes are described below:

1. Unbraced System - this scheme has only vertical supports. The unbraced scheme represents a piping system which has been installed with gravity supports only. Lack of lateral bracing would be typical of most industrial piping systems, except for fire lines or systems at facility locations considered to be earthquake prone (e.g., some California facilities).

2. Longitudinal Bracing Only - this scheme has longitudinal braces installed parallel to the pipe's axis, but does not have any transverse bracing. Figure 5-2 shows the PVC System with longitudinal bracing only.

   The longitudinal-bracing only scheme does not represent a complete method of laterally restraining a piping system. Rather, this scheme was used to evaluate the degree by which potential failures would be reduced by restraining longitudinal movement of larger pipe runs.

3. Longitudinal plus Partial Transverse Bracing - this scheme has longitudinal braces as described above, plus transverse braces at <u>every other</u> vertical support. Figure 5-3 shows the PVC

system with longitudinal and transverse bracing (at every other support).

The longitudinal plus partial transverse scheme represents a piping system with a significant amount of lateral bracing. This scheme corresponds, approximately, to the amount of bracing necessary to meet the requirements of this document for systems containing moderately hazardous materials (Category B) located in an extreme seismic environment (e.g., upper-floor response for 0.4g EPGA event). The bracing of this scheme exceeds the brace spacing requirements of both NFPA-13 [Ref. 18] and SMACNA [Ref. 23].

4. Longitudinal plus Full Transverse Bracing - this scheme has longitudinal braces, as described above, plus transverse braces at <u>every</u> vertical support. Figure 5-4 shows the PVC system with longitudinal and transverse bracing (at every support).

   The longitudinal plus full transverse bracing scheme represents a piping system with the maximum amount of lateral bracing. This scheme corresponds, approximately, to the amount of bracing necessary to meet the requirements of this document for systems containing extremely hazardous materials (Category A) located in an extreme seismic environment (e.g., upper-floor response for 0.4g EPGA event).

(5) Energy-Dissipative Bracing - this scheme has longitudinal and transverse braces spaced similar to Scheme 3, described above, but uses flexible, damped braces for controlling response of the portions of the piping system not rigidly attached to the structure. Figure 5-5 shows the PVC system with energy-dissipative bracing.

   The energy-dissipative scheme represents a new and innovative concept for restraining hung equipment which utilizes flexible, damped braces to control piping system response.

The steel and PVC piping systems braced in accordance with each of the above schemes were dynamically analyzed and peak bending stresses calculated in key elements.

The steel system with each of the four bracing schemes was analyzed for four different seismic environments (i.e., 0.4g EPGA ground shaking, 0.2g EPGA ground shaking, 0.4g EPGA upper-floor vibration and 0.2g EPGA upper-floor vibration). A more complete description of the work and the results may be found in Appendix C.

Likewise the PVC system with each of the four bracing schemes was analyzed for the same four different seismic environments, and the results are presented in Appendix D.

Additionally, both the steel and PVC piping systems, restrained using energy-dissipative braces, were analyzed for 0.4g EPGA upper-floor vibration. A description of the bracing and the results are presented in Appendix E.

The following section summarizes and compares peak bending stress results of the 0.4g EPGA analyses for each bracing scheme.

5.3 Summary of Results

Table 5-1 summarizes peak seismic bending stresses for the steel piping system and Table 5-2 summarizes peak seismic bending stresses for the PVC piping system. In both tables peak stresses are compared for the unbraced scheme, the longitudinal plus transverse bracing (at every other support) scheme, the longitudinal plus transverse bracing (at every support) scheme, and the energy-dissipative bracing scheme.

The following sections summarize results for conventional bracing schemes (i.e., unbraced, and longitudinal plus transverse bracing) and for the energy-dissipative bracing scheme, respectively.

5.3.1 Conventional Braces

The trend in the conventional bracing results is the same for both PVC and steel piping, although implications of overstress are potentially more critical for PVC piping.

If no seismic bracing is used, severe overstress of several piping elements results primarily in branch lines which attempt to restrain longitudinal movement of the heavier mainline. When longitudinal-only bracing was used, overstressing of lateral lines was eliminated, demonstrating the importance of longitudinal restraints.

If longitudinal plus transverse bracing, (at every other support) is used stresses would be reduced greatly and conform to the stress limits for Category B piping systems. For this bracing scheme peak pipe seismic bending stresses are greatly reduced from those which would occur in an unbraced system. However, the stress limits for Category A piping systems would still be exceeded in most piping elements. Thus, the longitudinal plus transverse bracing (at every other support) scheme, is adequate for most piping system's, but does not provide sufficient protection for piping systems containing extremely hazardous fluids.

If longitudinal plus transverse bracing at every support is used, peak seismic bending stresses are very small. In this case, even the stringent stress limits of Category A piping are met with margin. Thus, the longitudinal plus transverse bracing (at every support) scheme provides adequate protection for piping containing even the most hazardous fluids.

Clearly, there is a trade-off between the level of protection achieved and the expense of installing seismic bracing. In the case of piping systems containing extremely hazardous materials, transverse seismic bracing may be required at every hanger location to provide adequate protection against strong seismic vibration.

5.3.2 Energy-Dissipative Bracing

As an alternative to the conventional methods of rigidly or semi-rigidly restrained piping systems, the use of flexible, energy-dissipative braces was also examined.

If flexible, energy-dissipative braces (and some conventional braces) are positioned at locations conforming approximately to the longitudinal plus transverse bracing scheme, peak seismic bending stresses are small, generally about one-half of the level of stress permitted for Category A piping. The reason for the reduction in peak bending stress using energy-dissipative braces (below that corresponding to the same spacing of conventional braces) is two-fold. First, the response is less due to the higher effective damping of the energy-dissipative braces. Second, the use of flexible, rather than rigid restraints, effectively shifts the frequency of the dominant modes of piping vibration downward, below the peak energy region of floor response and ground vibration.

Thus the use of energy-dissipative braces (with transverse brace spacing at every other gravity support) will provide adequate protection for piping systems containing extremely hazardous fluids. The benefits of using such bracing would be realized by the savings in cost associated with installing significantly fewer braces to achieve the same level of protection.

TABLE 5-1

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		Unbraced System Stress[1]	Long. and Transverse Braced System Stress[1,2]	Long. and Transverse Braced System Stress[1,3]	Energy-Dissipative Braced System Stress[1,2]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	19.4	14.4	1.5	5.9
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	82.2	7.9	0.64	6.2
3	3" Diameter Branch Line (on Long Rod Hangers)	18.5	16.6	2.1	5.0
4	3" Diameter Riser (from 1 to 3)	18.1	18.8	3.0	5.0
5	3" Diameter Branch Line (on Short Rod Hangers)	57.0	14.4	2.0	6.7
6	3" Diameter Riser (from 1 to 5)	67.6	6.2	2.3	3.2
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	18.0	15.3	4.3	5.6
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	75.1	19.7	2.1	2.6
9	1" Diameter Feeder Line and Riser to Equipment	43.2	18.8	6.4	7.3
10	2" Diameter Branch Line (on Short Rod Hangers)	30.2	11.5	2.3	3.6

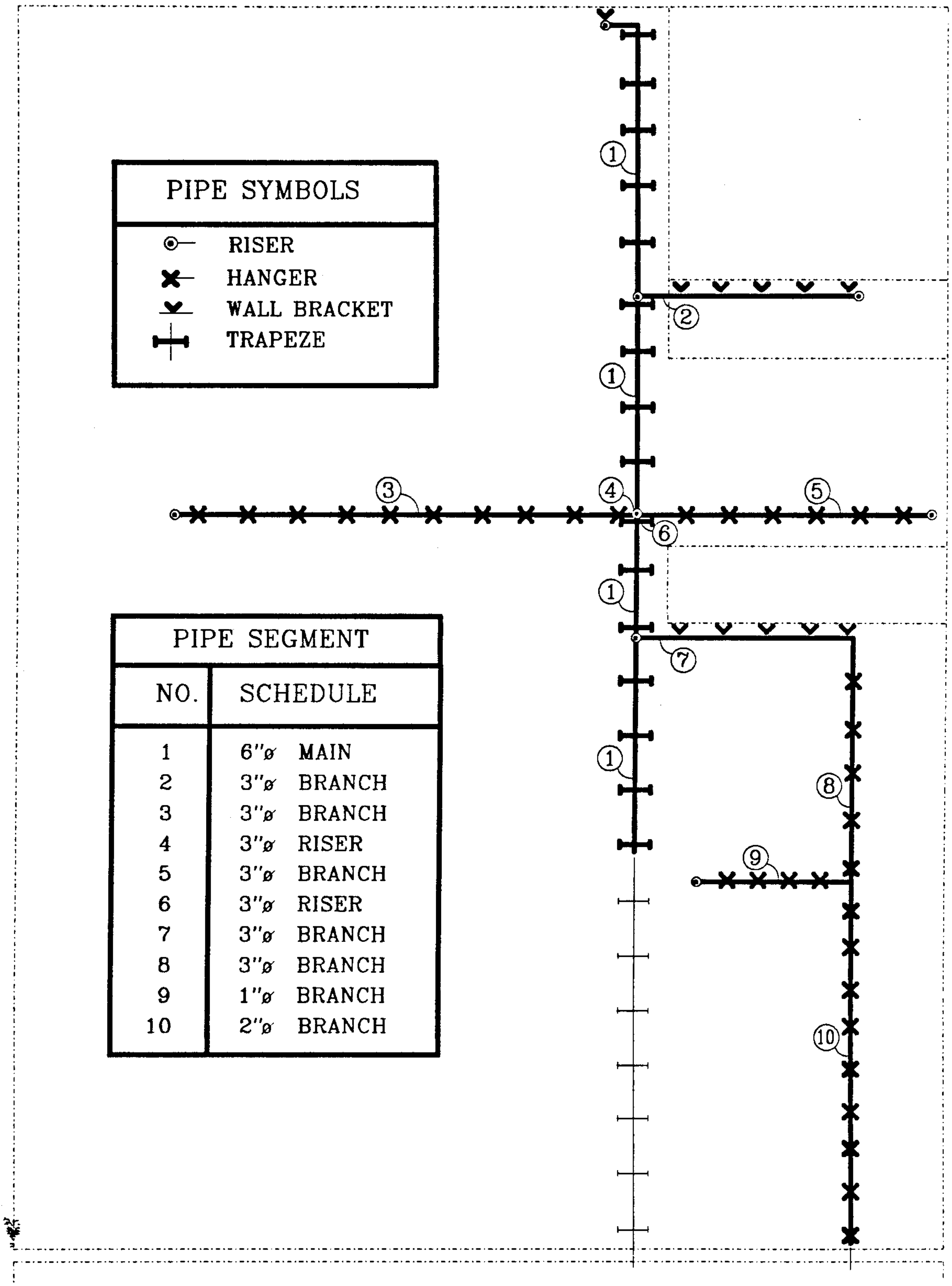
1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e. ASME B31.9, Ref. 20).
2. Transverse bracing at every other gravity support.
3. Transverse bracing at every gravity support.

TABLE 5-2

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		Unbraced System Stress[1]	Long. and Transverse Braced System Stress[1,2]	Long. and Transverse Braced System Stress[1,3]	Energy-Dissipative Braced System Stress[1,2]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	0.72	0.94	0.02	0.48
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	2.20	0.34	0.44	0.21
3	3" Diameter Branch Line (on Long Rod Hangers)	0.58	1.20	0.01	0.30
4	3" Diameter Riser (from 1 to 3)	2.80	0.80	0.16	0.85
5	3" Diameter Branch Line (on Short Rod Hangers)	0.67	1.10	0.01	0.40
6	3" Diameter Riser (from 1 to 5)	0.94	0.69	0.16	0.46
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	1.20	0.14	0.20	0.58
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	1.20	0.96	0.01	0.22
9	1" Diameter Feeder Line and Riser to Equipment	5.10	0.99	0.01	0.32
10	2" Diameter Branch Line (on Short Rod Hangers)	1.00	1.30	0.95	0.35

1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73 F is 1.0 ksi.
2. Transverse bracing at every other gravity support.
3. Transverse bracing at every gravity support.



PIPE SEGMENT	
NO.	SCHEDULE
1	6"ø MAIN
2	3"ø BRANCH
3	3"ø BRANCH
4	3"ø RISER
5	3"ø BRANCH
6	3"ø RISER
7	3"ø BRANCH
8	3"ø BRANCH
9	1"ø BRANCH
10	2"ø BRANCH

FIGURE 5-1 BASIC SCHEDULE 80 PVC PIPING SYSTEM MODEL, PLAN VIEW.

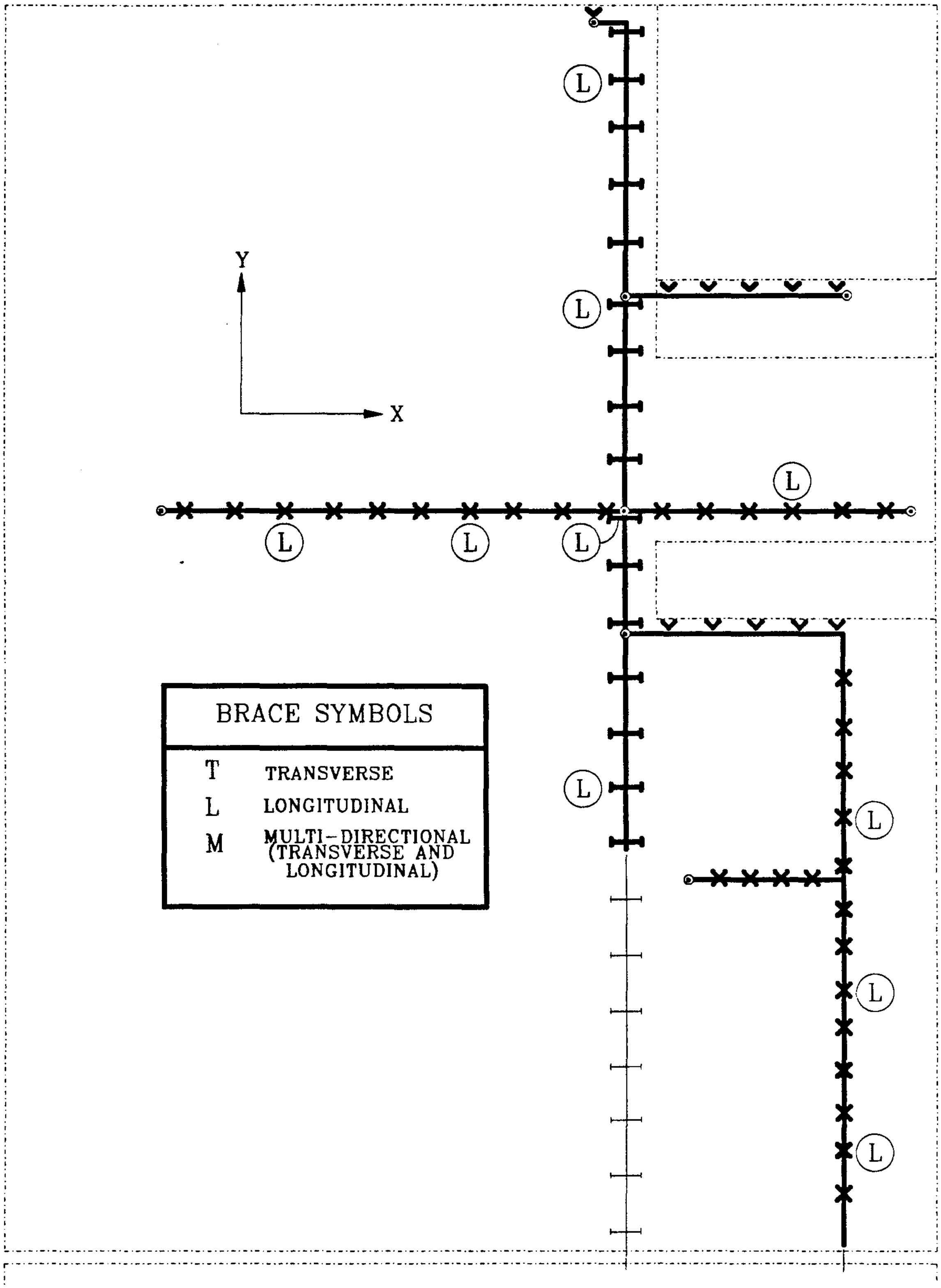


FIGURE 5-2 SCHEDULE 80 PVC PIPING SYSTEM WITH LONGITUDINAL BRACING ONLY.

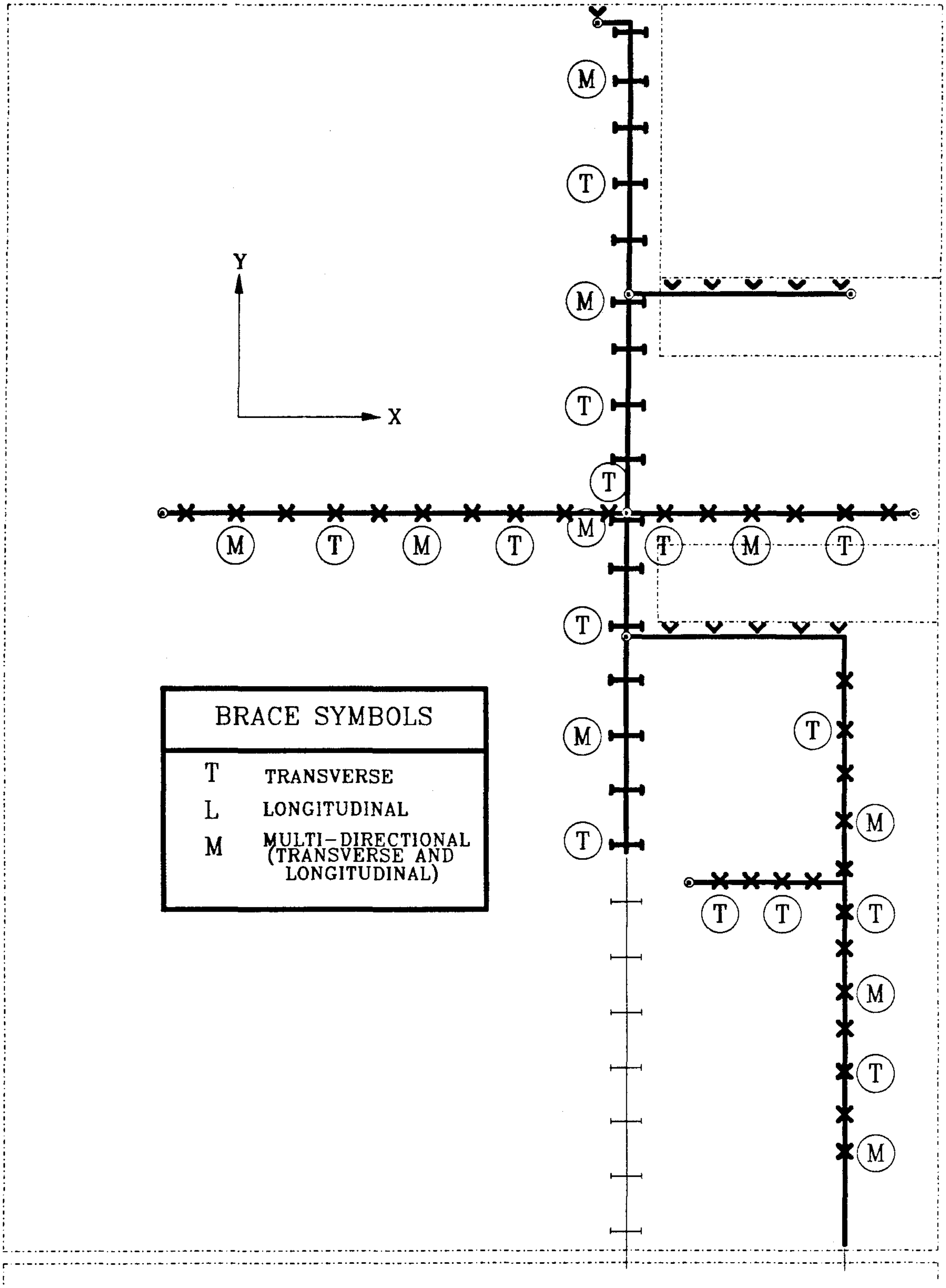


FIGURE 5-3 SCHEDULE 80 PVC PIPING SYSTEM WITH LONGITUDINAL PLUS PARTIAL TRANSVERSE BRACING.

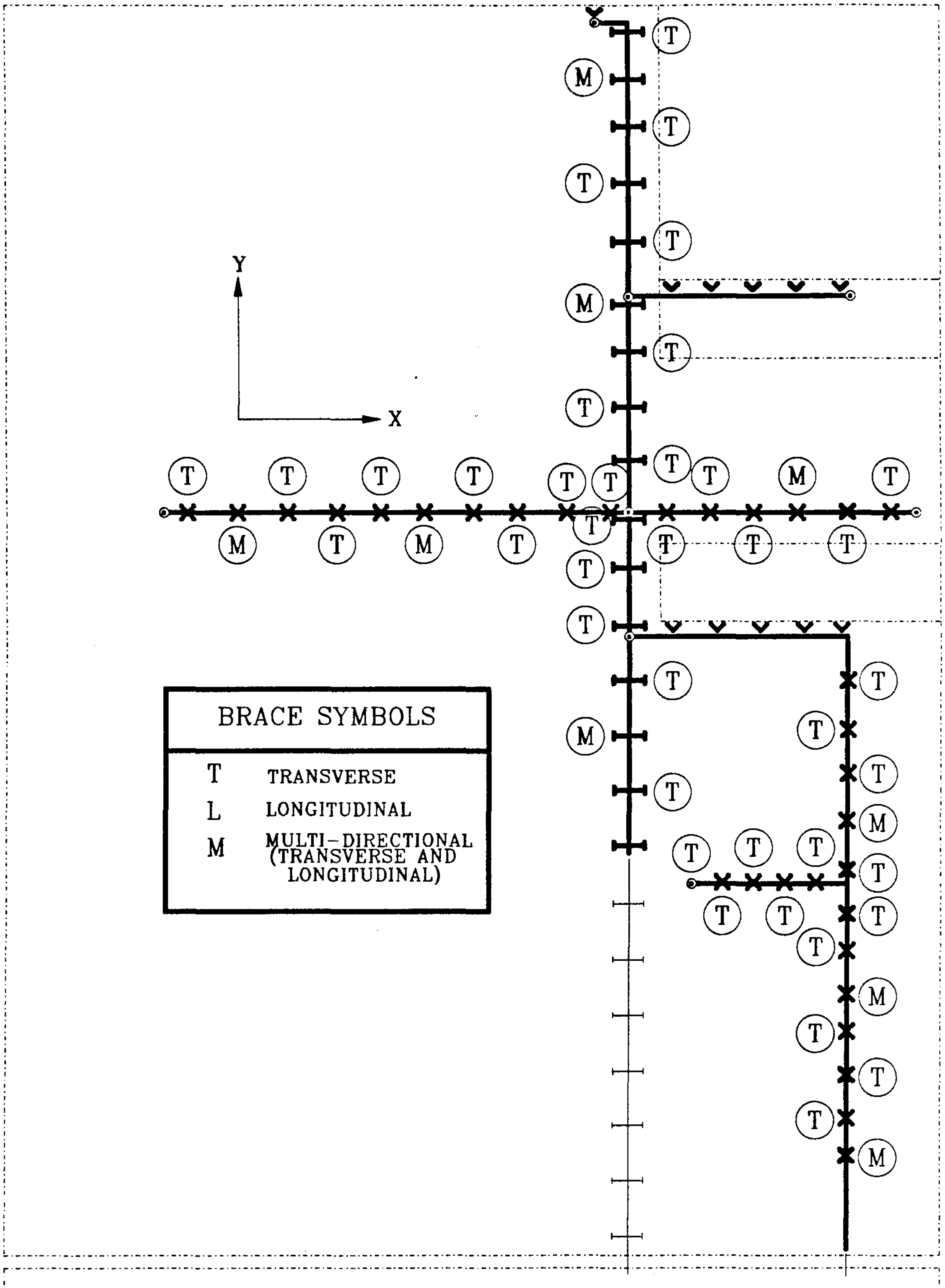


FIGURE 5-4 SCHEDULE 80 PVC PIPING SYSTEM WITH LONGITUDINAL PLUS FULL TRANSVERSE BRACING.

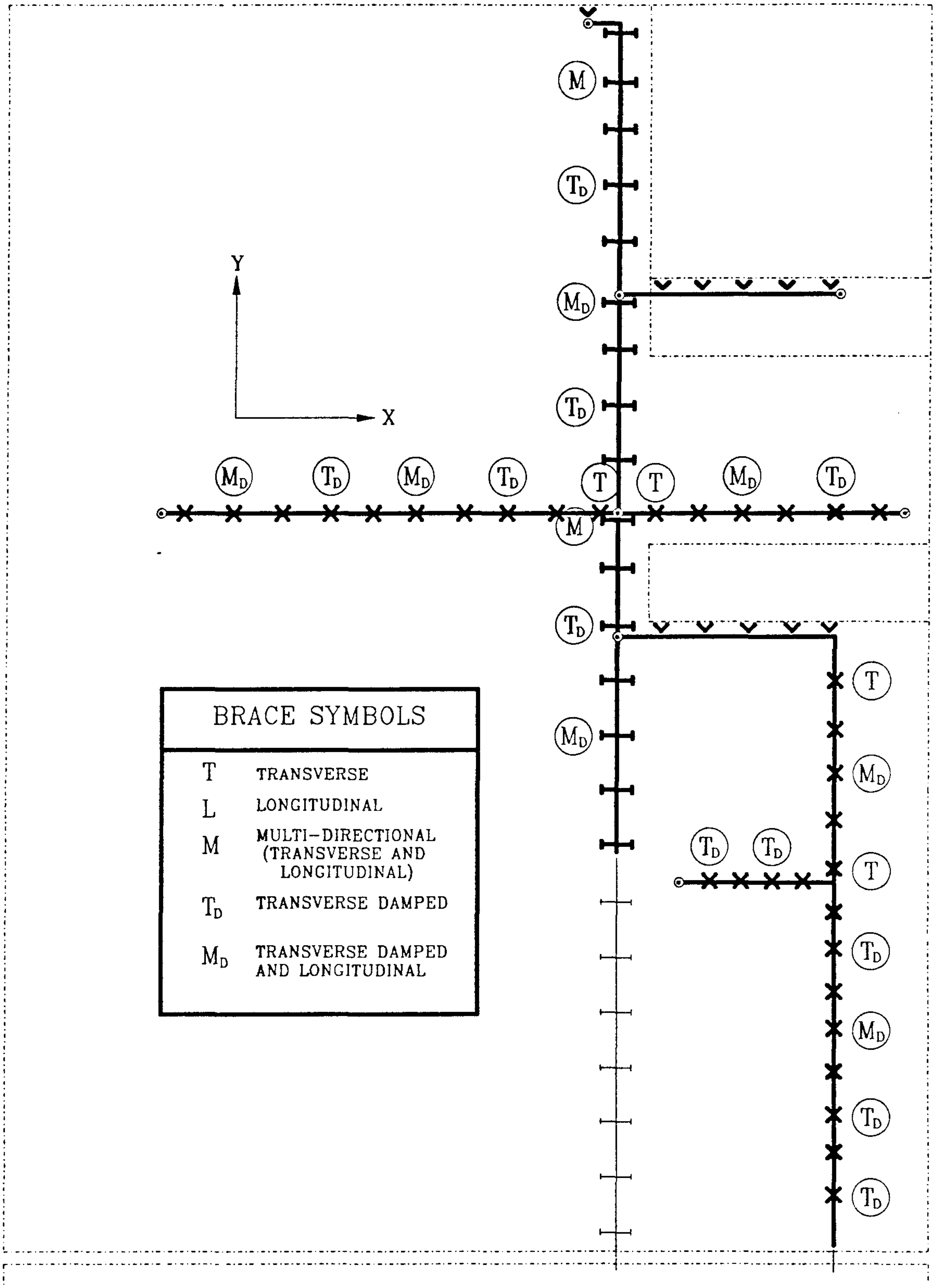


FIGURE 5-5 SCHEDULE 80 PVC PIPING SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

CHAPTER 6

CONCLUSION

6.1 Summary of Phase I Work and Results

This report documents the results of Phase I of a multi-phase project to develop design requirements and guidelines for seismic restraint of piping systems containing hazardous materials. Work performed as part of Phase I included the following:

- survey of applicable design codes and criteria documents,
- delineation of design criteria,
- development of (tentative) design procedures,
- analyses of example PVC and steel piping systems restrained by various conventional bracing schemes, and
- analyses of example PVC and steel piping systems, restrained by energy-dissipative braces.

On the basis of the requirements of the tentative design procedures and the results of analyses of example PVC and steel systems, the following findings are summarized:

- piping systems containing hazardous materials require greater seismic protection (e.g., more bracing) than systems which are not hazardous,
- piping systems exposed to higher levels of vibration (e.g., systems located in zones of high seismicity and/or attached to flexible portions of a structure) require

greater seismic protection than systems which are located in zones of low seismicity and/or attached to portions of structure which do not amplify ground vibration,

- piping systems containing hazardous materials located in zones of medium to high seismicity may not be adequately restrained by bracing installed in accordance with existing procedures and guidelines, which do not consider piping system importance,

- PVC, and other non-steel piping systems, may not be adequately restrained by bracing installed in accordance with existing procedures and guidelines, which implicitly assume the pipe to be made of steel, and

- piping systems restrained by flexible, energy-dissipative braces, may achieve the same level of seismic protection with a smaller number of braces than that required for conventional, rigid restraint of systems.

6.2 Recommendations for Phase II Study

Phase II should be undertaken to continue the development of appropriate measures for seismically protecting piping containing hazardous materials. Phase II should pursue, in parallel, two primary objectives: development of a seismic bracing guide and development of flexible, energy-dissipative braces. Specific recommendations are provided in the following sections for the two objectives.

Seismic Bracing Guide

The tentative design procedures of Phase I should be further developed as the basis to create a practical seismic bracing guide. This guide would be used by practicing engineers (and contractors) to rapidly identify the type and location of braces required for seismic restraint of hazardous piping systems. The following specific item is recommended for Phase II study:

- refine Phase I categorization of piping system importance and the associated performance requirements (i.e., allowable stresses), considering the relative risk of pipe failure and building failure. Specifically, perform seismic risk analyses of a representative industrial facility as necessary to establish the level of protection which ensures that risk due to hazardous piping system failure does not exceed other inherent risks, such as general building collapse. This work will necessarily address the categorization of piping system importance on the basis of the quantity of hazardous materials used, and the potential for exposure of building personnel and the public, should a release occur.

Flexible, Energy-Dissipative Restraints

The concept of laterally restraining piping systems with flexible, energy-dissipative restraints should be further examined. The following specific items are recommended for Phase II study:

- develop and test a prototype flexible, energy-dissipative restraint. The restraint should be capable of being easily installed as part of currently available piping/support hardware, and

- perform an economic analysis to evaluate the potential cost savings of using a fewer number of flexible, damped restraints, rather than a greater number of conventional rigid braces.

CHAPTER 7

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APPENDIX A

SEISMIC ANALYSIS OF A SIMPLE THREE-SPAN PIPING MODEL

A.1 Purpose and Objectives

The purpose of the work contained in Appendix A is to perform parametric seismic analyses of simple three-span models in order that lateral dynamic piping response may be quantified in terms of unbraced span length, type of pipe material, and the spectral content of the vibratory motion. The results of this effort will provide a basis for dynamic amplification terms used in Appendix B to develop design-aid curves which describe peak seismic pipe stress and peak seismic brace force as a function of unbraced span length.

The objectives of Appendix A are summarized below:

1. Examine peak seismic pipe bending stress and peak seismic brace force for a three-span piping system with various span lengths between lateral braces.

2. Examine peak seismic pipe bending stress and peak seismic brace force for response spectrum analysis which uses both raw (unbroadened) spectra as well as broadened spectra to account for uncertainty in building response.

A.2 Description of the Model

A simple three-span model, shown in Figure A-1, was used for each seismic analysis. The model has the following characteristics:

1. lateral braces are uniformly spaced and positioned at the ends and one-third points of the model,

2. lateral braces are modeled to have a slight degree of flexibility representing typical seismic brace stiffness,

3. piping mass is lumped at quarter points on each span (i.e., thirteen total mass points),

4. one end of the model was not restrained against rotation, and

5. the other end of the model is fully restrained against rotation.

The purpose behind the use of a model with three spans between lateral braces with the boundary conditions described above is to simulate the following diverse piping span conditions:

1. simulate a span of piping at the free end of a long run where one end of the span is discontinuous and the other end is continuous with piping of comparable stiffness,

2. simulate a span of piping in the middle of a run for which both ends of the span are continuous with piping of comparable stiffness, and

3. simulate a span of piping which is continuous at one end with piping of comparable stiffness but which, at the other end, connects to a branch line, tank, etc., of much greater stiffness.

Lateral braces are usually modeled as infinitely rigid components although this is inconsistent with the seismic brace hardware typically used in construction. To account for a small amount of flexibility inherent in typical seismic braces, springs were used at each of the brace locations. Spring stiffness was selected such, that if the pipe itself is infinitely rigid the flexibility in the supports would cause the fundamental transverse frequency of the piping to be about 10 Hz.

This corresponds approximately to 0.1 inch deflection for a 1.0g level of vibration (i.e., full weight of pipe acting laterally). The assumption of support flexibility has little or no effect on the response of flexible long-span segments, where each displacement is dominated by pipe bending, rather than support displacement. However, for stiff short-span segments, this assumption assures that spectral loads will be based on a realistic fundamental-mode frequency of the piping system.

A simple three-span model was developed for two basic types of piping: six-inch diameter Schedule 80 PVC pipe and six-inch diameter Schedule 40 steel pipe. For the PVC piping system, span lengths of 9′, 18′, 27′, 36′ and 45′ are modeled; while for the stiffer steel piping system, span lengths of 18′, 36′, 54′, 72′, and 90′ are used. These span lengths are selected to represent piping system flexibility which ranged from the stiff side of the spectrum (i.e., all piping frequencies are greater than the frequency for the peak of the spectrum) to the soft-side of the spectrum (i.e., piping system frequencies of dominant modes are less than the frequency of the peak of the spectrum). The shortest spans used (i.e., 9′ for PVC and 18′ for steel) correspond, approximately, to the spacing commonly used for vertical support of a six-inch diameter pipe.

A.3 Analysis Methods

The models described in the preceding section are dynamically analyzed using standard response spectrum methods, and modal responses are combined using the square-root-sum-of-the-squares (SRSS) method. The SRSS method, rather than more conservative methods (e.g., absolute sum method), is used to combine all modes, including closely-spaced modes, since this technique was found to estimate the peak response accurately.

The piping systems are analyzed in a single direction for transverse response (i.e., response transverse to the pipe's axis) using each one of the six 7%-damped floor response spectra shown in Figure A-2. These spectra include five "individual" spectra, each with a relatively narrow peak, and one "envelope" spectrum with a broadened peak which bounds all five individual spectra. The five individual spectra represent the peak response of a system in five different buildings each with a slightly different fundamental-mode frequency. The envelope spectrum represents peak response which could occur in any one of the five buildings. Thus, analyses using individual spectra determine peak response when the buildings's dynamic characteristics are well known, and the analyses using the envelope spectra determine an upper-bound estimate which could occur, for a system in a building whose dynamic characteristics are not well known. Since arbitrary broadening of spectra can over-estimate floor (roof) vibration, broadened spectra have the potential to overpredict piping response, particularly for multi-degree-of-freedom systems which have several modes with frequencies coincident with the broadened peak.

Each of the six spectra described above are developed from the JBA program "FLRSPEC" [Ref. 79]. This program automatically generates floor (roof) spectra given a ground (site) response spectrum and the dynamic properties of the building or buildings considered. For this work a ground response spectrum was used which corresponds to that recommended by NEHRP/ATC-3 for the design of buildings located on medium-stiff soil in Map Area No. 7. Consequently, the spectrum values calculated correspond to the peak response of piping systems located in a flexible building during a major earthquake.

A.4 Summary of Results

Summaries of peak seismic stresses are given in Tables A-1 and A-2 for Schedule 40 steel piping system analyses, and Tables A-3 and A-4 for PVC piping system analyses. Two tables of stresses are given for steel and for PVC to identify and distinguish between peak stress occurring at the restrained end of the model, and from the largest peak stress occurring anywhere along the pipe. Summaries of peak seismic brace forces are given in Table A-5 for steel, and in Table A-6 for PVC.

The values given in the tables indicate that for either very soft (long-span) systems or for very stiff (short-span) systems the peak response results of each individual spectrum analyses are quite similar. In contrast, systems with seismic-brace spans between these extremes tend to have peak responses which often vary greatly from one individual spectrum analysis to another. Clearly, the peak response of a piping system is very sensitive to the seismic input when dominant piping modes have the same frequency as building modes (i.e., the amplified portion of the spectra), and can be overpredicted by as much as, or more than a factor of 2 using envelope spectra. However, some individual spectrum analyses produced peak response values almost as great as the envelope spectrum.

For very soft systems, peak seismic stress in the pipe based on the broadened envelope spectrum appears to be approximately equal to the peak response based on any one individual spectrum. For very stiff systems, peak seismic stress based on the broadened envelope spectrum is consistently 20% to 50% higher than any one individual spectrum analysis.

A.5 <u>Conclusions</u>

The following summarizes the conclusions of the seismic analyses of simple three-span models:

1. In general, seismic stresses due to lateral response of the piping system should be calculated using broadened (envelope) spectra, without reduction, to conservatively bound peak response.

2. Seismic force in lateral braces which are inherently ductile may be appropriately calculated using broadened envelope spectra, slightly reduced (e.g., by 67%), to estimate peak response.

TABLE A-1

SUMMARY OF THE PEAK SEISMIC STRESS WHICH OCCURS AT THE FIXED-END OF EACH THREE-SPAN, SIX-INCH DIAMETER, SCHEDULE 40 STEEL PIPING MODELS

Unbraced Span Length L_p (Feet)	Peak Bending Stress[1] (ksi)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
18	1.25	1.34	1.48	1.30	1.40	1.89
36	6.63	8.60	15.51	7.33	11.14	17.34
54	26.51	13.25	12.27	27.64	12.55	33.70
72	19.04	18.61	18.54	18.71	18.71	19.70
90	19.22	19.32	20.28	19.23	19.57	20.50

1. Basic allowable (tensile) stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e., ASME B31.9, Ref. 20).

TABLE A-2

SUMMARY OF THE LARGEST PEAK SEISMIC STRESS WHICH OCCURS ANYWHERE AWAY FROM THE FIXED-END OF EACH THREE-SPAN, SIX-INCH DIAMETER, STEEL PIPING MODEL

Unbraced Span Length L_p (Feet)	Peak Bending Stress[1] (ksi)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
18	1.38	1.49	1.72	1.44	1.58	2.14
36	5.36	6.49	12.97	5.78	8.32	13.96
54	22.14	10.86	9.87	23.55	10.29	28.48
72	15.83	15.41	15.37	15.52	15.51	16.38
90	16.05	16.14	16.93	16.07	16.33	17.10

1. Basic allowable (tensile) stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e., ASME B31.9, Ref. 20).

TABLE A-3

SUMMARY OF PEAK SEISMIC STRESS WHICH OCCURS AT THE FIXED-END OF EACH THREE-SPAN, SIX-INCH DIAMETER, SCHEDULE 80 PVC PIPING MODEL

Unbraced Span Length L_p (Feet)	Peak Bending Stress[1] (ksi)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
9	0.11	0.11	0.13	0.11	0.12	0.16
18	0.59	0.94	0.97	0.67	1.24	1.46
27	1.85	0.99	0.99	1.05	1.00	1.90
36	1.24	1.26	1.25	1.26	1.26	1.29
45	1.21	1.27	1.24	1.22	1.30	1.35

1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73°F is 1.0 ksi (i.e., ASME B31.9, Ref. 20).

TABLE A-4

SUMMARY OF THE LARGEST PEAK SEISMIC STRESS WHICH OCCURS ANYWHERE AWAY FROM THE FIXED-END OF EACH THREE SPAN, SIX-INCH DIAMETER, SCHEDULE 80 PVC PIPING MODEL

Unbraced Span Length L_p (Feet)	Peak Bending Stress[1] (ksi)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
9	0.10	0.11	0.13	0.10	0.12	0.16
18	0.47	0.72	0.83	0.50	1.06	1.19
27	1.58	0.81	0.81	0.86	0.82	1.62
36	1.03	1.05	1.05	1.05	1.06	1.08
45	1.02	1.07	1.05	1.03	1.10	1.14

[1] Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73°F is 1.0 ksi (i.e., ASME B31.9, Ref. 20).

TABLE A-5

SUMMARY OF LARGEST PEAK SEISMIC BRACE FORCE FOR EACH THREE-SPAN, SIX-INCH DIAMETER, SCHEDULE 40 STEEL PIPING MODEL

Unbraced Span Length L_p (Feet)	Peak Brace Force[1] (kips)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
18	0.48	0.51	0.57	0.49	0.53	0.72
36	1.02	1.25	2.51	1.11	1.61	2.68
54	2.70	1.35	1.23	2.86	1.27	3.46
72	1.46	1.43	1.45	1.44	1.45	1.57
90	1.23	1.27	1.57	1.24	1.34	1.63

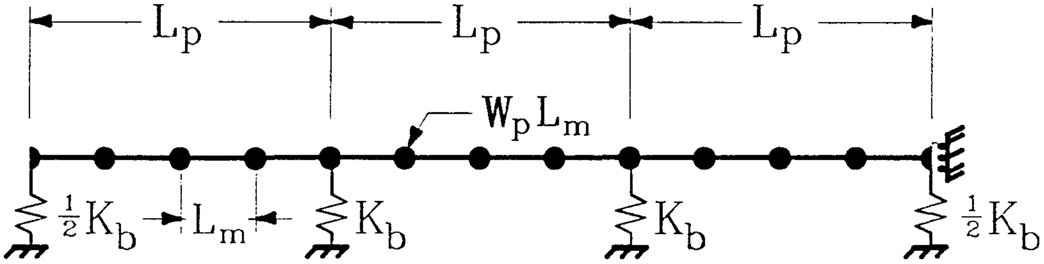
[1] Standard sway bracing capacity is about 1-2 kips (i.e., SUPERSTRUT, Ref. 22).

TABLE A-6

SUMMARY OF LARGEST PEAK SEISMIC BRACE FORCE FOR EACH THREE-SPAN, SIX-INCH DIAMETER, SCHEDULE 80 PVC PIPING MODEL

Unbraced Span Length L_p (Feet)	Peak Brace Force[1] (kips)					
	Individual Spectrum 1 Analysis	Individual Spectrum 2 Analysis	Individual Spectrum 3 Analysis	Individual Spectrum 4 Analysis	Individual Spectrum 5 Analysis	Envelop Spectrum Analysis
9	0.13	0.14	0.16	0.14	0.15	0.21
18	0.25	0.39	0.45	0.27	0.57	0.64
27	0.55	0.29	0.29	0.31	0.29	0.57
36	0.28	0.29	0.30	0.28	0.29	0.32
45	0.23	0.29	0.27	0.24	0.32	0.35

1. Standard sway bracing capacity is about 1-2 kips (i.e., SUPERSTRUT, Ref. 22).



L_p = Length of Pipe Between Braces (i.e., 9′,18′,27′,36′ or 45′ for PVC and 18′,36′,54′,72′ or 90′ for Steel)

L_m = Length of Pipe Between Discrete Mass Points (i.e., 2.25′ for PVC and 4.5′ for Steel)

K_b = Stiffness of Semi-flexible Brace, Estimated as:

$$[(2\pi)^2(10\text{Hz})^2/(32.2\ \text{ft/sec}^3)]\ L_pW_p$$

W_p = Weight Per Unit Length of Pipe (lb/ft)

FIGURE A-1 SCHEMATIC ILLUSTRATION OF SIMPLE THREE-SPAN MODEL USED TO ANALYZE PEAK RESPONSE OF LATERALLY-BRACED PIPING SYSTEM

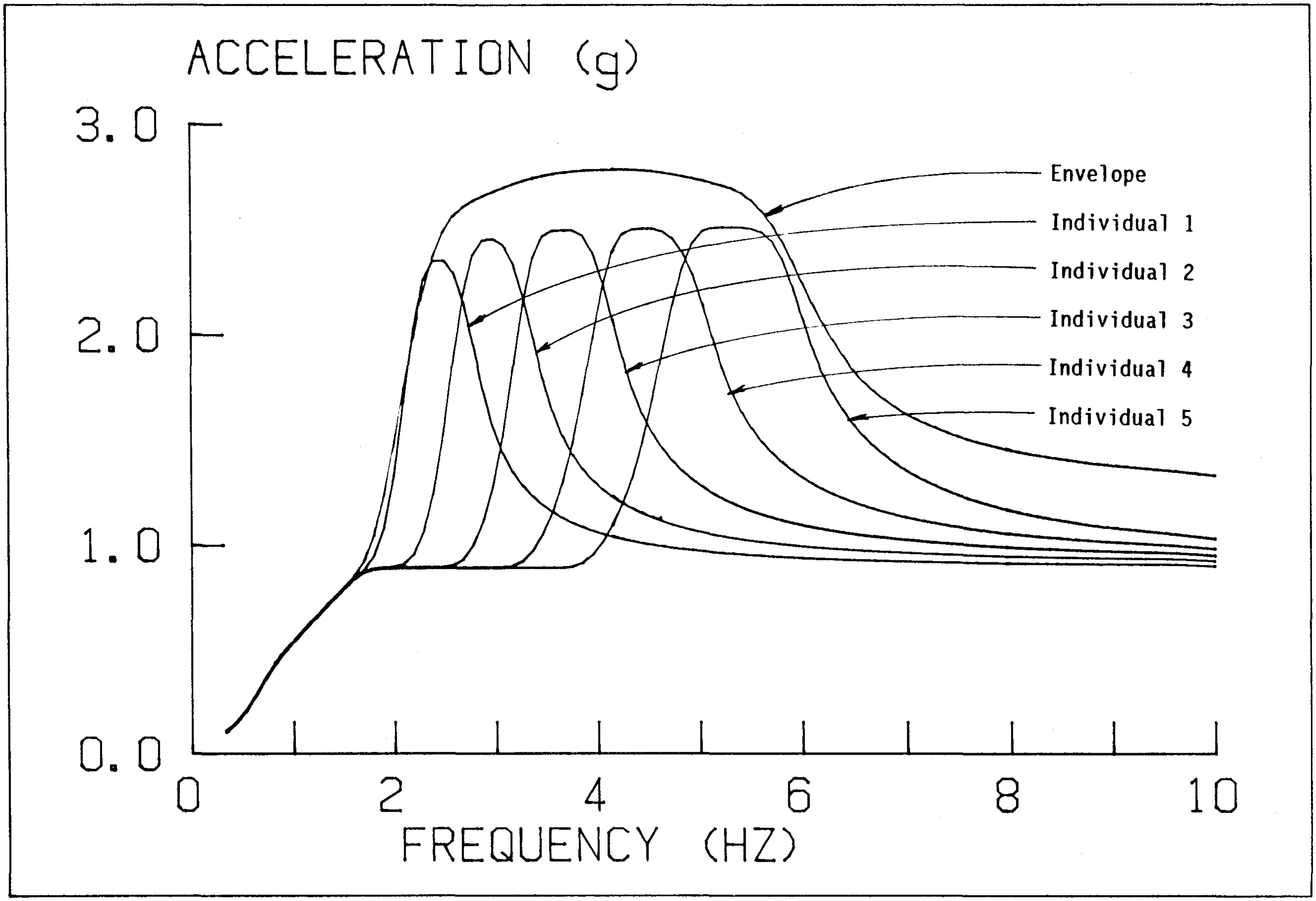


FIGURE A-2 FIVE INDIVIDUAL AND ENVELOPE SPECTRA USED IN THE ANALYSIS OF SIMPLE, THREE-SPAN MODEL.

APPENDIX B

GENERIC REPRESENTATION OF PEAK SEISMIC PIPE STRESS AND BRACE FORCE AS A FUNCTION OF UNBRACED SPAN LENGTH

B.1 Purpose and Objectives

The purpose of the work contained in Appendix B is to develop generic representations of the peak seismic pipe bending stress and brace force as a function of unbraced span length. The results of this effort will be design-aid plots which enable the engineer to rapidly select appropriate locations and spacing of transverse seismic braces on a piping system. Additionally, these plots will provide insight into the spacing of lateral braces required to make a piping system either essentially rigid or, conversely, to isolate the piping system from building vibration.

The objectives of Appendix B are summarized below:

1. Develop plots of peak seismic pipe bending stress and peak seismic brace force as a function of unbraced span length for 1"Ø, 2"Ø, 3"Ø, and 6"Ø steel, and 1"Ø, 2"Ø, 3"Ø, and 6"Ø PVC pipe (i.e., pipe diameters and materials of components used in complex piping system examples of Appendices C, D, and E).
2. Develop plots of the above for vibratory motion corresponding to both upper-floor and ground floor motion, NEHRP/ATC-3 Map Area No. 7 (i.e., EPGA of 0.4g).

B.2 Description of Methodology

The response curves, described above, were developed on the basis of factored fundamental-mode frequency response, where the fundamental-mode frequency, f_1, is defined by the following formula,

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{g}{\frac{L_p^4 w_p}{X^2\ EI} + D_b}} \qquad \text{(B-1)}$$

where:

L_p = length of unsupported segment of the distributed system (inches),

w_p = weight per unit length of the segment of the distributed system (lbs/in),

X = boundary condition factor,

E = material modulus of elasticity (lbs/in.^{2}),

I = moment of inertia (in^4), and

D_b = average displacement of braces at each end of segment, in inches, due to a force equal to the segment's weight, w_pL_p, applied in the direction under consideration.

In the above formula a valve of 0.1 inches was used for D_b to account for gaps and flexibility commonly found in seismic braces. This value effectively limited the fundamental-mode frequency to 10 Hz, or less, even for very stiff pipe spans. For the boundary condition factor X, values of 9.87 (for pinned-pinned end conditions), 15.42 (for pinned-fixed end conditions), and 22.37 (for fixed-fixed end conditions) were used and the resulting responses enveloped.

On the basis of the fundamental-mode frequency, the peak seismic bending stress in the pipe, S_{max}, and the peak seismic brace force F_{max} were approximated by the following simple-span formulas,

$$S_{max} = A\ SA_1\ L_p^2\ w_p/12\ S \tag{B-2}$$

$$F_{max} = B\ SA_1\ L_p\ w_p \tag{B-3}$$

where:

A = effective multi-mode response participation factor for bending stress,

B = effective multi-mode response participation factor for brace force,

SA_1 = spectral acceleration at fundamental-mode frequency, f_1,

L_p = unbraced span length (inches),

w_p = weight per unit length of pipe (kips/in), and

S = section modulus of pipe (in^3).

In the above formulas, the effective multi-mode response participation factor for bending stress A, was taken as 1.0 and the effective multi-mode response participation factor for brace force B, was taken as 0.67. These factors account for the effective participation of all dominant modes in lateral vibration of the piping system. The brace force factor B, was selected to be less than the bending stress factor A, based on Appendix A conclusions.

A computer program was written to develop plots representing generic peak seismic pipe bending stress and brace force curves using the above formulas.

B.3 Summary of Results

Plots of peak seismic bending stress as a function of unbraced span length in 1"Ø, 2"Ø, 3"Ø, and 6"Ø Schedule 40 steel pipe are shown in Figures B-1 and B-2, for seismic vibration corresponding to upper-floor response and ground motion of NEHRP/ATC-3 Map Area No. 7, respectively. Figures B-3 and B-4 show similar pipe stress curves for Schedule 80 PVC pipe. Likewise, plots of peak seismic brace force as a function of unbraced span length for 1"Ø, 2"Ø, 3"Ø, and 6"Ø Schedule 40 steel pipe are shown in Figures B-5 and B-6, for upper-floor and ground floor seismic motion respectively, and Figures B-7 and B-8 show similar brace force curves for Schedule 80 PVC pipe.

For figures corresponding to upper-floor vibratory motion (i.e., (Figures B-1, B-3, B-5, and B-7), Appendix A results of the simple three-span model analyses for six-inch diameter pipe are superimposed on the plots. As confirmed by comparisons with Appendix A results, the generic design curves of bending stress and brace force (based on fundamental-mode response) reliably predict peak response of all piping system modes.

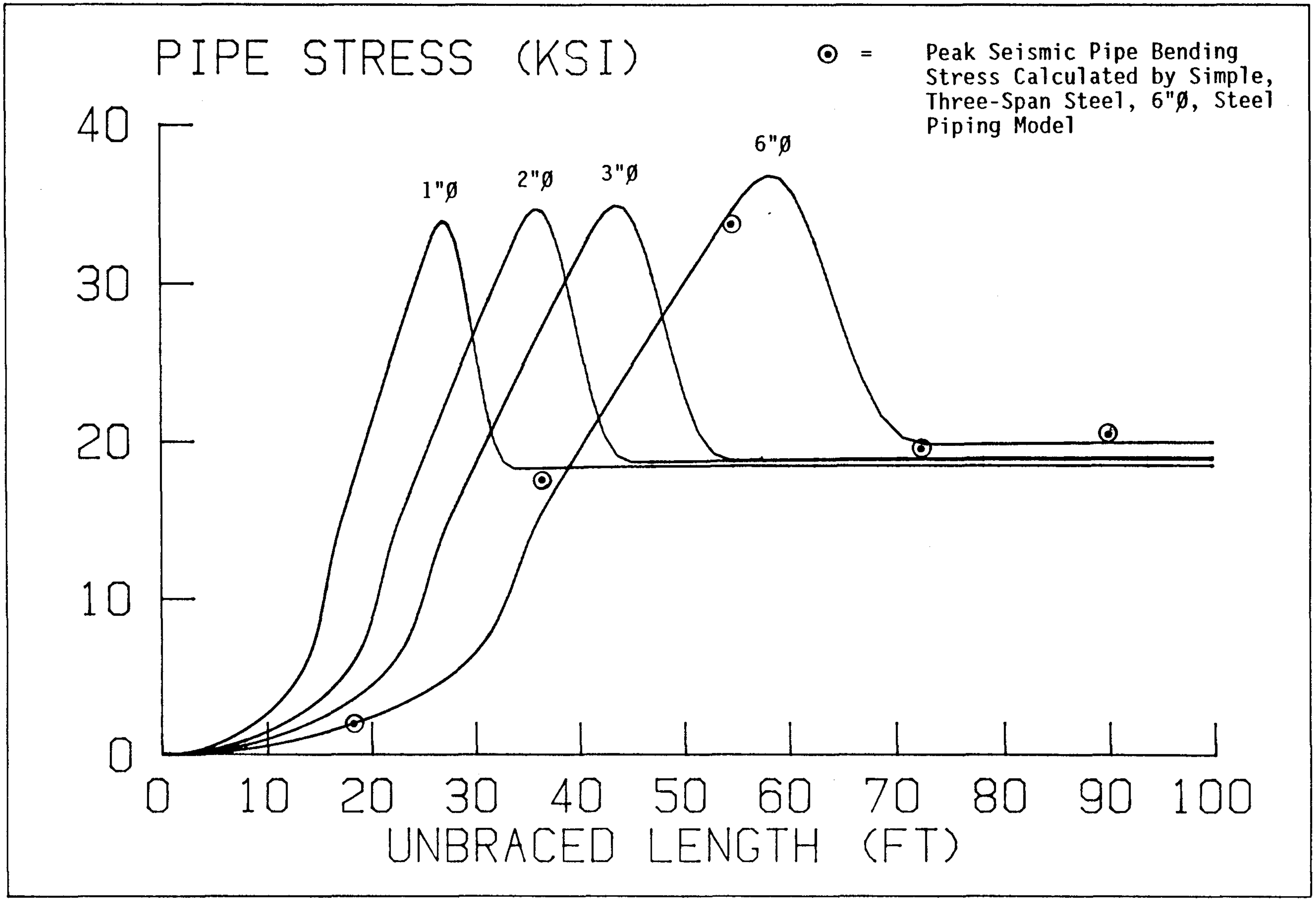


FIGURE B-1 PEAK SEISMIC BENDING STRESS IN 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 40 STEEL PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

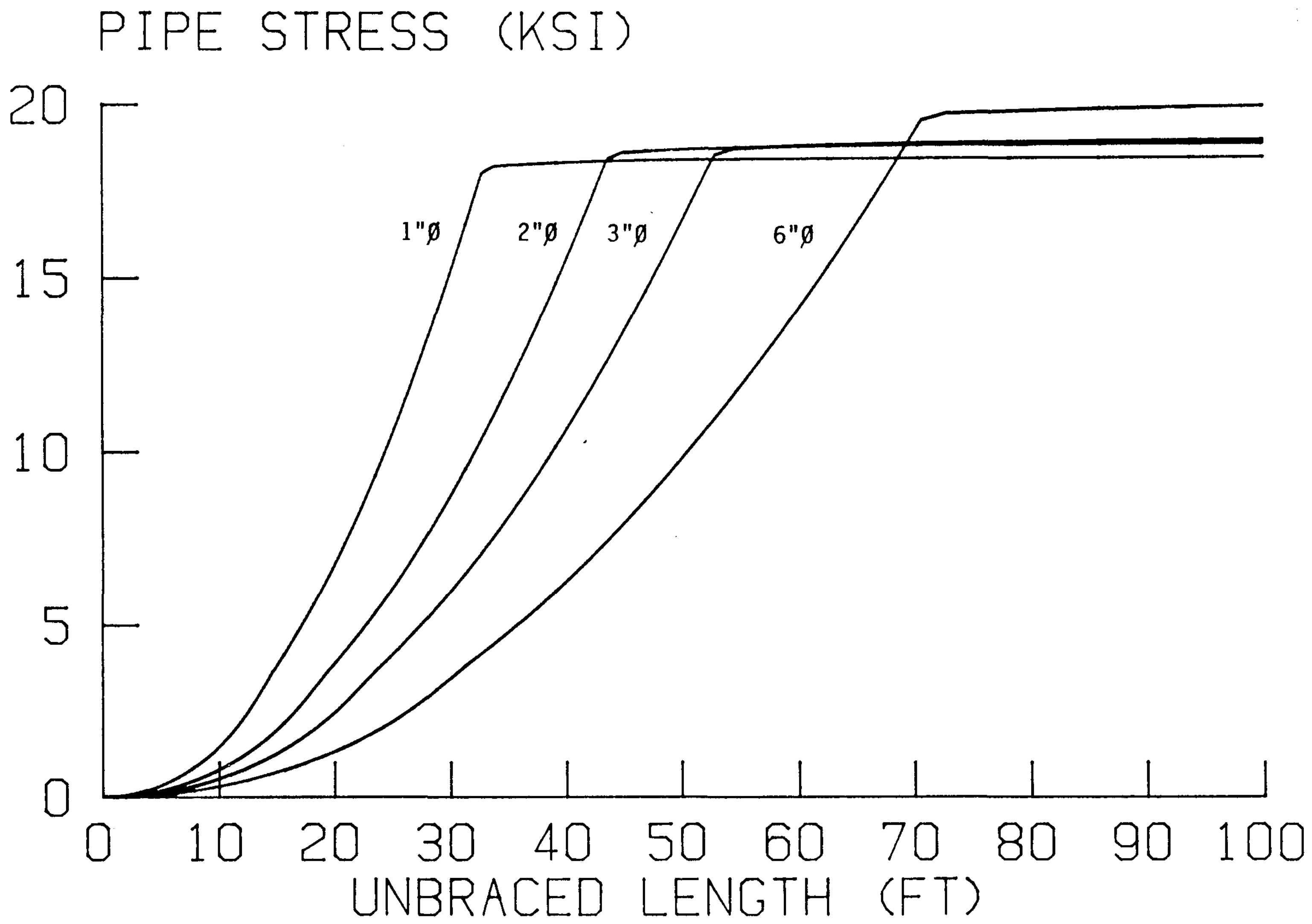


FIGURE B-2 PEAK SEISMIC BENDING STRESS IN 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 40 STEEL PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, GROUND VIBRATION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

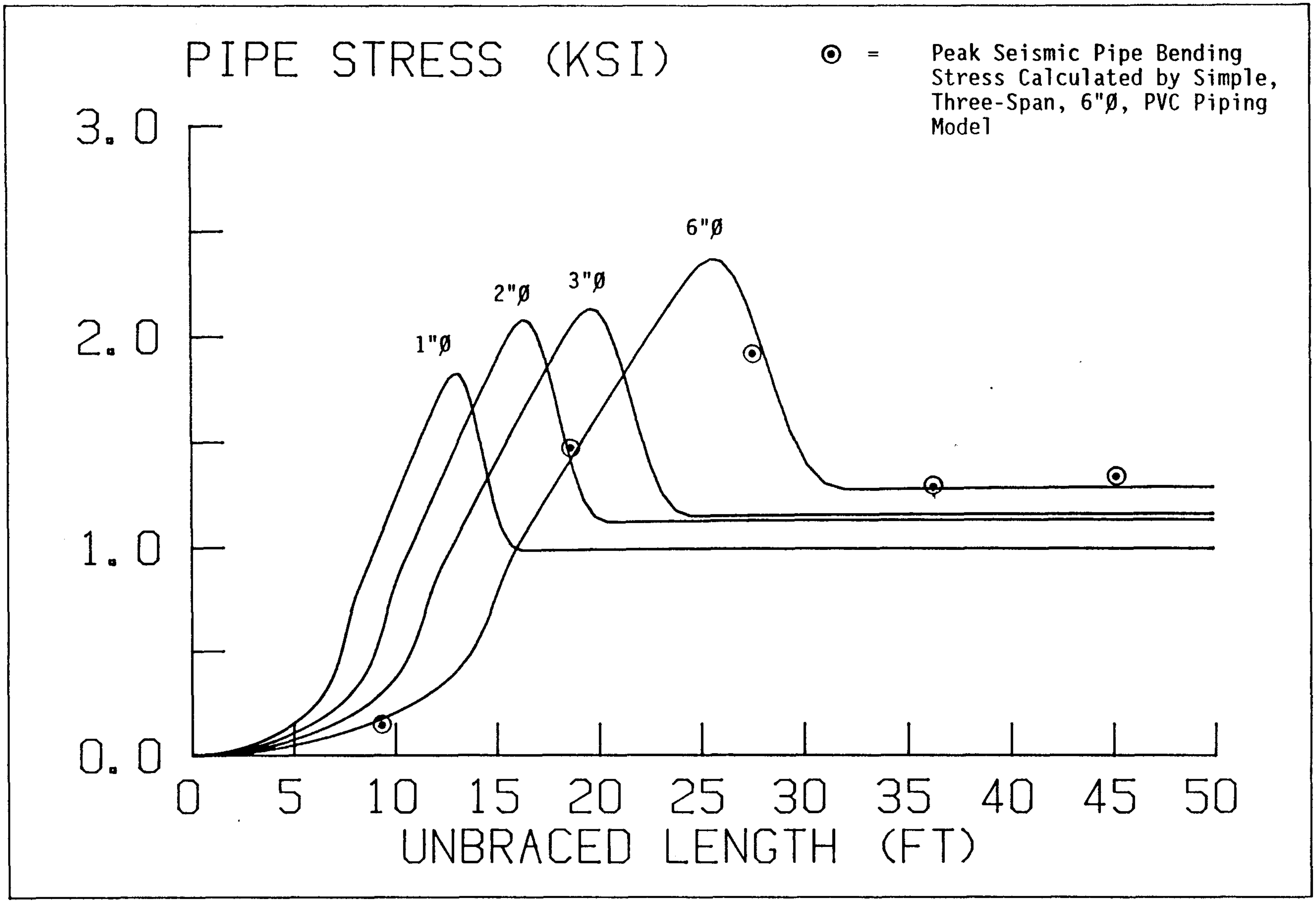


FIGURE B-3 PEAK SEISMIC BENDING STRESS IN 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 80 PVC PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO.7.

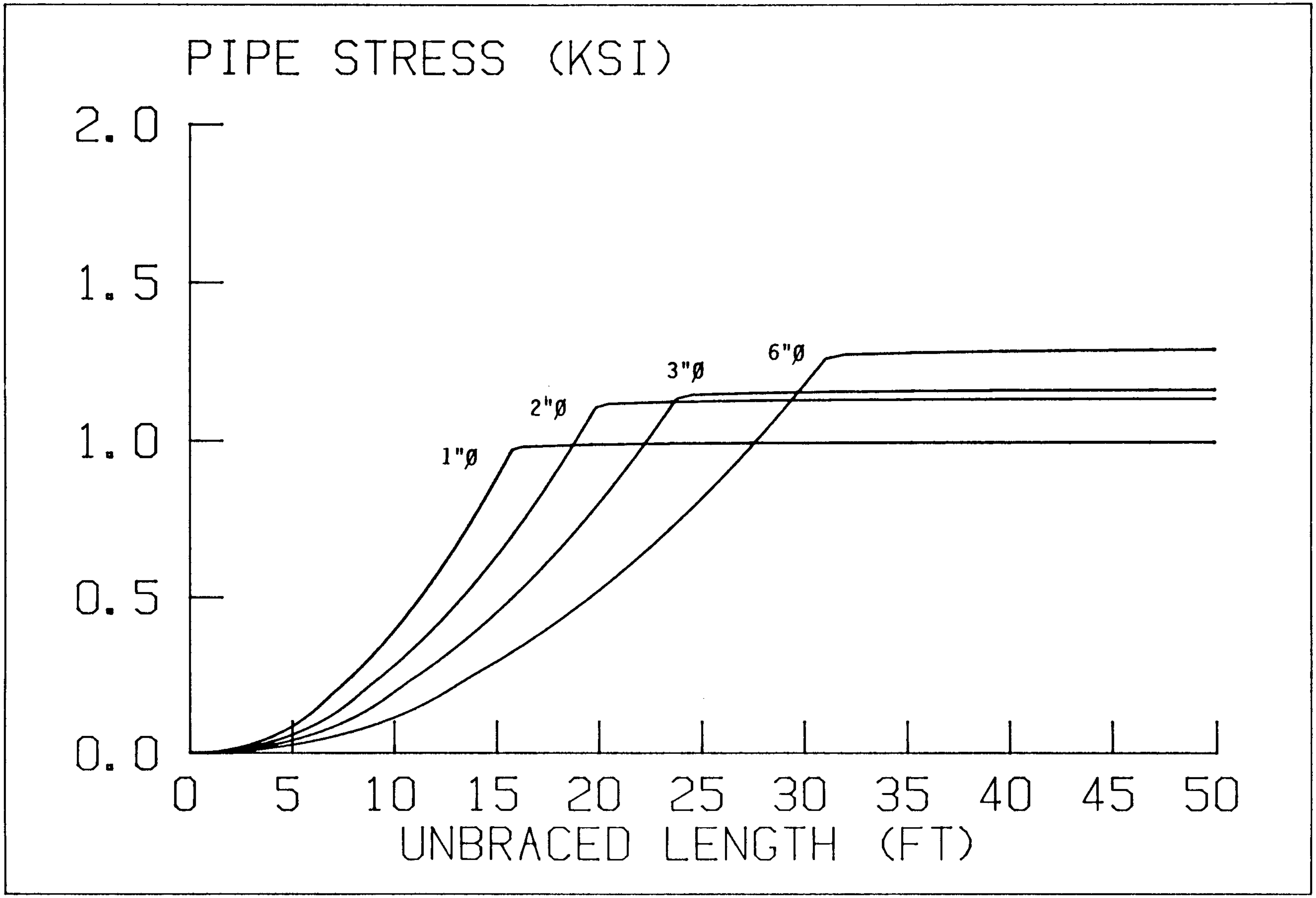


FIGURE B-4 PEAK SEISMIC BENDING STRESS IN 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 80 PVC PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, GROUND VIBRATION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

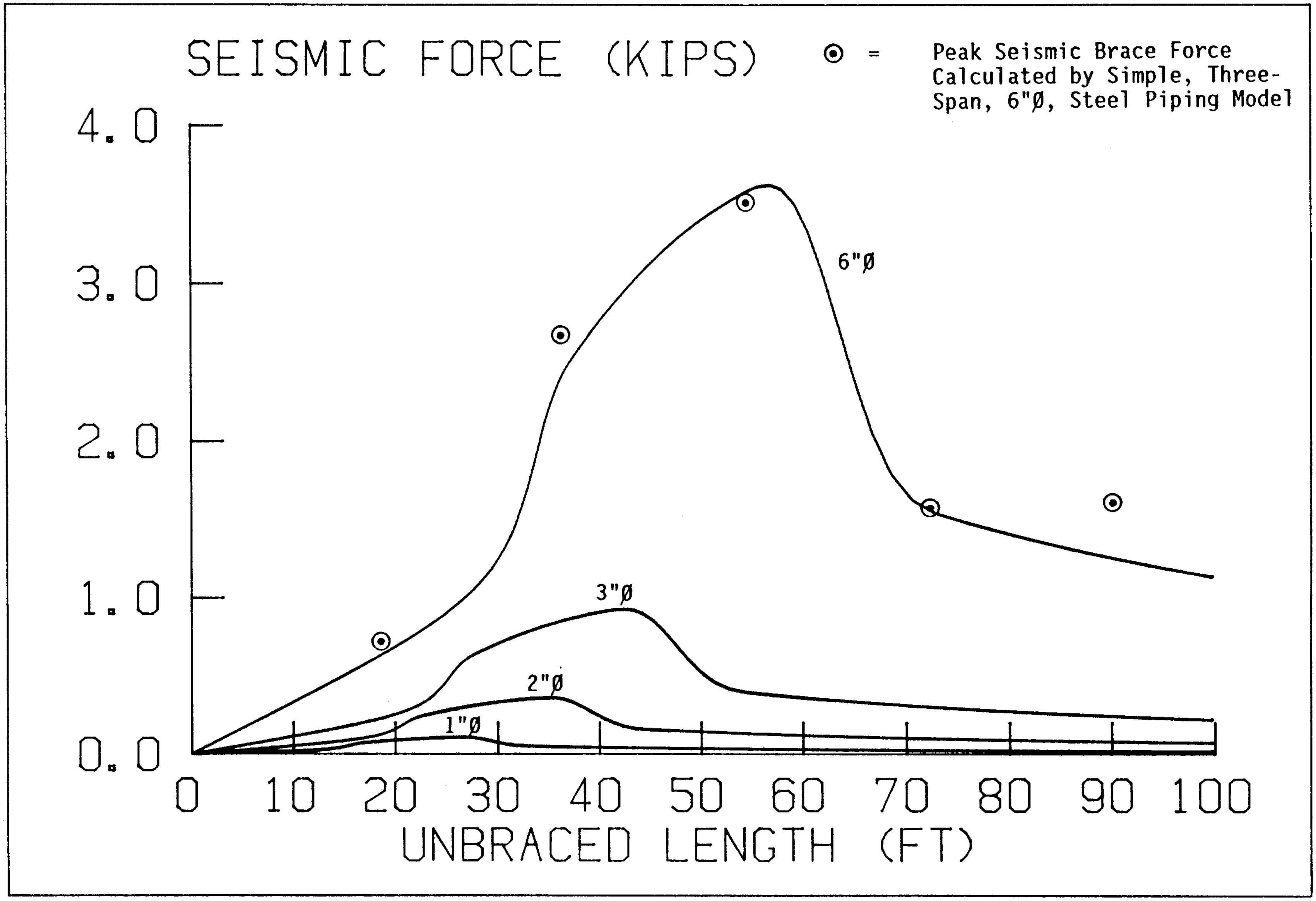


FIGURE B-5 PEAK SEISMIC BRACE FORCE FOR 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 40 STEEL PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

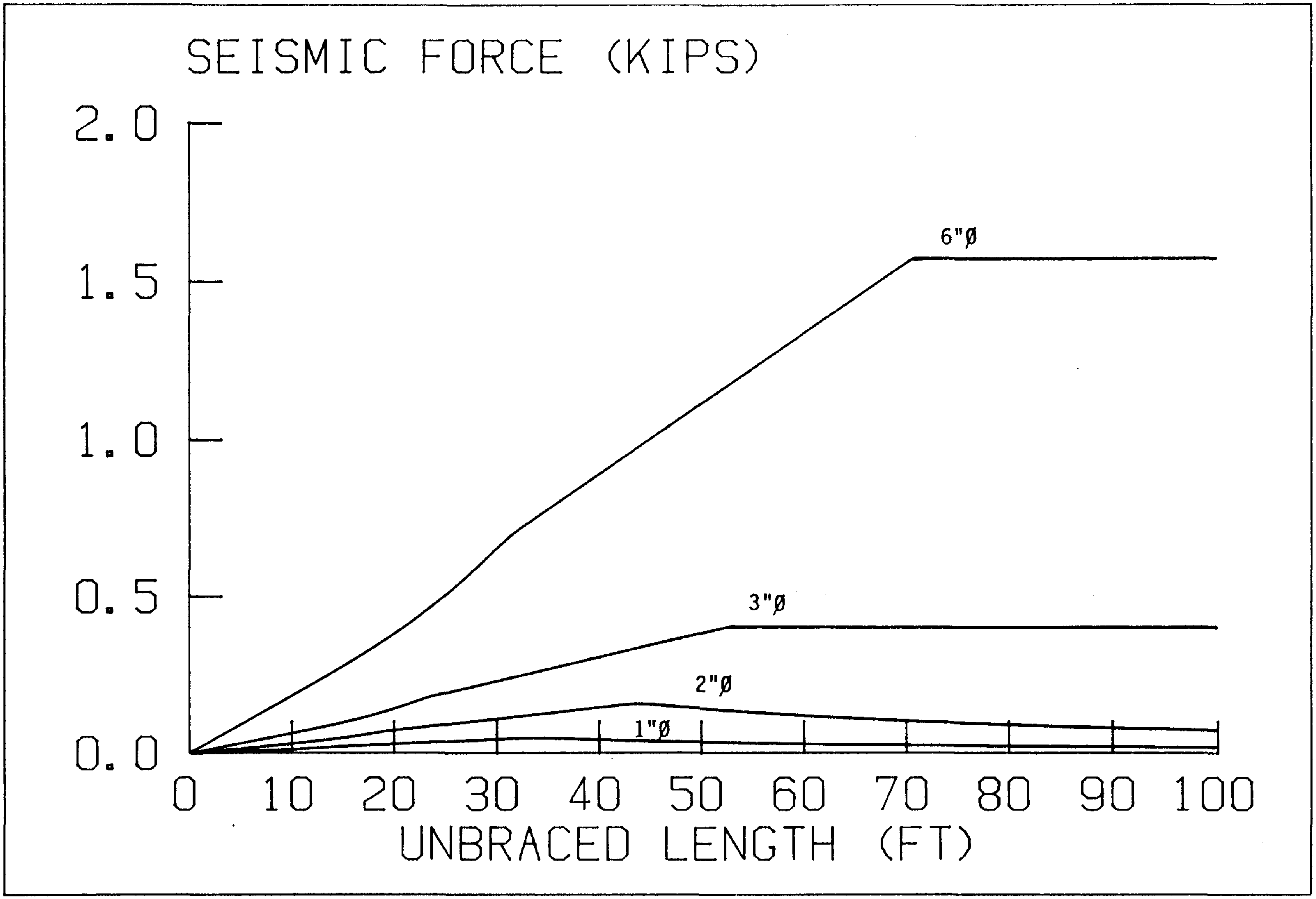


FIGURE B-6 PEAK SEISMIC BRACE FORCE FOR 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 40 STEEL PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

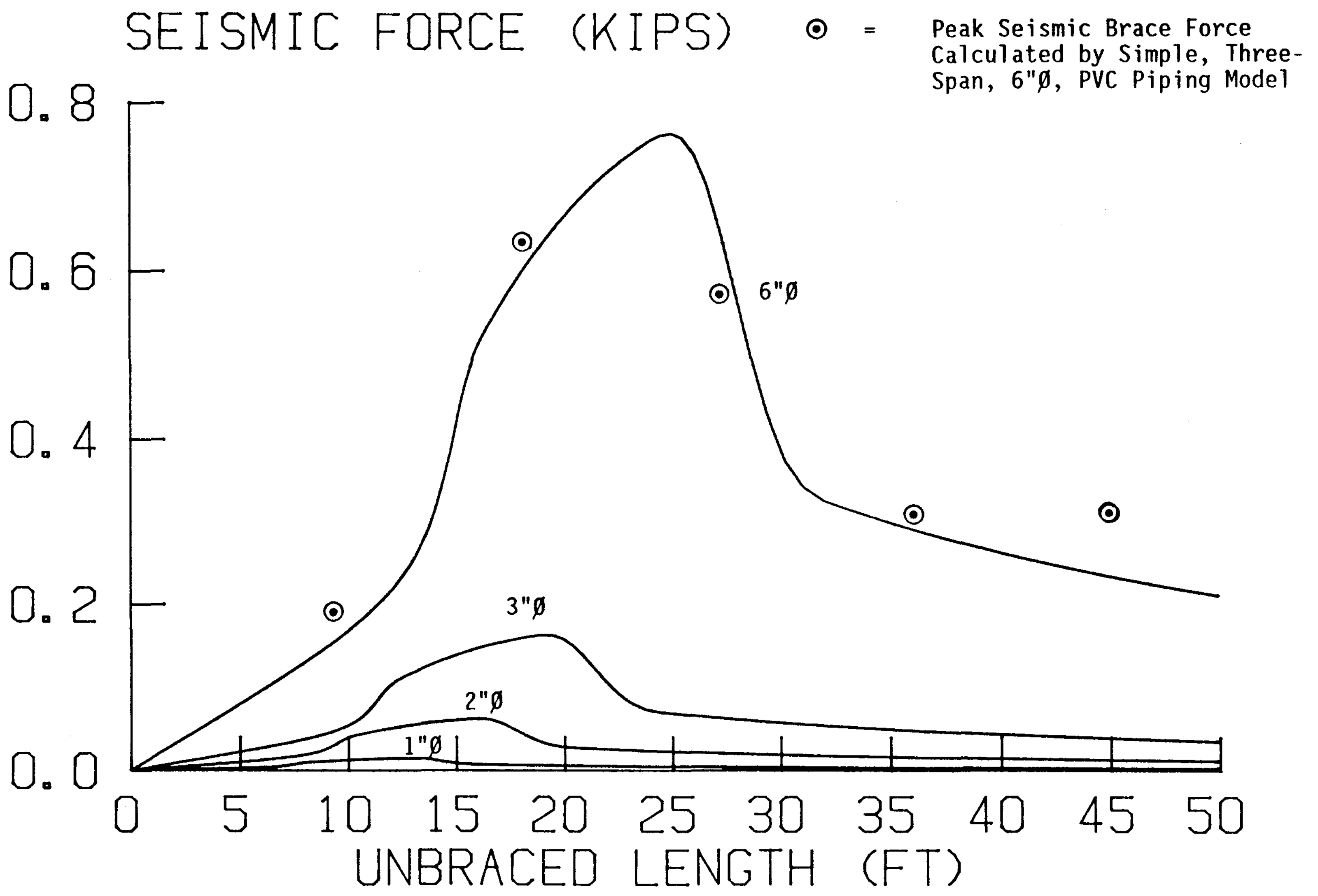


FIGURE B-7 PEAK SEISMIC BRACE FORCE FOR 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 80 PVC PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

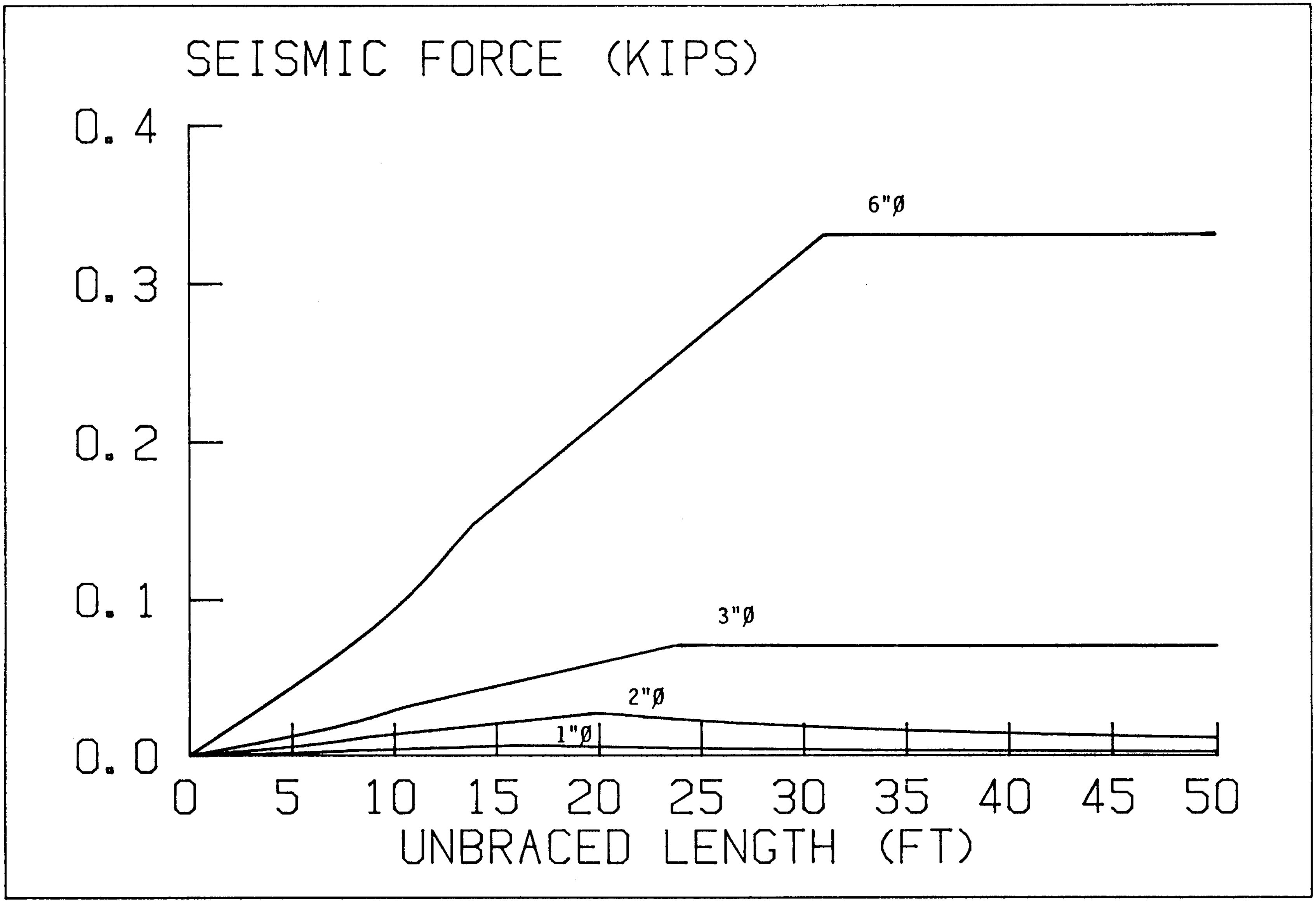


FIGURE B-8 PEAK SEISMIC BRACE FORCE FOR 1"Ø, 2"Ø, 3"Ø, AND 6"Ø SCHEDULE 80 PVC PIPE AS A FUNCTION OF UNBRACED SPAN LENGTH, GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7.

APPENDIX C

SEISMIC ANALYSIS OF A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS LATERAL-BRACING SCHEMES

C.1 Purpose and Objectives

The purpose of the work contained in Appendix C is to examine the seismic response of a complex, steel piping system with various lateral-bracing schemes. The steel piping system examined has segments of various diameters, is supported by trapeze hangers, rod hangers of various lengths, or wall-mounted supports, and is representative of piping configurations commonly found at industrial facilities. The intent of modeling a large, complex system is to examine response for a variety of conditions which have the potential to generate excessive seismic stresses.

The objectives of Appendix C are summarized below:

1. Examine the peak bending stresses at selected locations on the piping system model for four different bracing schemes and four different seismic environments.

2. Compare and contrast peak piping system bending stress for the following four seismic bracing schemes:

    a. Unbraced System (UB) - this scheme has only vertical supports.

    b. Longitudinal Bracing Only (LB) - this scheme has longitudinal braces installed parallel to the pipe axis, but does not have any transverse bracing.

c. Longitudinal plus Transverse Bracing (LTB1) - this scheme has longitudinal braces, as described above, plus transverse braces at every other vertical support.

d. Longitudinal plus Transverse System (LTB2) - this system has longitudinal braces as in system LTB1, plus transverse braces at every gravity support.

3. Compare and contrast peak piping system bending stress for the following four seismic environments:

   a. Upper-floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 7 (0.4g EPGA).

   b. Ground motion corresponding to NEHRP/ATC-3 Map Area No. 7 (0.4g EPGA).

   c. Upper-floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 5 (0.2g EPGA).

   d. Ground motion corresponding to NEHRP/ATC-3 Map Area No. 5 (0.2g EPGA).

C.2 Description of the Models

The basic piping system model and the four bracing schemes are described in the following sections.

C.2.1 Steel Piping System Model

Figure C-1 shows the basic Schedule 40 steel piping system model, in plan view, and its location in a typical industrial building (i.e., one-story structure approximately 160 feet by 200 feet). The piping system runs the length of the building with branch lines extending the width of the building. The piping system is primarily supported by trapeze or rod hangers, with some branch lines supported by wall brackets. Location and type of vertical supports are shown in Figure C-1. Spacing of vertical supports is consistent with the requirement of ASME B31.9 [Ref. 20] for Schedule 40 steel pipe.

The piping system is composed of a six-inch diameter mainline (Element No. 1) on trapezes which runs the length of the building. Other pipes not shown in Figure C-1 were also modeled on the trapeze to simulate typical trapeze loading. A three-inch diameter branch line (Element No. 2) runs perpendicular from the mainline along an interior wall. Other three-inch diameter branch lines run perpendicular from the mainline and are supported on relatively long rod hangers (i.e., Element No. 3) or relatively short rod hangers (i.e., Element No. 5). Short risers (Elements No. 4 and No. 6) connect these branch lines to the mainline.

A three-inch diameter branch line (Element No. 7) runs perpendicular to the mainline along an interior wall, and connects to a 3-inch diameter line (Element no. 8) on very short rod hangers. This line is reduced at a tee intersection and forms a one-inch line (Element No. 9) which runs to a rigidly-held piece of equipment, and a two-inch line (Element No. 10) which runs to the end of the building.

The piping system was modeled as a discrete, lumped-mass system with four mass points per span of pipe between gravity supports. The pipes were modeled as beam elements, including the effects of shear and bending deformations.

The piping system model is discontinued at the building's boundaries and at a point along the mainline removed from the elements of interest. At those points where the model is discontinued, appropriate boundary conditions have been used to simulate pipe continuity.

The effects of gravity on lateral vibration are commonly ignored in the analysis of piping systems with lateral restraints. However, for pipes on hangers without lateral restraint, dynamic response is primarily a function of pendulum-type motion which is influenced by force of gravity. To simulate the restoring force of gravity, relatively soft lateral springs were introduced at each mass point. The stiffness of these springs is calculated such that the spring force is approximately equal to the effective gravity force at small displacements.

C.2.2 Seismic Bracing Schemes

Four seismic bracing schemes, described below, were used to examine the effects of different types of bracing on the steel piping system.

Unbraced (UB) Scheme - The unbraced scheme is shown in Figure C-2, which consists of the basic piping system without either transverse or longitudinal seismic braces. Although there are no seismic braces, lateral restraint is provided at each wall bracket in the direction perpendicular to the pipe axis.

Longitudinally-Braced (LB) Scheme - The longitudinally-braced scheme is shown in Figure C-3. In this scheme longitudinal braces (5) have been added at every fourth gravity support in accordance with the spacing recommendations of Section 4.3.2 for Category A piping. It should be noted, however, that the spacing to the second longitudinal support on a run has no influence on piping system behavior, and other spacing rules could have been used.

Longitudinally and Transversely-Braced (LTB1) Scheme - The first longitudinally and transversely-braced scheme is shown in Figure C-4. In this scheme transverse braces (12) have been added to the LB scheme at every other gravity support location. Whenever possible, transverse braces have been positioned to be coincident with longitudinal braces and are designated as multi-dimensional braces.

Longitudinally and Transversely-Braced (LTB2) Scheme - The second longitudinally and transversely-braced scheme is shown in Figure C-5. In this scheme transverse braces (24) have been added to the LB scheme at every gravity support. This system is fully braced and represents the bracing which would be required for protection of Category A piping in an extreme seismic environment.

C.3 Description of Analysis

Each of the four piping system models, representing a different bracing scheme, was dynamically analyzed to determine natural frequencies, mode shapes, and participation factors. Subsequently, four response spectrum analyses were run for each model/bracing scheme using, respectively; upper-floor and ground floor spectra of NEHRP/ATC-3 Map Area No. 7 (i.e., 0.4g EPGA) and upper-floor and ground spectra of NEHRP/ATC-3 Map Area No. 5 (i.e., 0.2g EPGA). Ground spectra and upper-floor spectra of NEHRP/ATC-3 Map Area No. 5 are similar in shape, but one-half to two-thirds the size of NEHRP/ATC-3 Map Area No. 7 spectra.

Modal combinations were performed using the square-root-sum-of-the-squares (SRSS) method. The SRSS method was used for all modes, including closely-spaced modes, since it was deemed to better represent true peak response. Combination of the effects of two horizontal earthquake components was also performed using the SRSS. The effects of gravity load and the vertical component of earthquake were not included in the analyses, since peak pipe bending response is not governed by the horizontal earthquake components. In all analyses stresses due to pressure, temperature, or other normal operating loads have been excluded. Thus, the stresses calculated represent the effects of horizontal earthquake loads only.

All dynamic and response spectrum analyses were run on SAP 100, a finite element program for microcomputers based on SAP IV [Ref. 36].

C.4 Summary of Results

C.4.1 Modal Analyses

The results of the modal analyses are summarized in Table C-1 for each of the four bracing schemes, and plots of the shapes of dominant modes (i.e., modes with significant participation) are shown in Figures C-6 through C-9, respectively.

Initially, the unbraced (UB System) has a natural frequency of about 0.61 Hz for the dominant mode of response in the X-direction (i.e., direction perpendicular to the mainline on trapeze supports), and over 80% of total mass was effective in modes below 20 Hz. Addition of longitudinal bracing (LB System) does not appreciable alter modal response perpendicular to the mainline, but does make the system essential rigid in the direction parallel to mainline (i.e., about 95% of the pipe's mass is effective in modes above 20 Hz).

The addition of transverse bracing at every other gravity support (LTB1 System) causes some additional mass to participate above 20 Hz and effectively increases the frequency of dominant modes of transverse response to be about 4-10 Hz. The addition of transverse bracing at every support (LTB2 System) increases the piping system rigidity significantly and causes all dominant modes of response to be greater than about 12 Hz.

C.4.2 Response Spectrum Analyses

The results of the response spectrum analysis are summarized in Tables C-2 through C-5, respectively. For each of the four seismic environments (i.e., 0.4g EPGA upper-floor spectra, 0.4g EPGA ground floor spectra, and 0.2g EPGA upper-floor spectra and 0.2g EPGA ground floor spectra). For the purpose of assessing acceptable response, peak bending stress should not exceed 12 ksi for Category A piping and 30 ksi for

Category B piping (i.e., based on the criteria of Section 3.6 and the allowables of ASME B31.9 for ASTM 53 Grade A steel pipe).

As shown in Table C-2, unbraced (UB System) response can be quite high for upper-floor 0.4g EPGA seismic loads, far exceeding both Category A and Category B stress limits. This is due primarily to longitudinal shifting of the mainline and related overstressing of lateral runs (e.g., Element 2). Addition of longitudinal bracing (LB System) decreases excessive stress in all elements, (except the 1"Ø line to equipment), basically meeting Category B stress limits but still exceeding Category A stress limits significantly. Addition of transverse bracing at every other support does little to lower stresses from the results of the longitudinal-only bracing (except for 1"Ø line). In fact, peak response is increased in some elements. In contrast, addition of transverse bracing at every support lowers peak responses to a level which seldom exceeds one-half of Category A stress limits.

Ground floor, 0.4g EPGA (Table C-4) and upper-floor 0.2g EPGA, (Table C-3) seismic loadings have comparable levels of peak responses (with the 0.4g ground floor results being slightly higher). In general, elements of the unbraced systems do not meet Category A stress limits, but meet or almost meet these limits when longitudinal bracing is added. Transverse bracing at every other support reduced stress in some elements, particularly for unamplified ground motion. Transverse bracing at every support reduces stress levels well below Category A limits.

In summary, the selection of the type and spacing of seismic braces to achieve defined limits on steel pipe stress is entirely related to the seismic environment and the level of stress permitted in the pipe. In general it can be stated:

1. Longitudinal braces on most runs and transverse braces at every gravity support are required for lateral restraint of hazardous (Category A) piping systems in high seismic environments (e.g., EPGA's greater than 0.2g).

2. Longitudinal bracing only is, in general, sufficient for lateral restraint of hazardous (Category A) steel piping systems in low to medium seismic environments (e.g., EPGA's less than 0.2g). Exceptions to this rule may exist for certain piping geometries.

3. Standard seismic bracing guidelines (e.g., SMACNA [Ref. 23]) may not provide the level of protection necessary for piping systems containing hazardous (Category A) material.

TABLE C-1

SUMMARY OF MODAL ANALYSIS RESULTS FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS LATERAL BRACING SCHEMES

Direction/ Dominant Mode[1]	Unbraced (UB) System			Longitudinally-Braced (LB) System		
	Mode No.	Frequency (Hz)	Participation[2]	Mode No.	Frequency (Hz)	Participation[2]
X 1st	2	0.61	50.2	2	0.67	49.3
X 2nd	7	1.55	32.4	6	1.53	26.6
X 3rd	14	3.48	2.3	13	3.12	6.1
X 4th	12	2.56	1.7	7	1.60	5.6
X 5th	15	3.54	1.5	3	0.85	1.2
X RIGID		>20	11.9		>20	11.2
Y 1st	14	3.48	28.0	1	0.42	3.7
Y 2nd	15	3.54	7.6	5	1.09	2.1
Y 3rd	6	1.43	5.7			
Y 4th	1	0.42	3.8			
Y 5th	5	1.09	2.6			
Y RIGID		>20	52.3		>20	94.2

Direction/ Dominant Mode[1]	Long./Tranversely-Braced (LTB1) System			Long./Tranversely-Braced (LTB2) System		
	Mode No.	Frequency (Hz)	Participation[2]	Mode No.	Frequency (Hz)	Participation[2]
X 1st	9	4.97	34.5	27	12.60	36.7
X 2nd	18	9.87	13.6	35	14.30	12.4
X 3rd	8	4.55	8.7	26	12.40	8.2
X 4th	1	2.51	1.8	31	13.40	4.7
X 5th	19	10.11	1.5	28	12.89	1.3
X RIGID		>20	39.9		>20	36.7
Y 1st	6	3.95	2.8	22	11.99	4.2
Y 2nd	3	3.14	1.5	29	12.99	1.4
Y 3rd				17	11.24	1.1
Y 4th						
Y 5th						
Y RIGID		>20	95.7		>20	93.3

1. A dominant mode is defined as having at least 1% participation in the direction under consideration.

2. Participation is defined as the percentage of total mass acting in the direction under consideration.

TABLE C-2

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	19.4	11.5	14.4	1.5
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	82.2	13.9	7.9	0.64
3	3" Diameter Branch Line (on Long Rod Hangers)	18.5	9.9	16.6	2.1
4	3" Diameter Riser (from 1 to 3)	18.1	12.8	18.8	3.0
5	3" Diameter Branch Line (on Short Rod Hangers)	57.0	13.3	14.4	2.0
6	3" Diameter Riser (from 1 to 5)	67.6	18.2	6.2	2.3
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	18.0	19.2	15.3	4.3
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	75.1	15.1	19.7	2.1
9	1" Diameter Feeder Line and Riser to Equipment	43.2	49.5	18.8	6.4
10	2" Diameter Branch Line (on Short Rod Hangers)	30.2	11.4	11.5	2.3

1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e. ASME B31.9, Ref. 20).

TABLE C-3

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO VIBRATORY GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	9.4	8.2	4.7	0.9
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	34.9	9.8	2.6	0.4
3	3" Diameter Branch Line (on Long Rod Hangers)	8.4	8.9	5.4	1.2
4	3" Diameter Riser (from 1 to 3)	10.5	9.9	8.0	1.8
5	3" Diameter Branch Line (on Short Rod Hangers)	18.3	6.2	4.8	1.1
6	3" Diameter Riser (from 1 to 5)	23.0	10.2	2.7	1.2
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	22.6	16.9	1.1	2.8
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	21.9	6.1	7.1	1.2
9	1" Diameter Feeder Line and Riser to Equipment	15.5	14.4	6.1	4.1
10	2" Diameter Branch Line (on Short Rod Hangers)	10.7	6.4	4.3	1.3

1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e. ASME B31.9, Ref. 20).

TABLE C-4

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 5

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	13.3	6.6	8.8	0.80
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	51.8	8.2	4.8	0.40
3	3" Diameter Branch Line (on Long Rod Hangers)	11.4	5.7	10.1	1.3
4	3" Diameter Riser (from 1 to 3)	10.7	7.2	11.4	1.8
5	3" Diameter Branch Line (on Short Rod Hangers)	36.7	8.5	8.9	1.4
6	3" Diameter Riser (from 1 to 5)	43.4	11.2	3.7	1.2
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	16.0	10.9	9.3	2.6
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	23.0	9.8	10.2	1.3
9	1" Diameter Feeder Line and Riser to Equipment	26.5		11.5	3.9
10	2" Diameter Branch Line (on Short Rod Hangers)	20.0	8.3	8.8	1.4

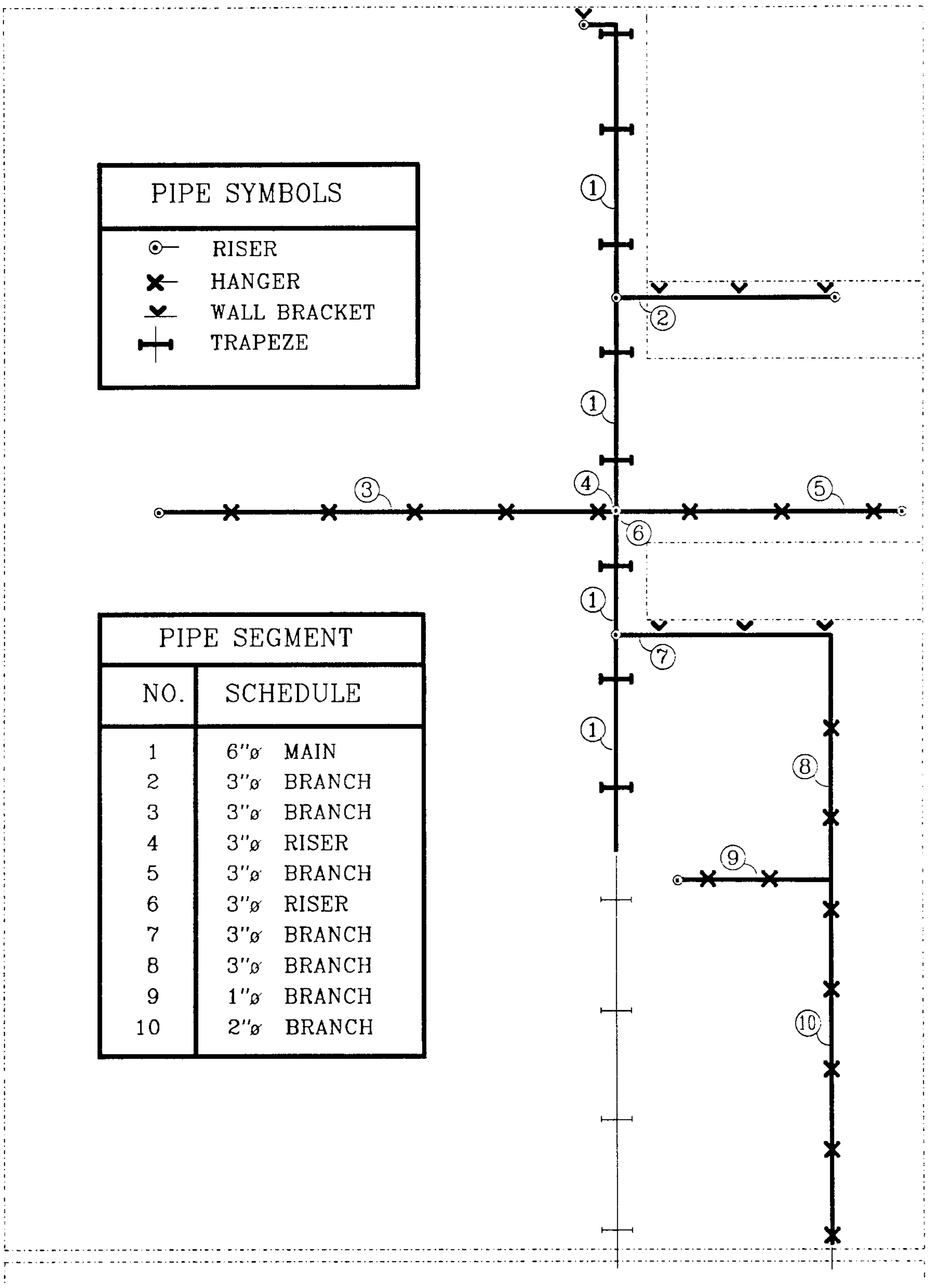
1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e. ASME B31.9, Ref. 20).

TABLE C-5

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX STEEL PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO VIBRATORY GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 5

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	4.60	4.10	2.40	0.40
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	17.40	4.90	1.30	0.20
3	3" Diameter Branch Line (on Long Rod Hangers)	4.2	4.4	2.7	0.60
4	3" Diameter Riser (from 1 to 3)	5.2	4.9	4.0	0.90
5	3" Diameter Branch Line (on Short Rod Hangers)	9.1	3.1	2.4	0.7
6	3" Diameter Riser (from 1 to 5)	11.5	5.1	1.4	0.6
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	11.0	9.1	0.54	1.4
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	10.3	2.6	2.8	0.60
9	1" Diameter Feeder Line and Riser to Equipment	7.8	7.2	3.1	2.0
10	2" Diameter Branch Line (on Short Rod Hangers)	6.5	3.2	2.1	0.70

1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi (i.e. ASME B31.9, Ref. 20).



PIPE SEGMENT	
NO.	SCHEDULE
1	6"ø MAIN
2	3"ø BRANCH
3	3"ø BRANCH
4	3"ø RISER
5	3"ø BRANCH
6	3"ø RISER
7	3"ø BRANCH
8	3"ø BRANCH
9	1"ø BRANCH
10	2"ø BRANCH

FIGURE C-1 BASIC SCHEDULE 40 STEEL PIPING SYSTEM MODEL, PLAN VIEW.

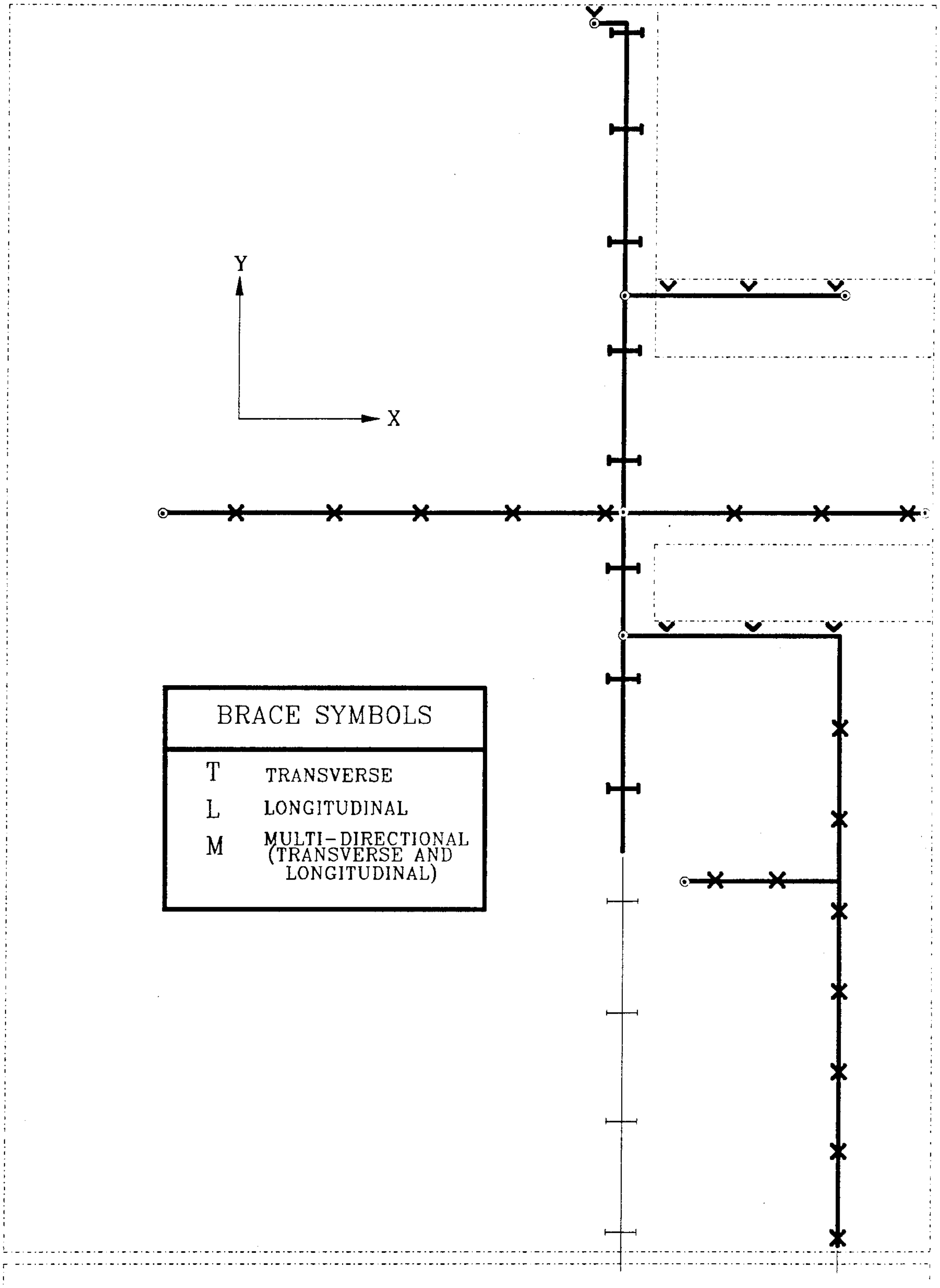


FIGURE C-2 UNBRACED SCHEDULE 40 STEEL PIPING SYSTEM (UB).

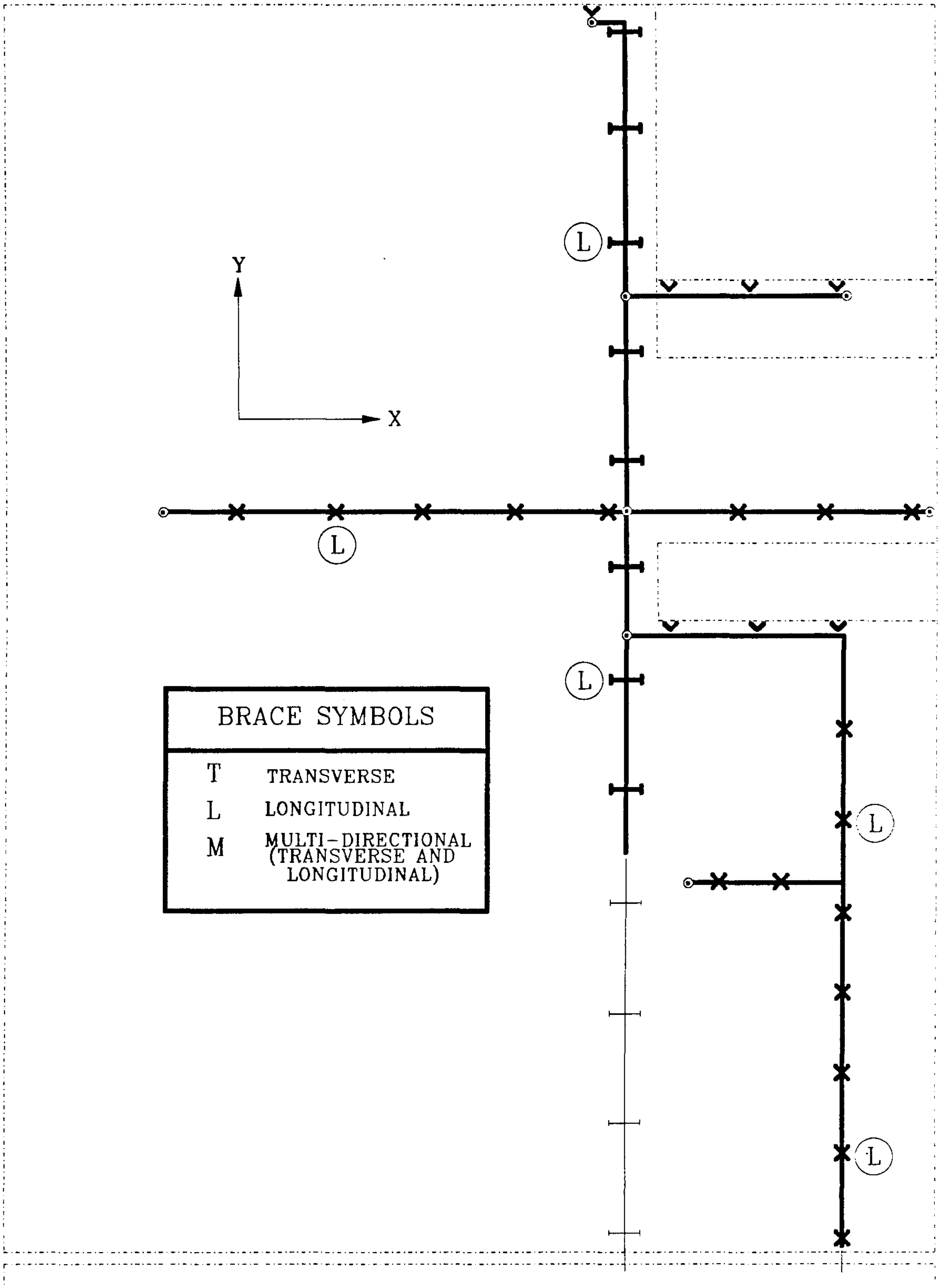


FIGURE C-3 LONGITUDINALLY-BRACED SCHEDULE 40 STEEL PIPING SYSTEM (LB).

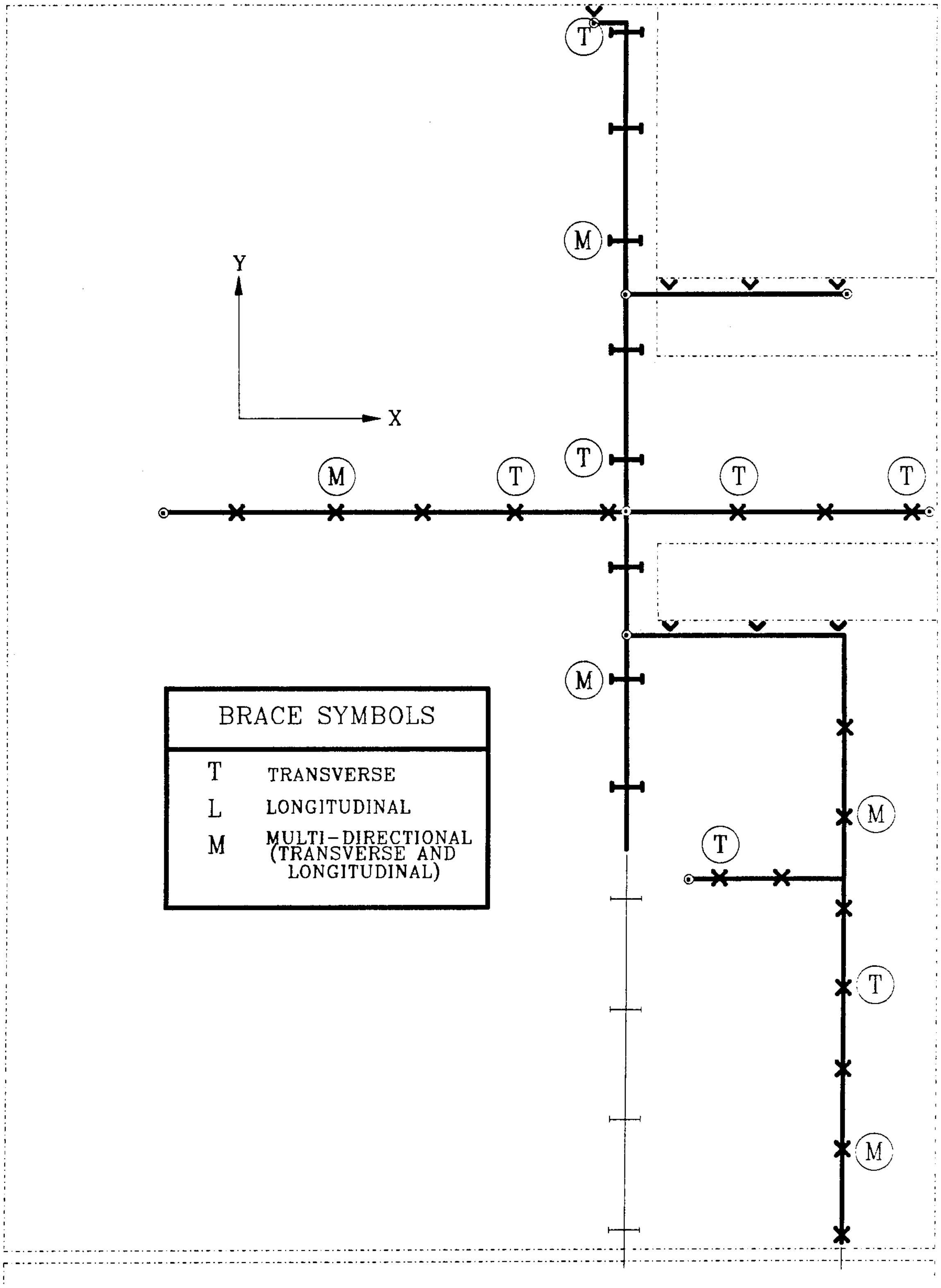


FIGURE C-4 LONGITUDINAL AND TRANSVERSELY-BRACED SCHEDULE 40 STEEL PIPING SYSTEM (LTB1).

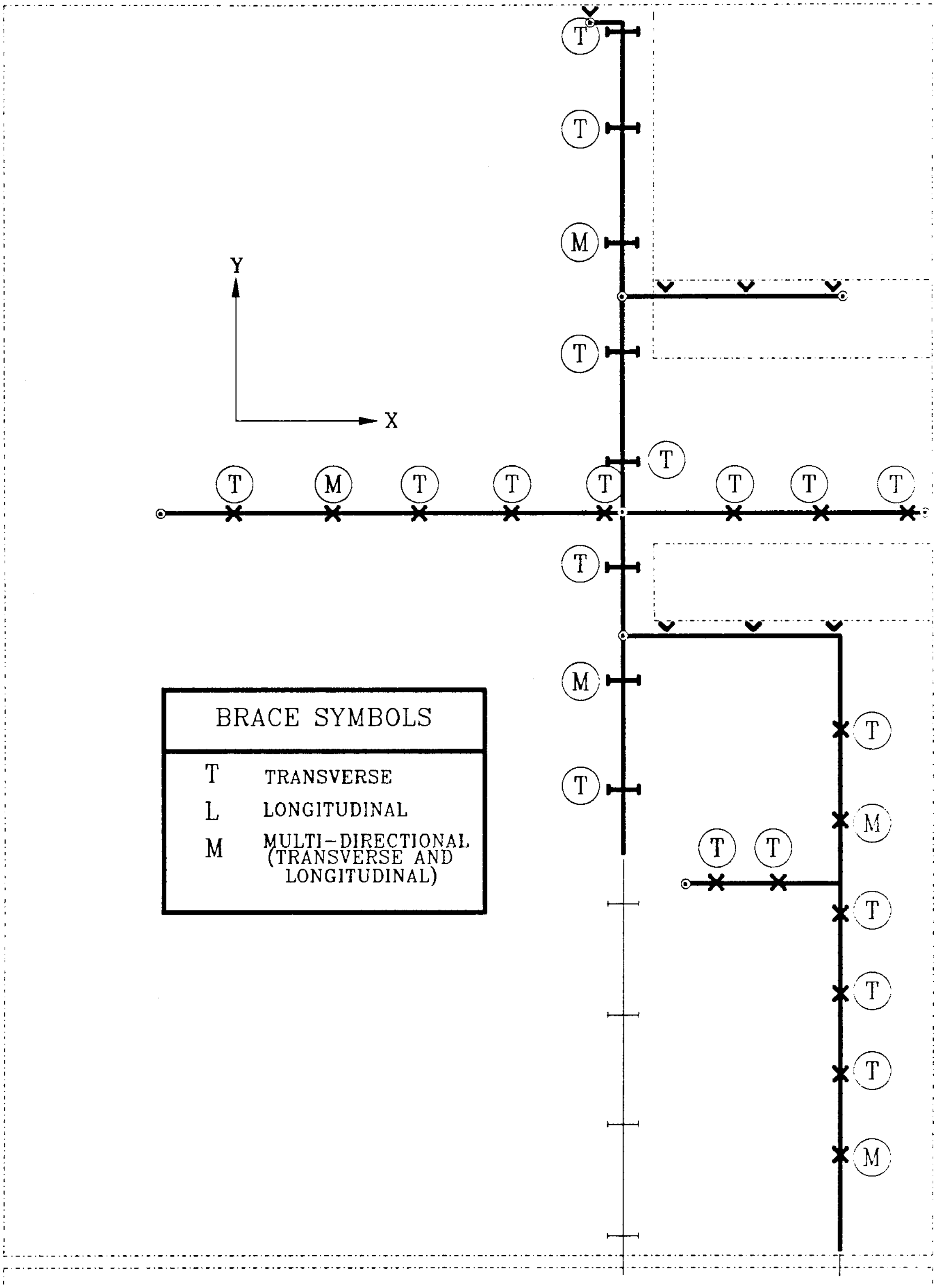


FIGURE C-5 LONGITUDINALLY AND TRANSVERSELY-BRACED SCHEDULE 40 STEEL PIPING SYSTEM (LTB2).

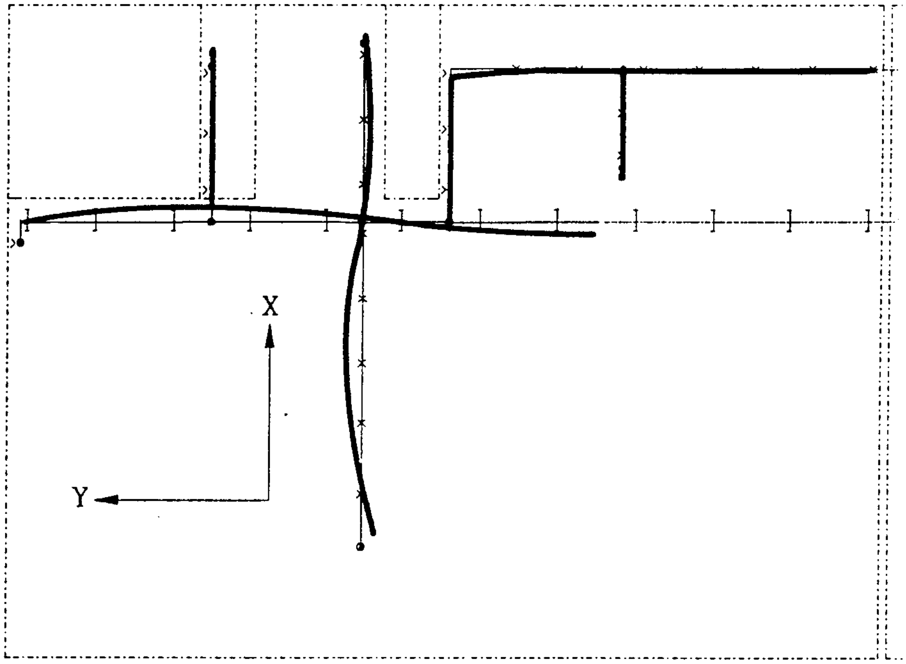


FIGURE C-6A SHAPE OF MODE NO. 2, 0.61 Hz, UNBRACED SYSTEM (UB).

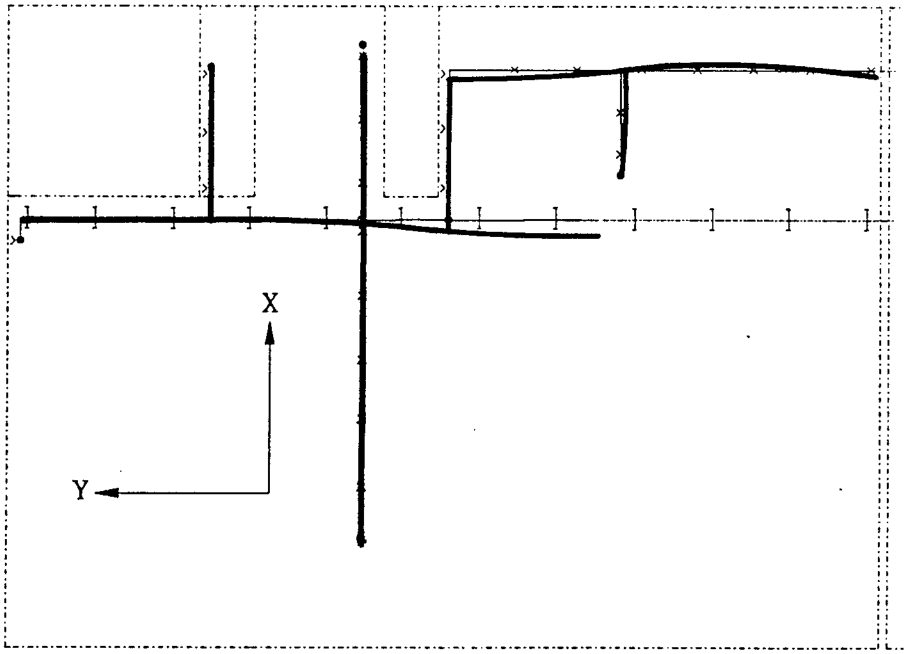


FIGURE C-6B SHAPE OF MODE NO. 7, 1.55 Hz, UNBRACED SYSTEM (UB).

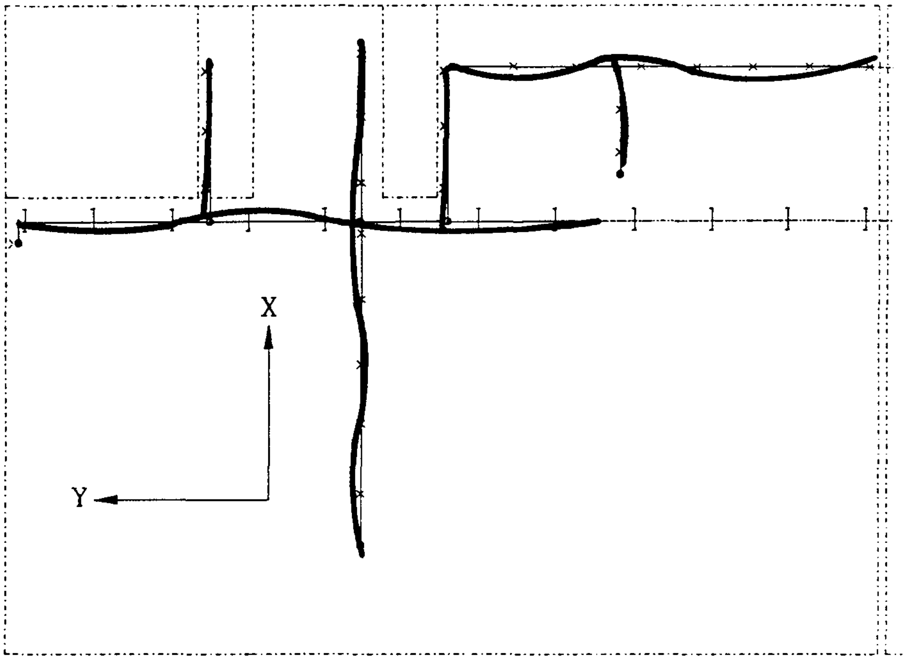


FIGURE C-6C SHAPE OF MODE NO. 14, 3.48 Hz, UNBRACED SYSTEM (UB).

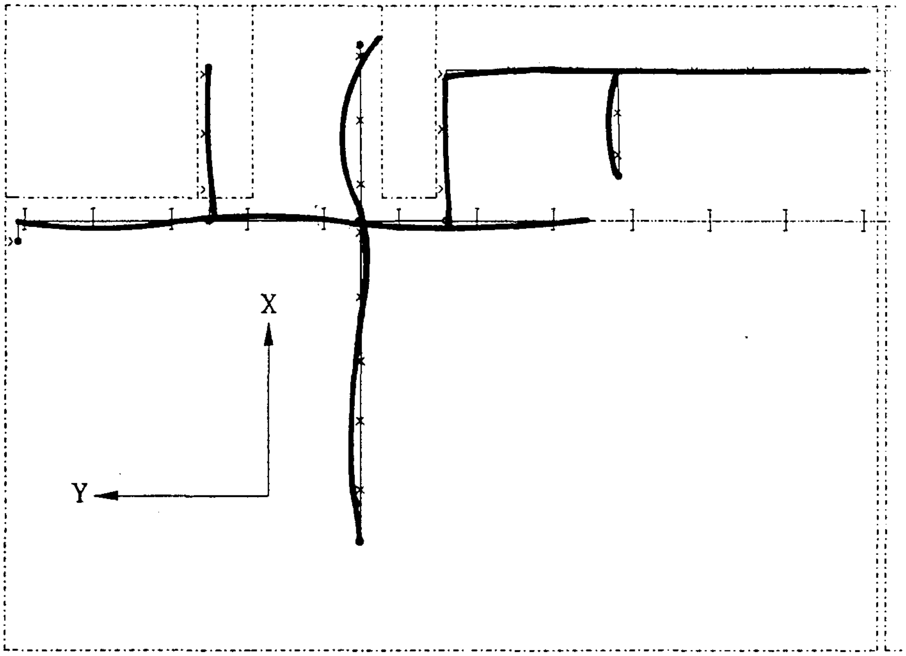


FIGURE C-6D SHAPE OF MODE NO. 12, 2.56 Hz, UNBRACED SYSTEM (UB).

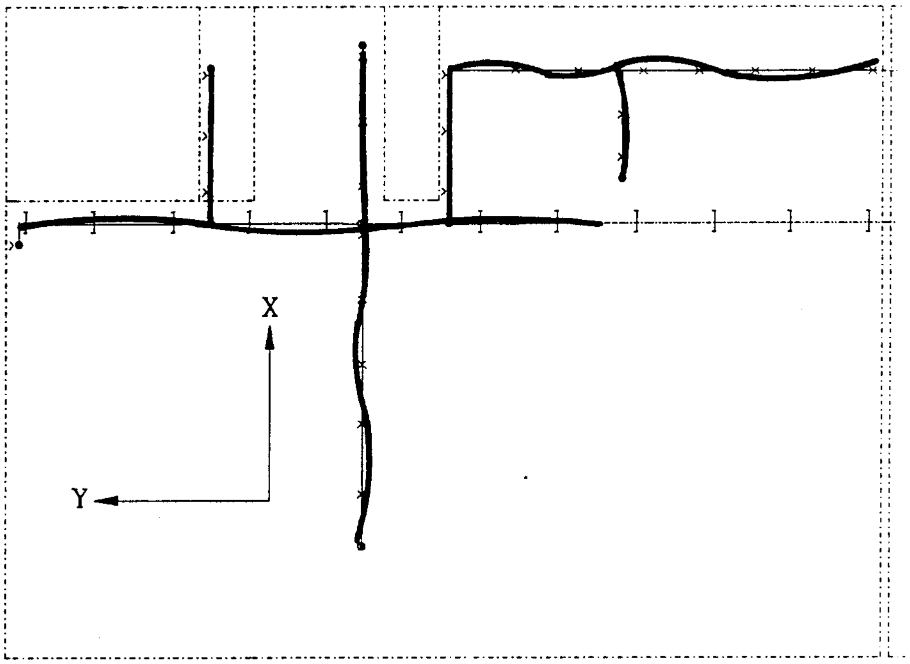


FIGURE C-6E SHAPE OF MODE NO. 15, 3.54 Hz, UNBRACED SYSTEM (UB).

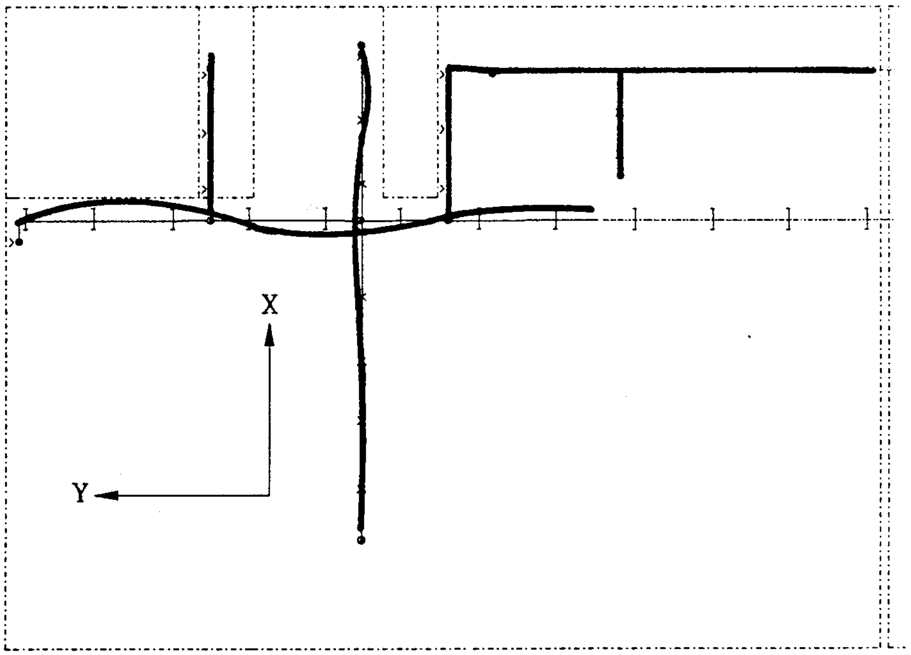


FIGURE C-6F SHAPE OF MODE NO. 6, 1.43 Hz, UNBRACED SYSTEM (UB).

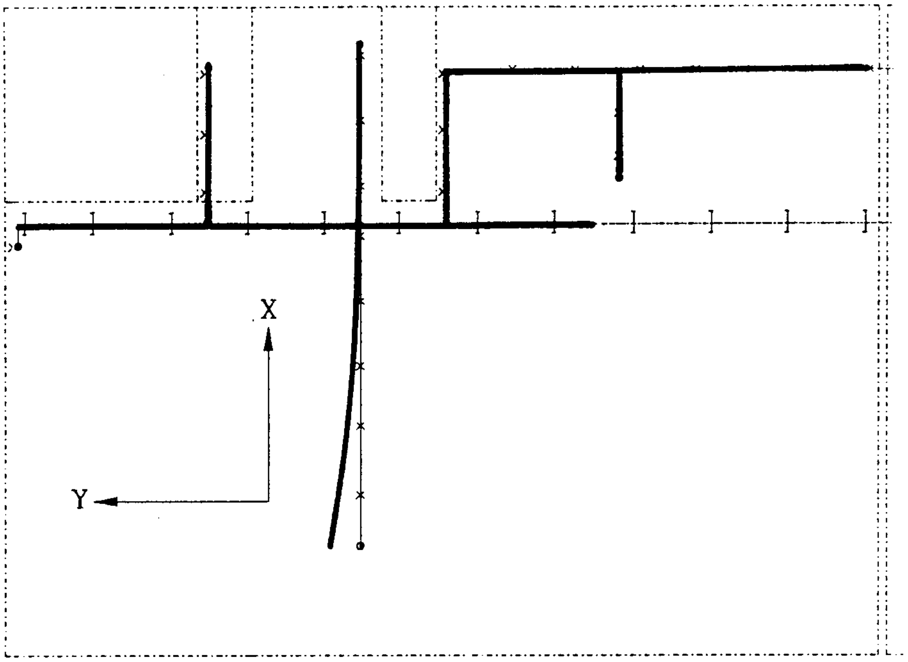


FIGURE C-6G SHAPE OF MODE NO. 1, 0.42 Hz, UNBRACED SYSTEM (UB).

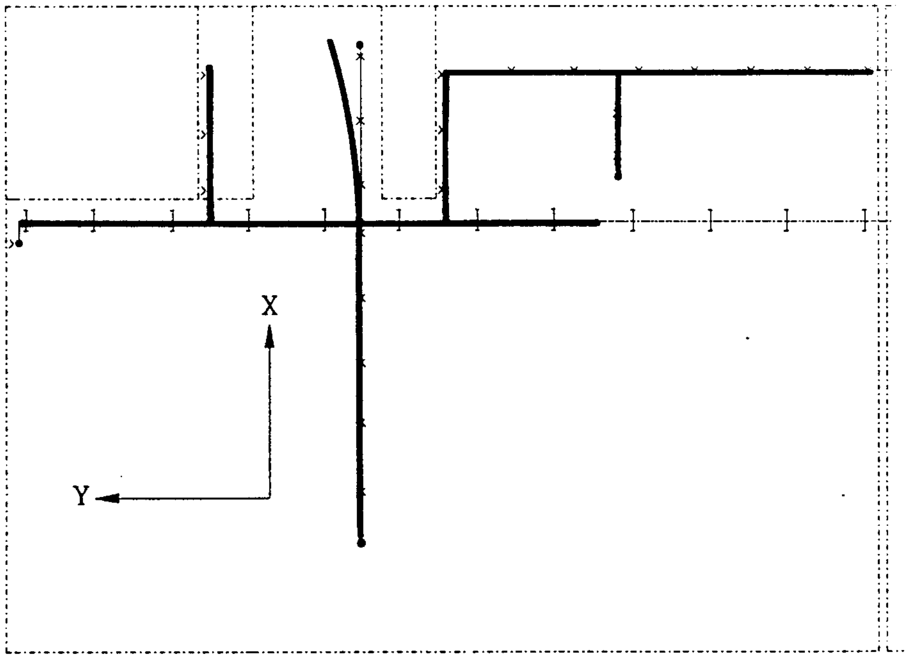


FIGURE C-6H SHAPE OF MODE NO. 5, 1.09 Hz, UNBRACED SYSTEM (UB).

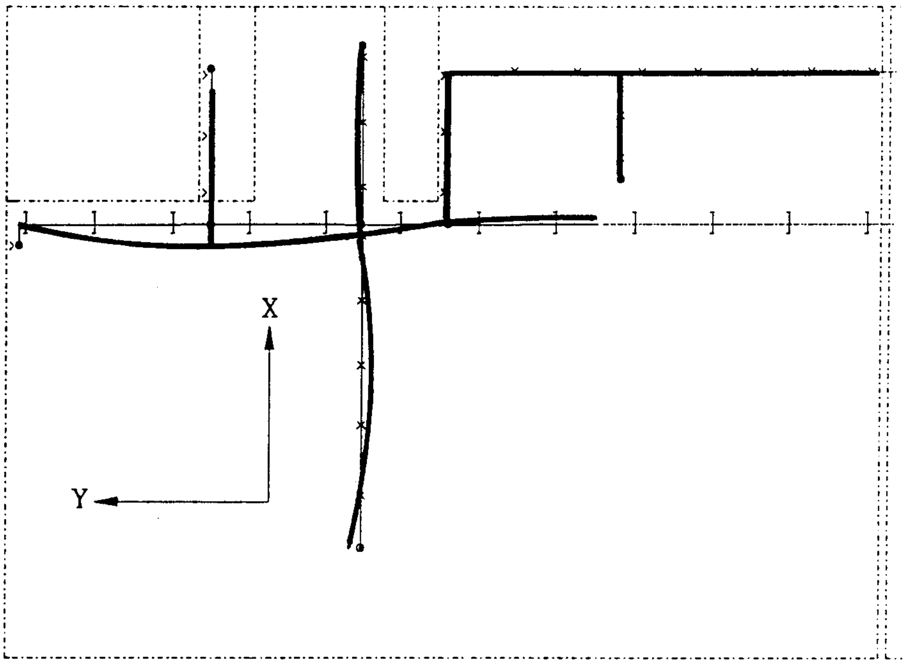


FIGURE C-7A SHAPE OF MODE NO. 2, 0.67 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

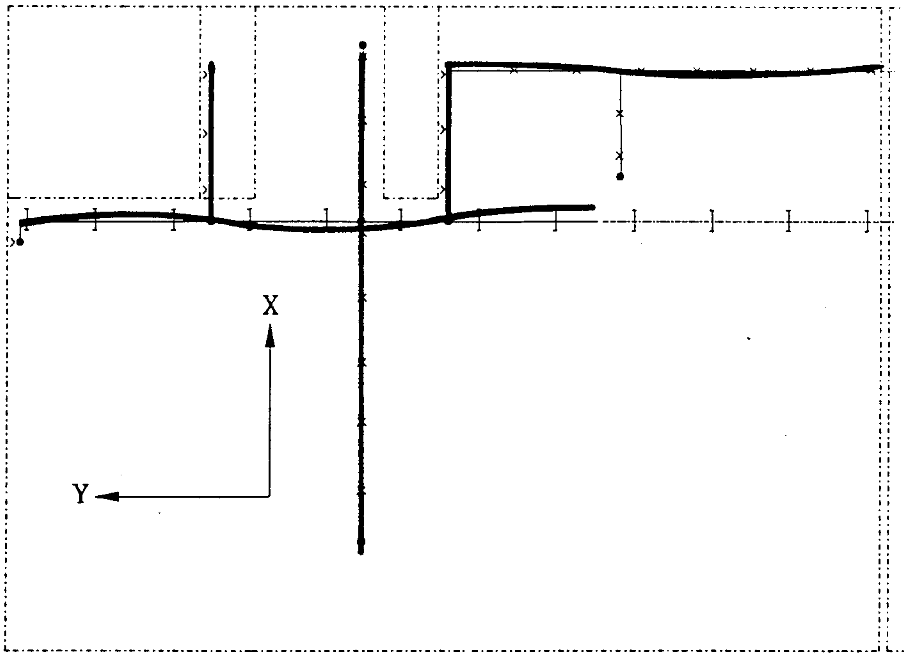


FIGURE C-7B SHAPE OF MODE NO. 6, 1.53 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

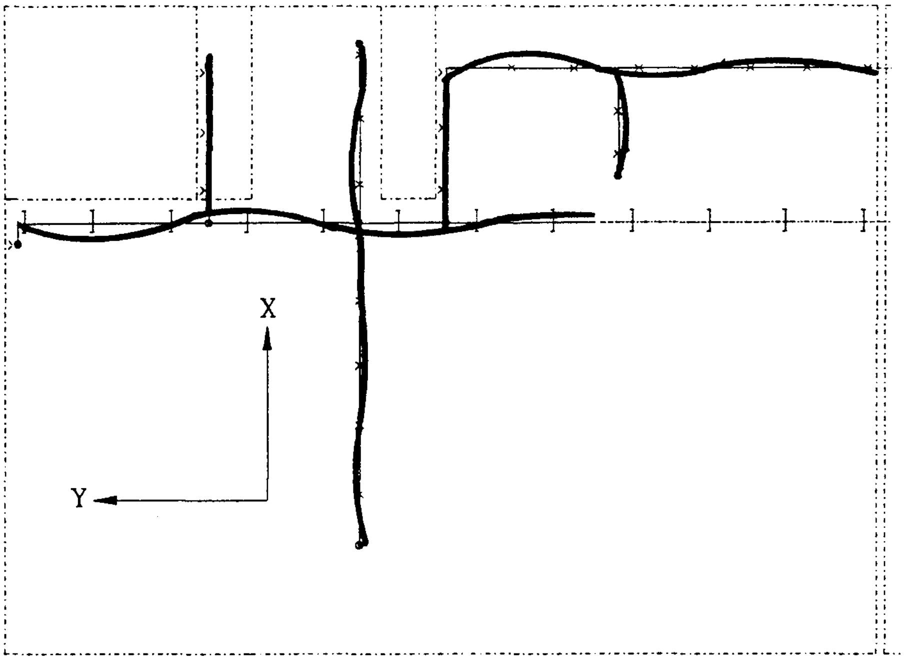


FIGURE C-7C SHAPE OF MODE NO. 13, 3.12 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

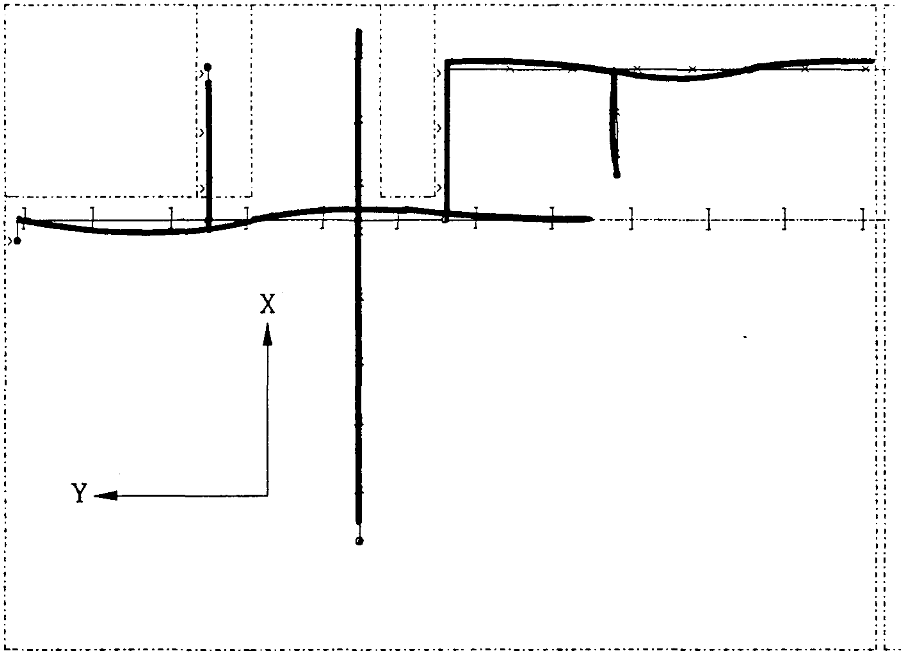


FIGURE C-7D SHAPE OF MODE NO. 7, 1.60 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

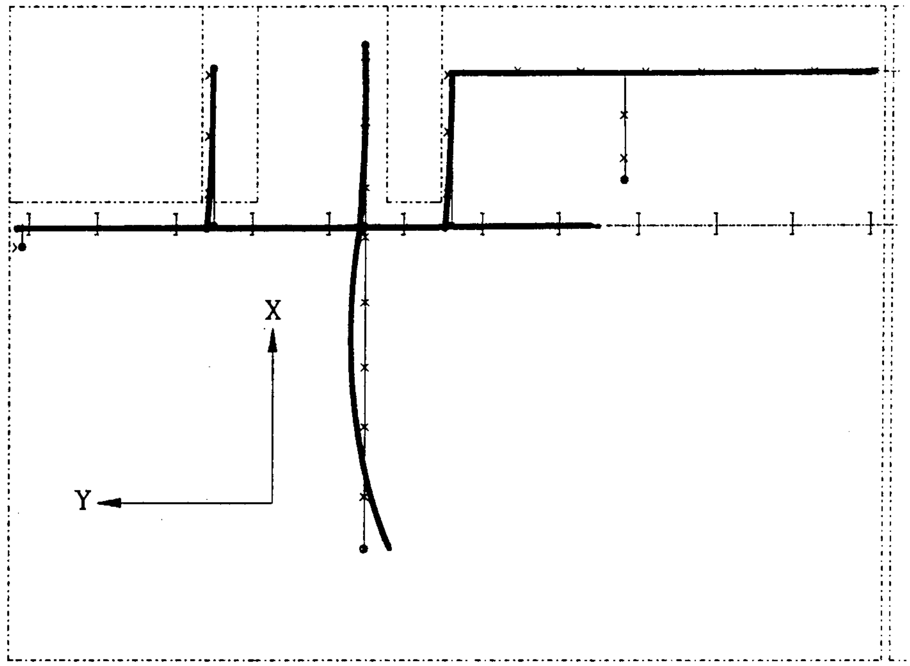


FIGURE C-7E SHAPE OF MODE NO. 3, 0.85 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

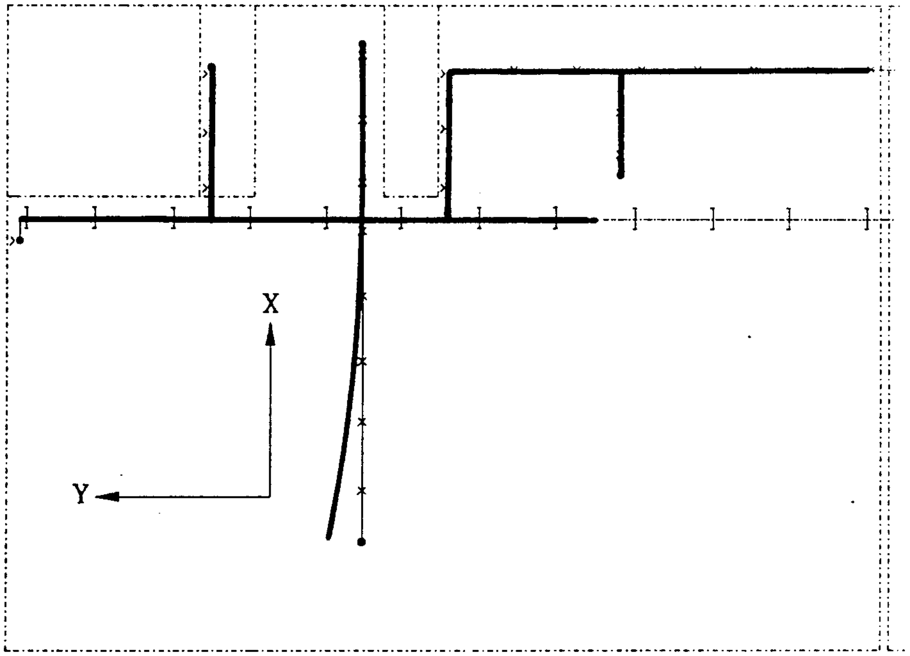


FIGURE C-7F SHAPE OF MODE NO. 1, 0.42 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

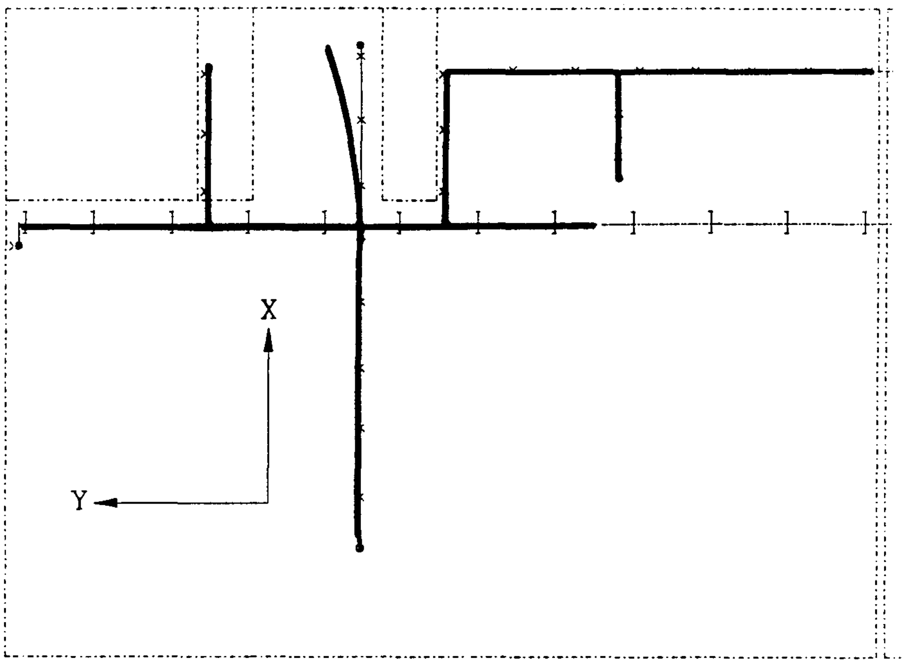


FIGURE C-7G SHAPE OF MODE NO. 5, 1.09 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

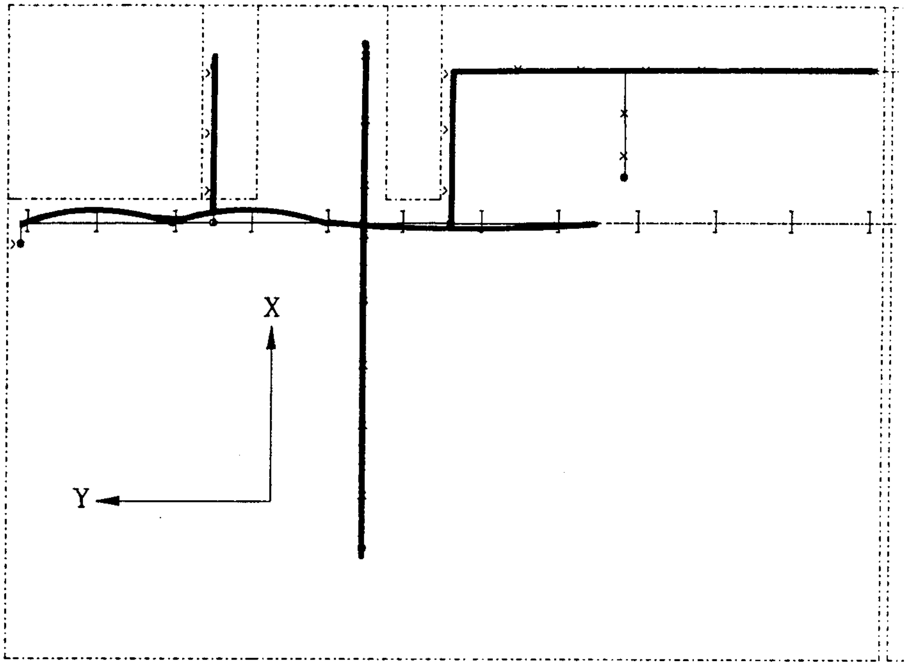


FIGURE C-8A SHAPE OF MODE NO. 9, 4.97 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

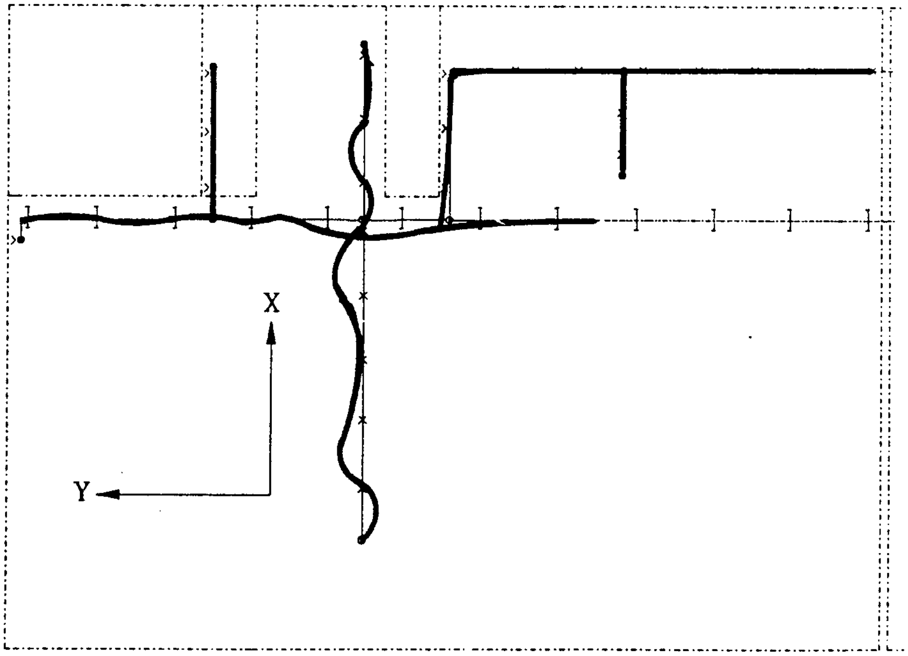


FIGURE C-8B SHAPE OF MODE NO. 18, 9.87 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

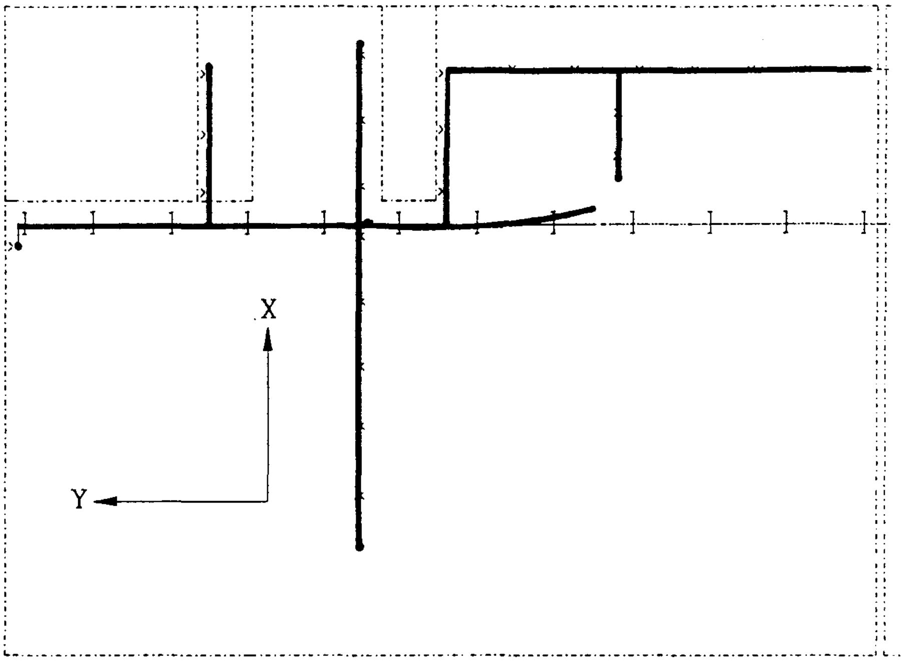


FIGURE C-8C SHAPE OF MODE NO. 8, 4.55 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

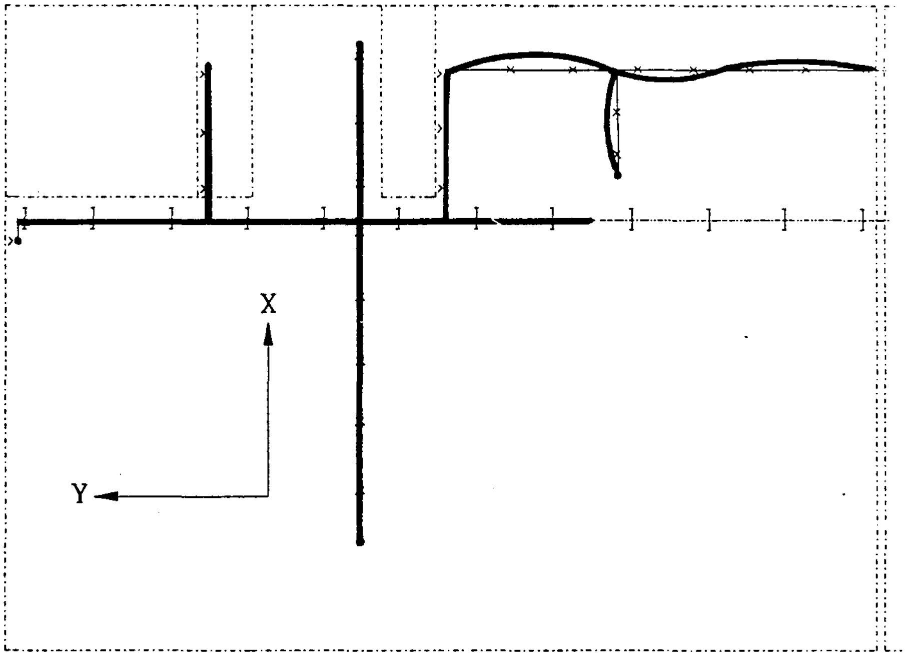


FIGURE C-8D SHAPE OF MODE NO. 1, 2.51 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

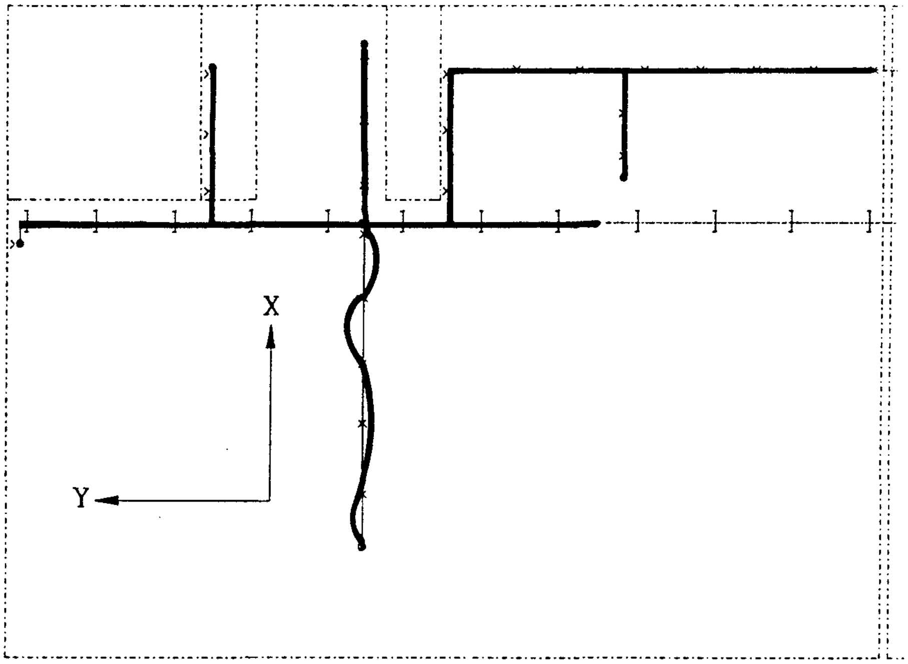


FIGURE C-8E SHAPE OF MODE NO. 19, 10.11 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

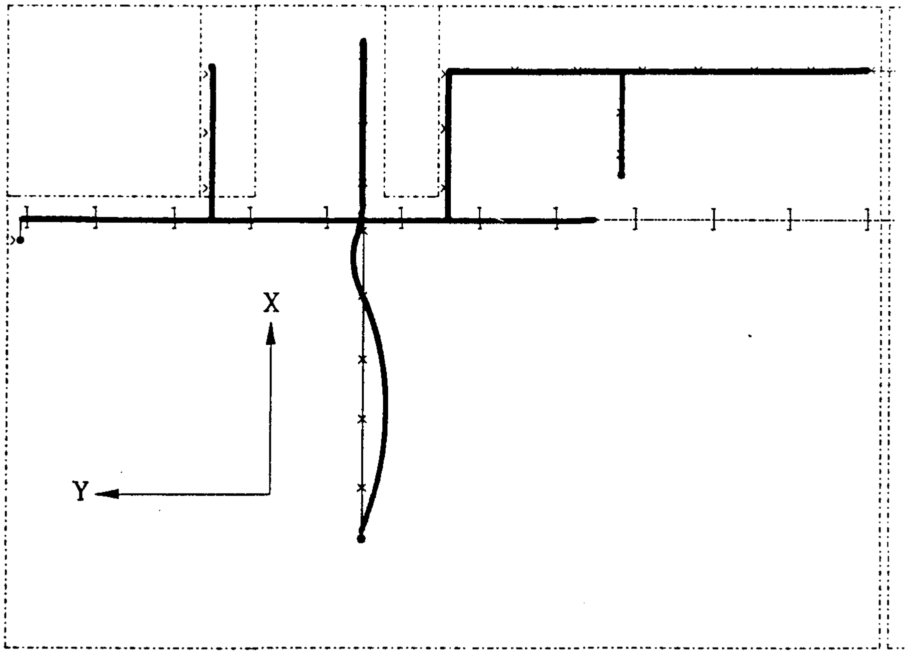


FIGURE C-8F SHAPE OF MODE NO. 6, 3.95 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

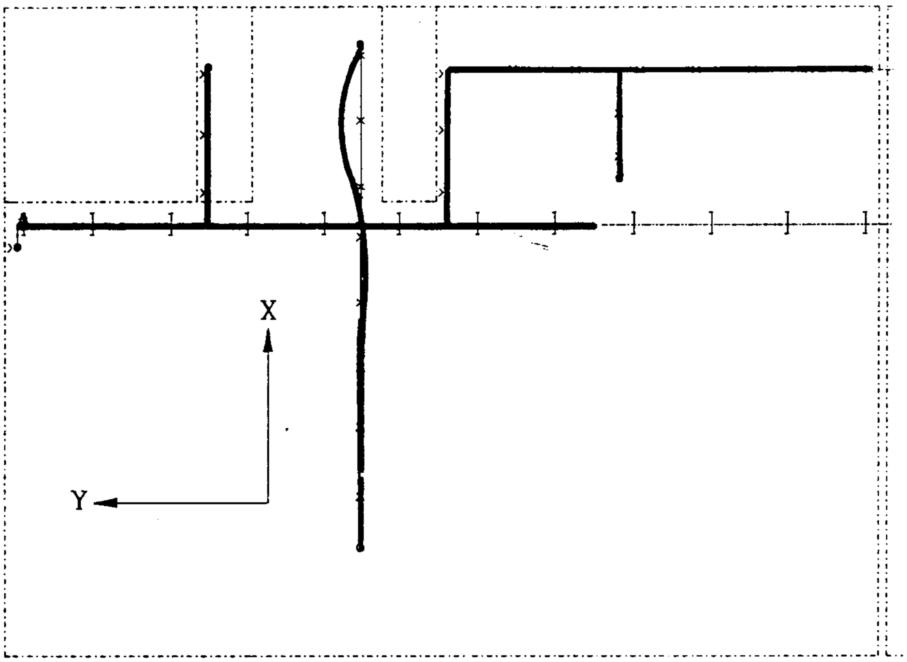


FIGURE C-8G SHAPE OF MODE NO. 3, 3.14 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

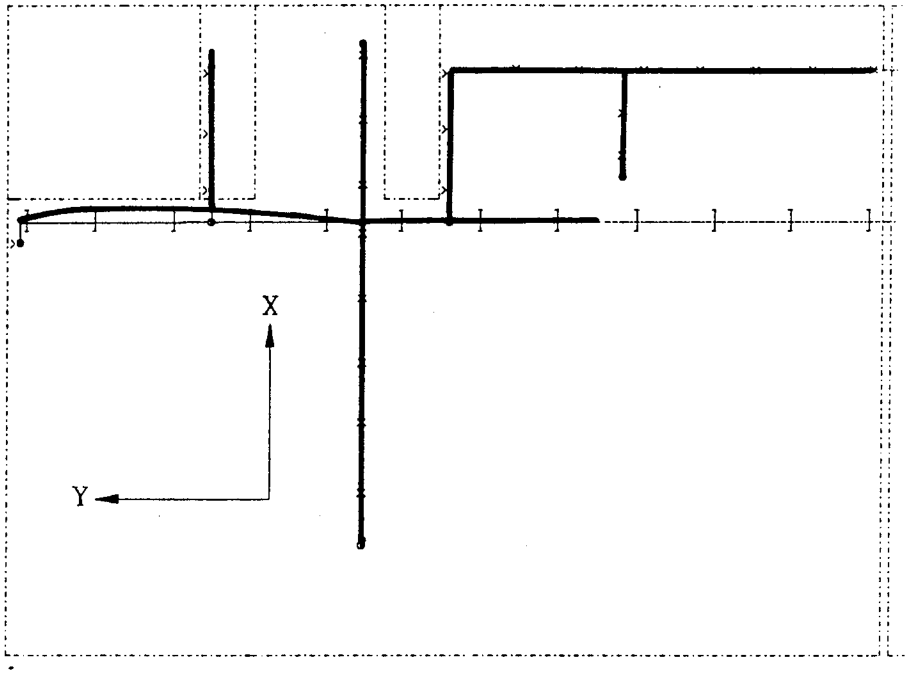


FIGURE C-9A SHAPE OF MODE NO. 27, 12.60 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

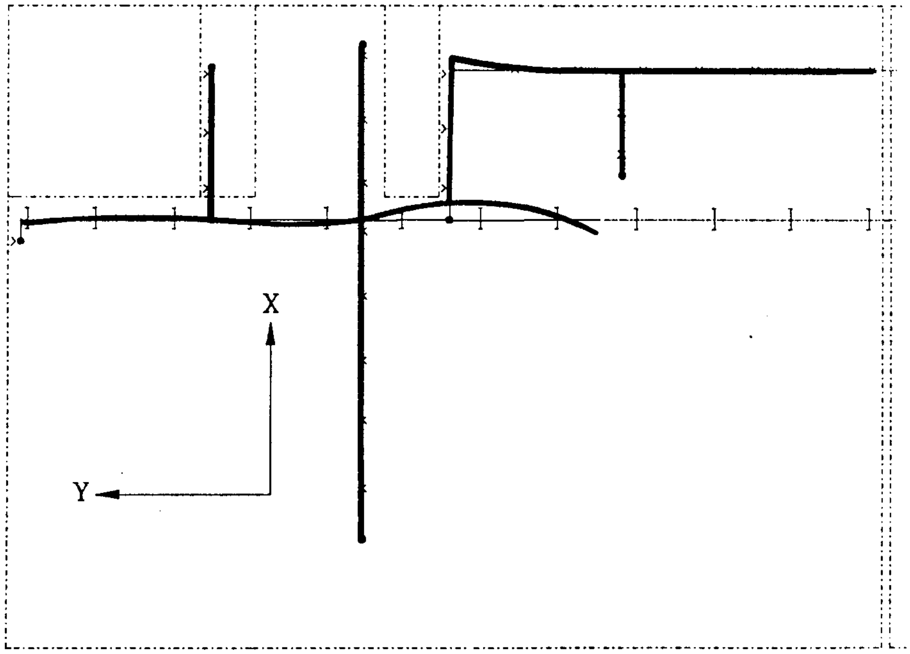


FIGURE C-9B SHAPE OF MODE NO. 35, 14.30 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

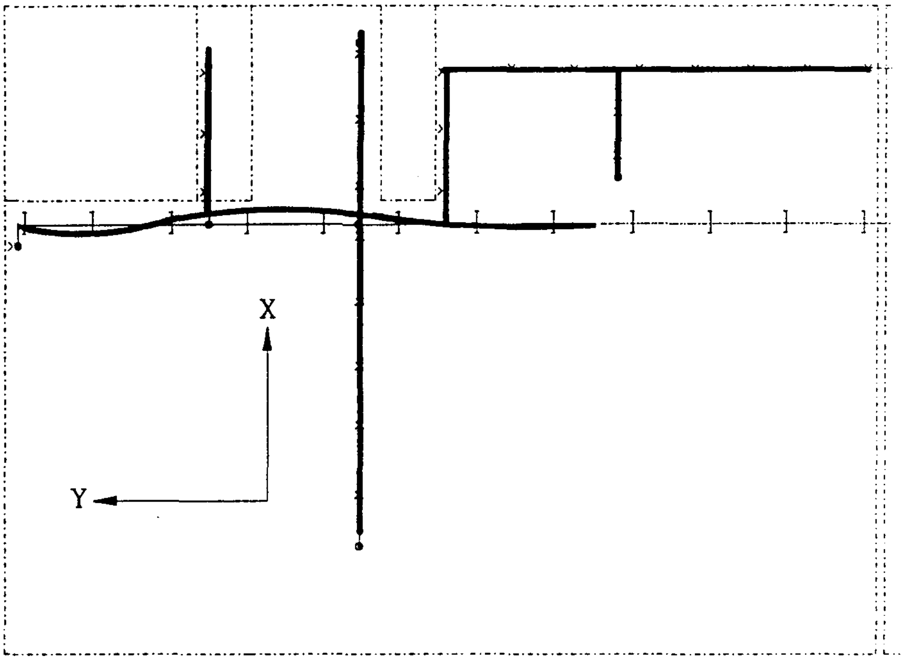


FIGURE C-9C SHAPE OF MODE NO. 26, 12.40 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

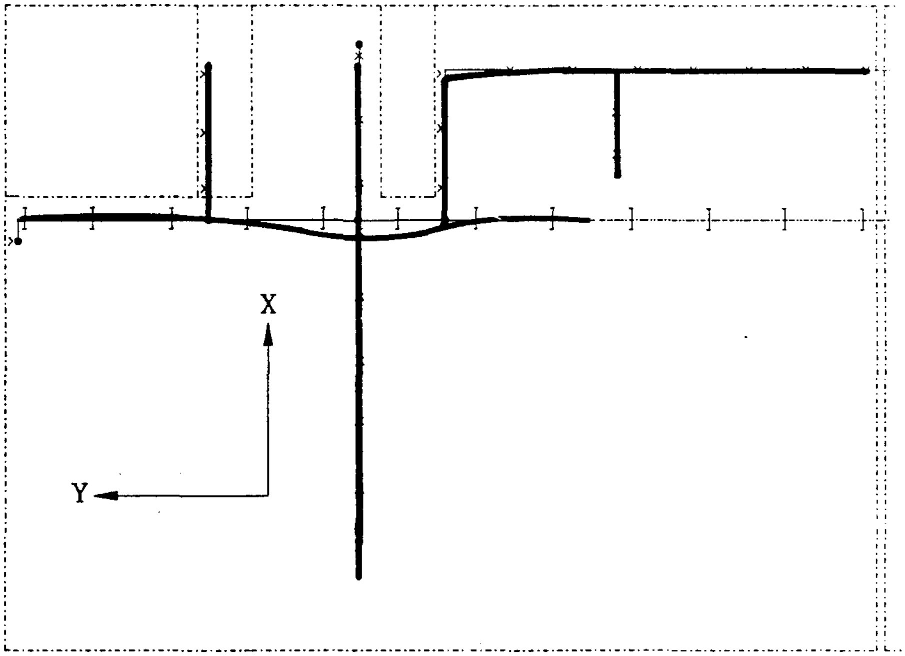


FIGURE C-9D SHAPE OF MODE NO. 31, 13.40 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

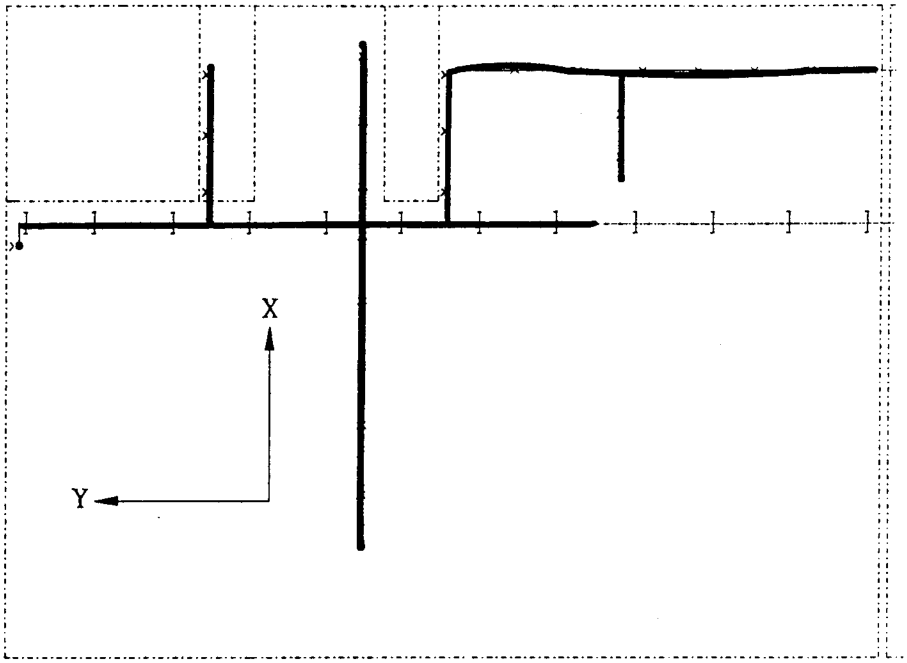


FIGURE C-9E SHAPE OF MODE NO. 28, 12.89 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

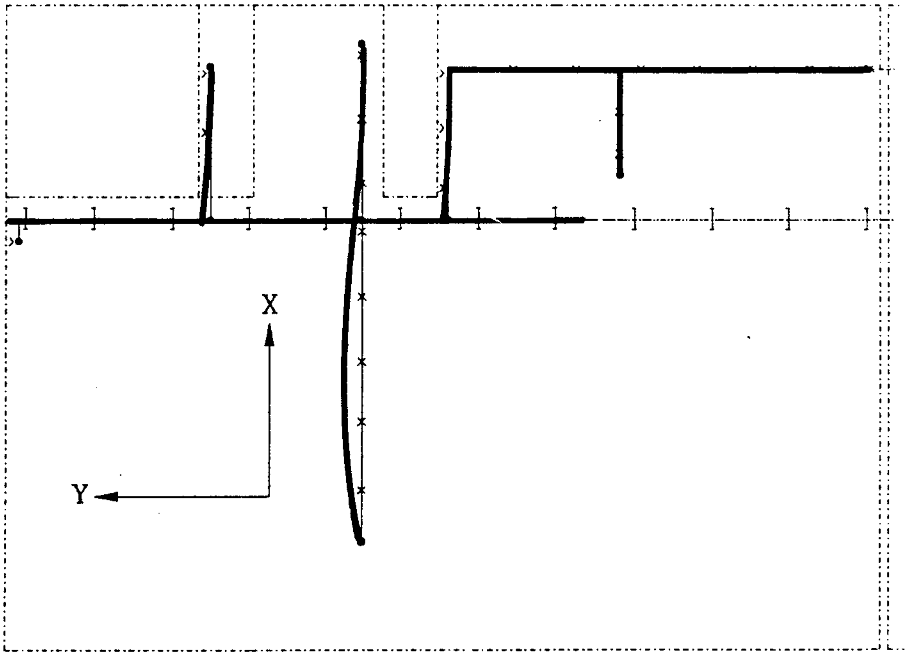


FIGURE C-9F SHAPE OF MODE NO. 22, 11.99 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

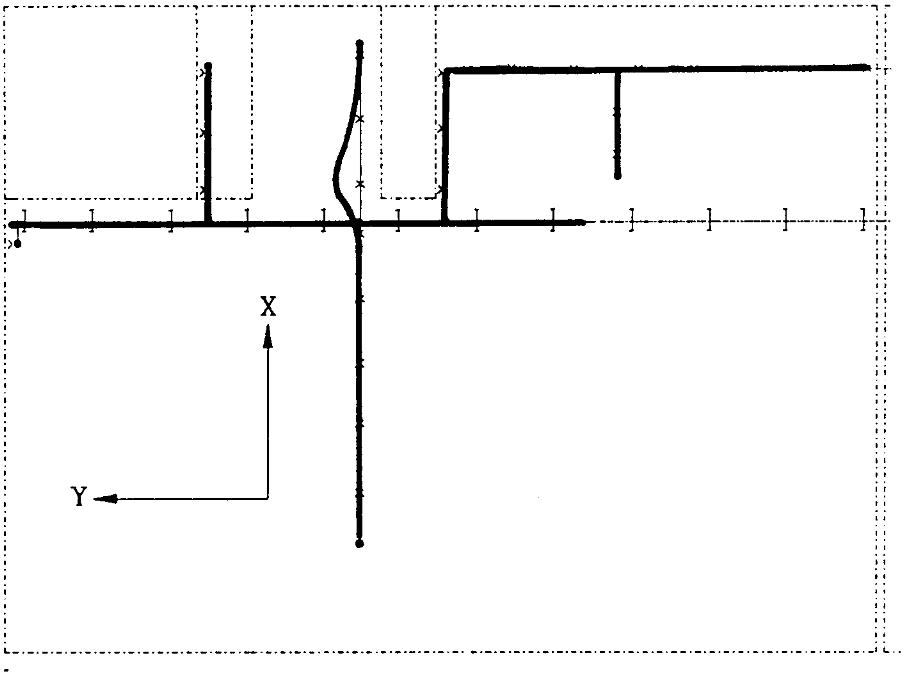


FIGURE C-9G SHAPE OF MODE NO. 29, 12.99 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

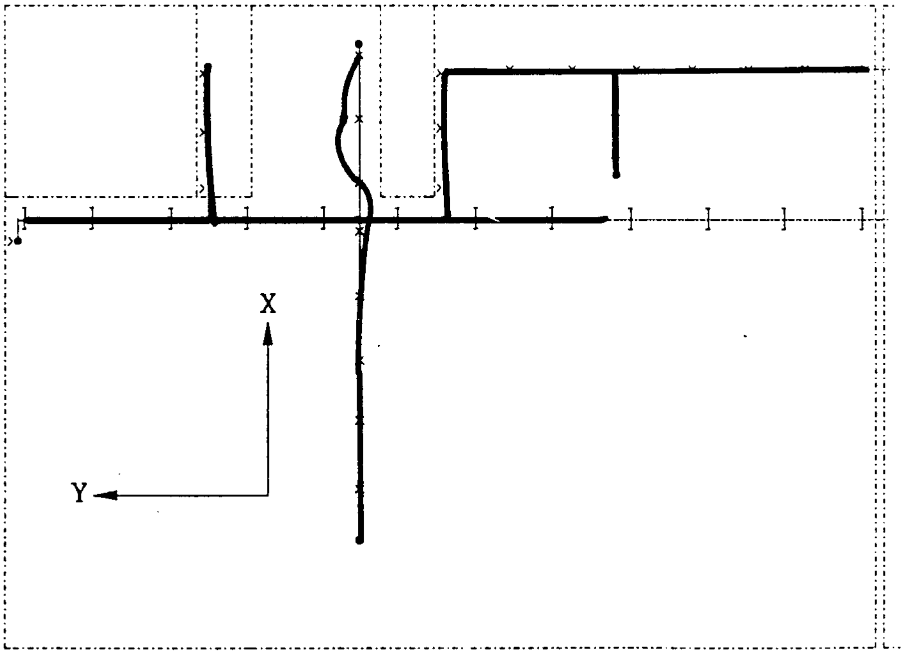


FIGURE C-9H SHAPE OF MODE NO. 17, 11.24 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

APPENDIX D

SEISMIC ANALYSIS OF A COMPLEX PVC PIPING SYSTEM WITH VARIOUS LATERAL-BRACING SCHEMES

D.1 Purpose and Objectives

The purpose of the work contained in Appendix D is to examine the seismic response of a complex, PVC piping system with various lateral-bracing schemes. The PVC piping system examined has segments of various diameters, is supported by trapeze hangers, rod hangers of various lengths, or wall-mounted supports, and is representative of piping configurations commonly found at industrial facilities. The intent of modeling a large, complex system is to examine response for a variety of conditions which have the potential to generate excessive seismic stresses.

The objectives of Appendix D are summarized below:

1. Examine peak bending stresses at selected locations on the piping system model for four different bracing schemes and four different seismic environments.

2. Compare and contrast peak piping system bending stress for the following four seismic bracing schemes:

    a. Unbraced System (UB) - this scheme has only vertical supports.

    b. Longitudinal Bracing Only (LB) - this scheme has longitudinal braces installed parallel to the pipe axis, but does not have any transverse bracing.

c. Longitudinal plus Transverse Bracing (LTB1) - this scheme has longitudinal braces, as described above, plus transverse braces at every other vertical support.

d. Longitudinal plus Transverse System (LTB2) - this system has longitudinal braces as in system LTB1, plus transverse braces at every gravity support.

3. Compare and contrast peak piping system bending stress for the following four seismic environments:

   a. Upper-floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 7 (0.4g EPGA).

   b. Ground motion corresponding to NEHRP/ATC-3 Map Area No. 7 (0.4g EPGA).

   c. Upper-floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 5 (0.2g EPGA).

   d. Ground motion corresponding to NEHRP/ATC-3 Map Area No. 5 (0.2g EPGA).

D.2 Description of the Models

The basic piping system model and the four bracing schemes are described in the following sections.

D.2.1 PVC Piping System Model

Figure D-1 shows the basic Schedule 80 PVC piping system, in plan view, and its location in a typical industrial building. The piping system layout and pipe diameter is identical to the basic Schedule 40 steel model described in Section C.2.1, except that vertical supports for the PVC system are installed twice as often as the steel system. This spacing conforms, approximately, to the spacing of vertical supports required by ASME 31.9 [Ref. 23] for Schedule 80 PVC pipe.

D.2.2 Seismic Bracing Schemes

Figure D-2, D-3, D-4 and D-5 show the PVC piping system with the unbraced (UB) scheme, the longitudinally-braced (LB) scheme, and the longitudinally and transversely-braced (LTB1 and LTB2) schemes, respectively. The approach for bracing the PVC piping system is identical to that used for steel (i.e., see Section C.2.2), except that approximately twice as many braces are used since there are twice as many gravity supports.

D.3 Description of Analyses

The analyses of the PVC piping systems are identical to those performed for the steel piping system (i.e., see Section C.3).

D.4 Summary of Results

D.4.1 Modal Analyses

The results of the modal analyses are summarized in Table D-1 for each of the four bracing schemes, and plots of the shapes of dominant modes (i.e., modes with significant participation) are shown in Figures D-6 through D-9, respectively.

The observations on the modal behavior of the steel piping system (i.e., see Section C.4.1) are generally applicable to the PVC piping system for each bracing scheme.

D.4.2 Response Spectrum Analyses

The results of the response spectrum analyses are summarized in Tables D-2 through D-5, respectively, for each of the four seismic environments (i.e., 0.4g EPGA upper-floor spectrum, 0.4g EPGA ground floor spectrum, 0.2g EPGA upper-floor spectrum. 0.2g ground floor spectrum). For the purpose of assessing acceptable response, peak bending stress should not exceed 1.0 ksi for Category A piping and 2.5 ksi for Category B piping (i.e., based on the criteria of Section 3.6 and the allowables of ASME B31.9 for ASTM D1785 PVC pipe at 73°F).

The observations on the stress behavior of the steel piping system (Section C.4.2) are generally applicable to the PVC piping system for each bracing system.

In summary, the selection of the type and spacing of seismic braces to achieve specified limits on PVC pipe stress is entirely related to the seismic environment and the level of stress permitted in the pipe. In general it can be stated:

1. Longitudinal braces on most runs and transverse braces at every gravity support are required, in general, for lateral restraint of hazardous (Category A) PVC piping systems in high seismic environments (e.g., EPGA's greater than 0.2g). In some cases, transverse braces at every other gravity support may be sufficient; however, PVC piping with connections susceptible to bending-induced failure require transverse braces at every gravity support.

2. PVC piping systems are inherently weaker and more flexible than steel piping system and, in general, require both longitudinal and transverse bracing to protect piping segments (e.g., short risers) at intersections of orthogonal lines or other points of stiffness or geometric irregularity.

3. Standard seismic bracing guidelines (e.g., SMACNA [Ref. 23]) may not provide the level of protection necessary for piping systems containing hazardous (Category A) materials.

TABLE D-1

SUMMARY OF MODAL ANALYSIS RESULTS FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS LATERAL BRACING SCHEMES

Direction/ Dominant Mode[1]	Unbraced (UB) System			Longitudinally-Braced (LB) System		
	Mode No.	Frequency (Hz)	Partici- pation[2]	Mode No.	Frequency (Hz)	Partici- pation[2]
X 1st	1	0.34	47.8	1	0.37	41.5
X 2nd	8	0.83	14.0	4	0.56	10.8
X 3rd	5	0.55	8.6	29	2.90	9.1
X 4th	7	0.65	7.8	25	2.55	7.1
X 5th	26	2.30	4.3	23	2.30	3.7
X RIGID		>20	17.5		>20	27.8
Y 1st	7	0.65	40.4	2	0.38	3.7
Y 2nd	8	0.83	16.5	9	0.95	2.2
Y 3rd	5	0.55	13.4			
Y 4th	4	0.46	8.5			
Y 5th	2	0.38	3.6			
Y RIGID		>20	17.6		>20	94.1

Direction Dominant Mode[1]	Long./Tranversely-Braced (LTB1) System			Long./Tranversely-Braced (LTB2) System		
	Mode No.	Frequency (Hz)	Partici- pation[2]	Mode No.	Frequency (Hz)	Partici- pation[2]
X 1st	24	4.22	39.0	10	14.20	29.6
X 2nd	45	15.00	4.8	23	14.40	10.4
X 3rd	28	12.20	7.1	7	14.16	10.1
X 4th	27	10.90	5.0	18	14.25	9.4
X 5th	23	4.03	4.4	26	14.50	8.0
X RIGID		>20	39.7		>20	32.5
Y 1st	19	3.54	2.2	5	14.15	3.4
Y 2nd	41	14.60	1.5	13	14.20	2.0
Y 3rd	18	3.50	1.4			
Y 4th						
Y 5th						
Y RIGID		>20	94.9		>20	94.6

1. A dominant mode is defined as having at least 1% participation in the direction under consideration.

2. Participation is defined as the percentage of total mass acting in the direction under consideration.

TABLE D-2

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	0.72	1.00	0.94	0.02
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	2.20	0.48	0.34	0.44
3	3" Diameter Branch Line (on Long Rod Hangers)	0.58	0.55	1.20	0.01
4	3" Diameter Riser (from 1 to 3)	2.80	5.20	0.80	0.16
5	3" Diameter Branch Line (on Short Rod Hangers)	0.67	1.70	1.10	0.01
6	3" Diameter Riser (from 1 to 5)	0.94	3.90	0.69	0.16
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	1.20	1.40	0.14	0.20
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	1.20	0.54	0.96	0.01
9	1" Diameter Feeder Line and Riser to Equipment	5.10	4.00	0.99	0.01
10	2" Diameter Branch Line (on Short Rod Hangers)	1.00	0.83	1.30	0.95

1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73°F is 1.0 ksi (i.e. ASME B31.9, Ref. 20).

TABLE D-3

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO VIBRATORY GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	**Description**				
1	6" Diameter Main Line (on Trapeze Hangers)	0.57	0.33	0.30	0.01
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	2.10	0.23	0.18	0.06
3	3" Diameter Branch Line (on Long Rod Hangers)	0.52	0.27	0.40	0.01
4	3" Diameter Riser (from 1 to 3)	1.20	1.60	0.28	0.10
5	3" Diameter Branch Line (on Short Rod Hangers)	0.52	0.61	0.36	0.02
6	3" Diameter Riser (from 1 to 5)	0.52	1.30	0.25	0.10
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	0.67	0.47	0.06	0.02
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	0.48	0.26	0.32	0.01
9	1" Diameter Feeder Line and Riser to Equipment	1.80	1.40	0.32	0.01
10	2" Diameter Branch Line (on Short Rod Hangers)	0.51	0.40	0.41	0.32

1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73^{o}F is 1.0 ksi (i.e. ASME B31.9, Ref. 20).

TABLE D-4

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 5

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	0.40	0.64	0.57	0.01
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	1.17	0.30	0.21	0.28
3	3" Diameter Branch Line (on Long Rod Hangers)	0.31	0.34	0.73	0.01
4	3" Diameter Riser (from 1 to 3)	1.68	3.29	0.49	0.10
5	3" Diameter Branch Line (on Short Rod Hangers)	0.41	1.15	0.65	0.01
6	3" Diameter Riser (from 1 to 5)	0.56	2.47	0.42	0.10
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	0.71	0.90	0.08	0.02
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	0.71	0.33	0.59	0.01
9	1" Diameter Feeder Line and Riser to Equipment	3.10	2.41	0.60	0.01
10	2" Diameter Branch Line (on Short Rod Hangers)	0.60	0.50	0.76	0.59

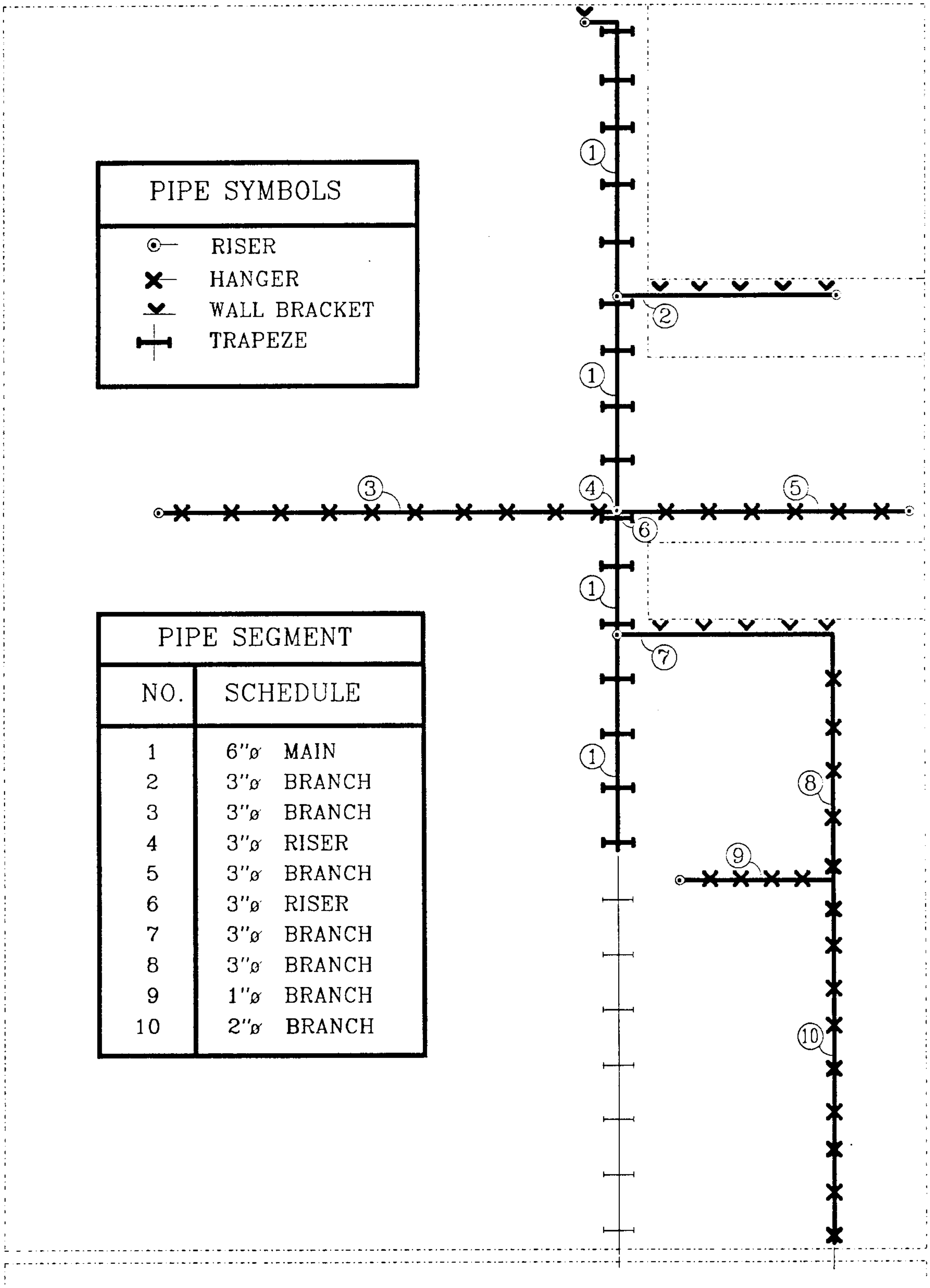
1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73^{o}F is 1.0 ksi (i.e. ASME B31.9, Ref. 20).

TABLE D-5

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR A COMPLEX PVC PIPING SYSTEM WITH VARIOUS BRACING SCHEMES SUBJECTED TO VIBRATORY GROUND MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 5

Piping Segment (Support Type)		UB System Stress[1]	LB System Stress[1]	LTB1 System Stress[1]	LTB2 System Stress[1]
No.	Description				
1	6" Diameter Main Line (on Trapeze Hangers)	0.28	0.16	0.15	0.01
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	1.07	0.11	0.09	0.12
3	3" Diameter Branch Line (on Long Rod Hangers)	0.26	0.14	0.20	0.01
4	3" Diameter Riser (from 1 to 3)	0.62	0.80	0.14	0.05
5	3" Diameter Branch Line (on Short Rod Hangers)	0.13	0.31	0.18	0.01
6	3" Diameter Riser (from 1 to 5)	0.26	0.67	0.13	0.05
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	0.34	0.23	0.03	0.01
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	0.24	0.16	0.16	0.01
9	1" Diameter Feeder Line and Riser to Equipment	0.90	0.68	0.16	0.01
10	2" Diameter Branch Line (on Short Rod Hangers)	0.26	0.20	0.20	0.16

1. Allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73°F is 1.0 ksi (i.e. ASME B31.9, Ref. 20).



PIPE SEGMENT

NO.	SCHEDULE
1	6"ø MAIN
2	3"ø BRANCH
3	3"ø BRANCH
4	3"ø RISER
5	3"ø BRANCH
6	3"ø RISER
7	3"ø BRANCH
8	3"ø BRANCH
9	1"ø BRANCH
10	2"ø BRANCH

FIGURE D-1 BASIC SCHEDULE 80 PVC PIPING SYSTEM MODEL, PLAN VIEW.

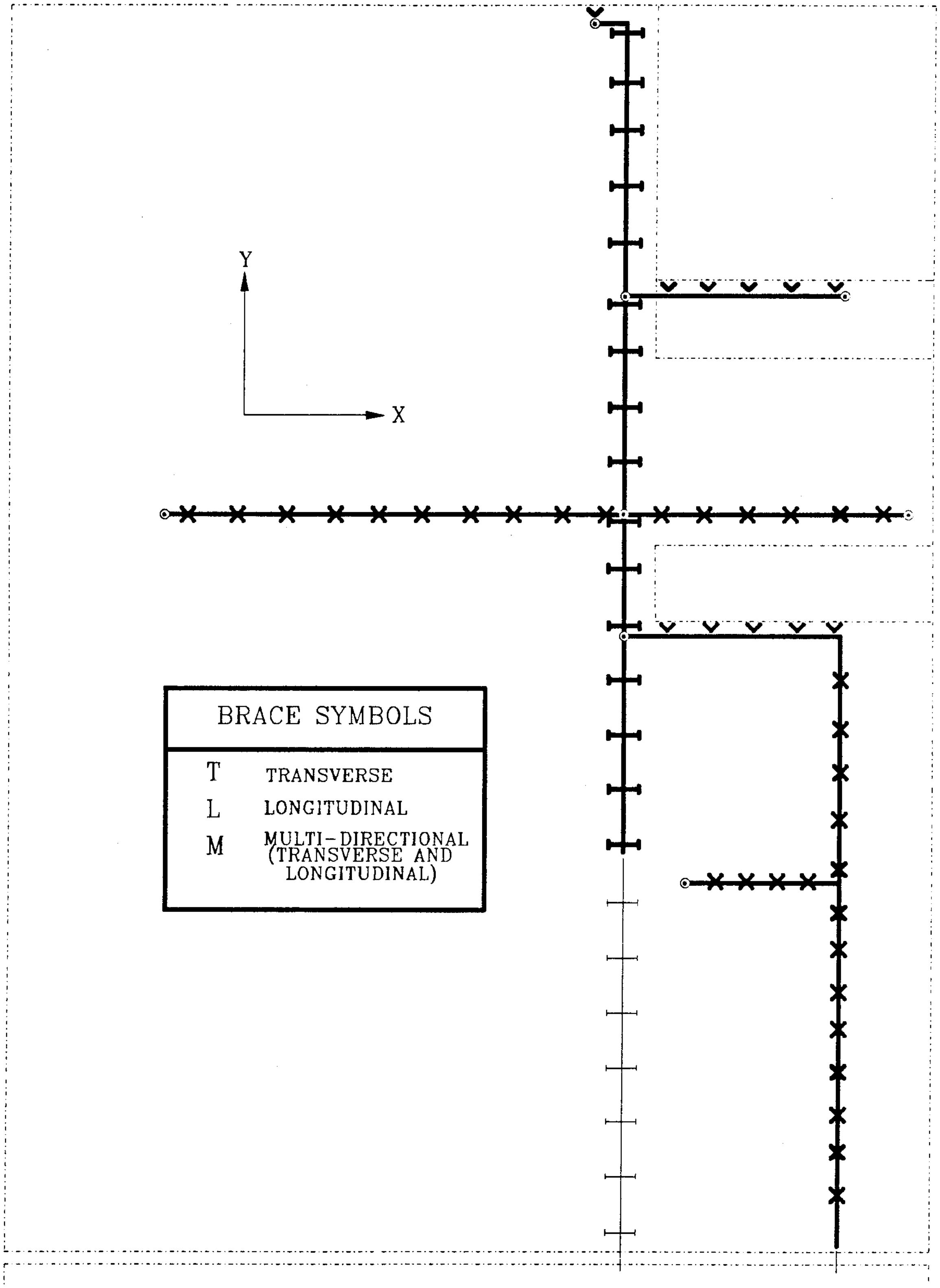


FIGURE D-2 UNBRACED SCHEDULE 80 PVC PIPING SYSTEM (UB).

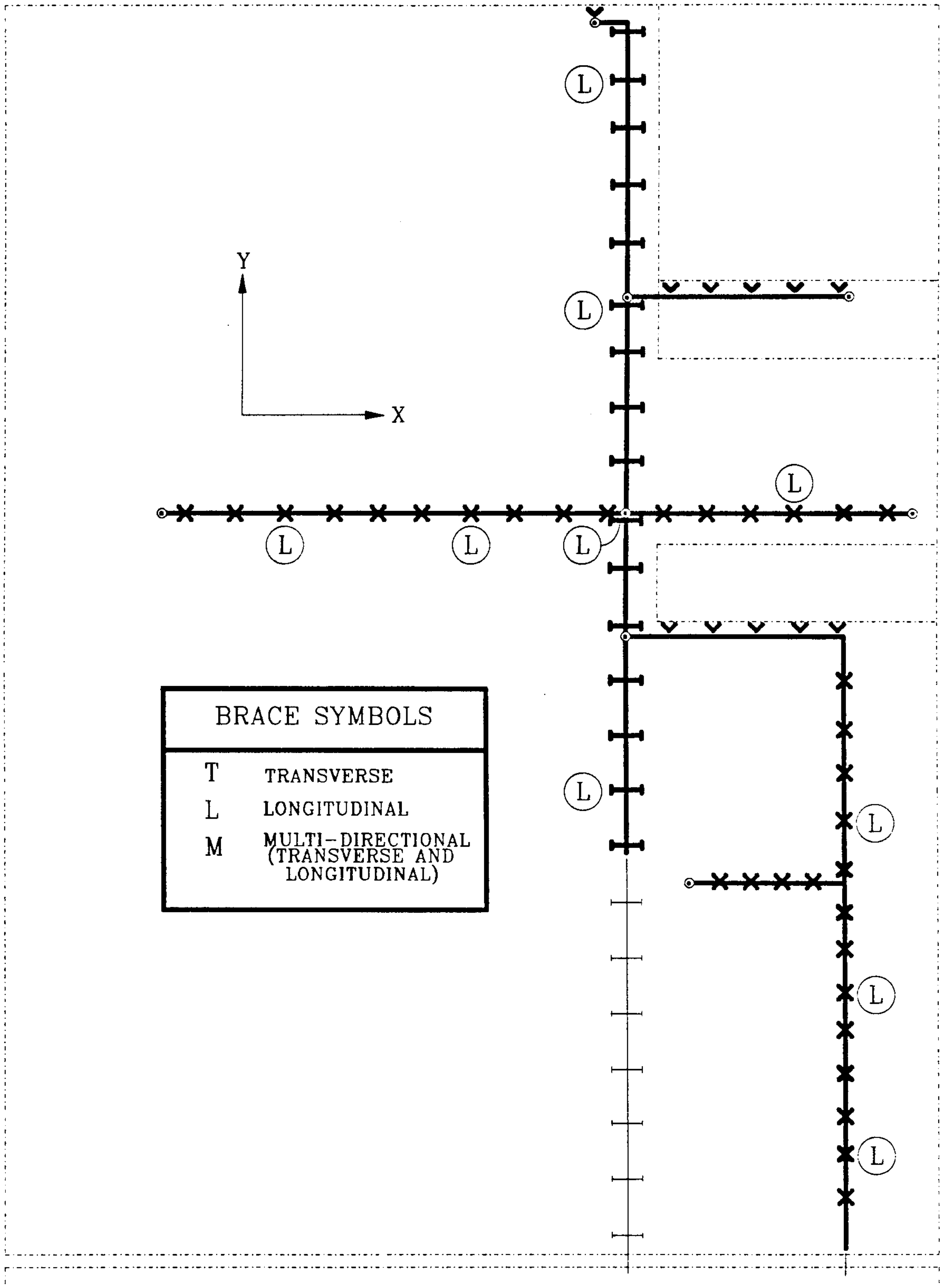


FIGURE D-3 LONGITUDINALLY-BRACED SCHEDULE 80 PVC PIPING SYSTEM (LB).

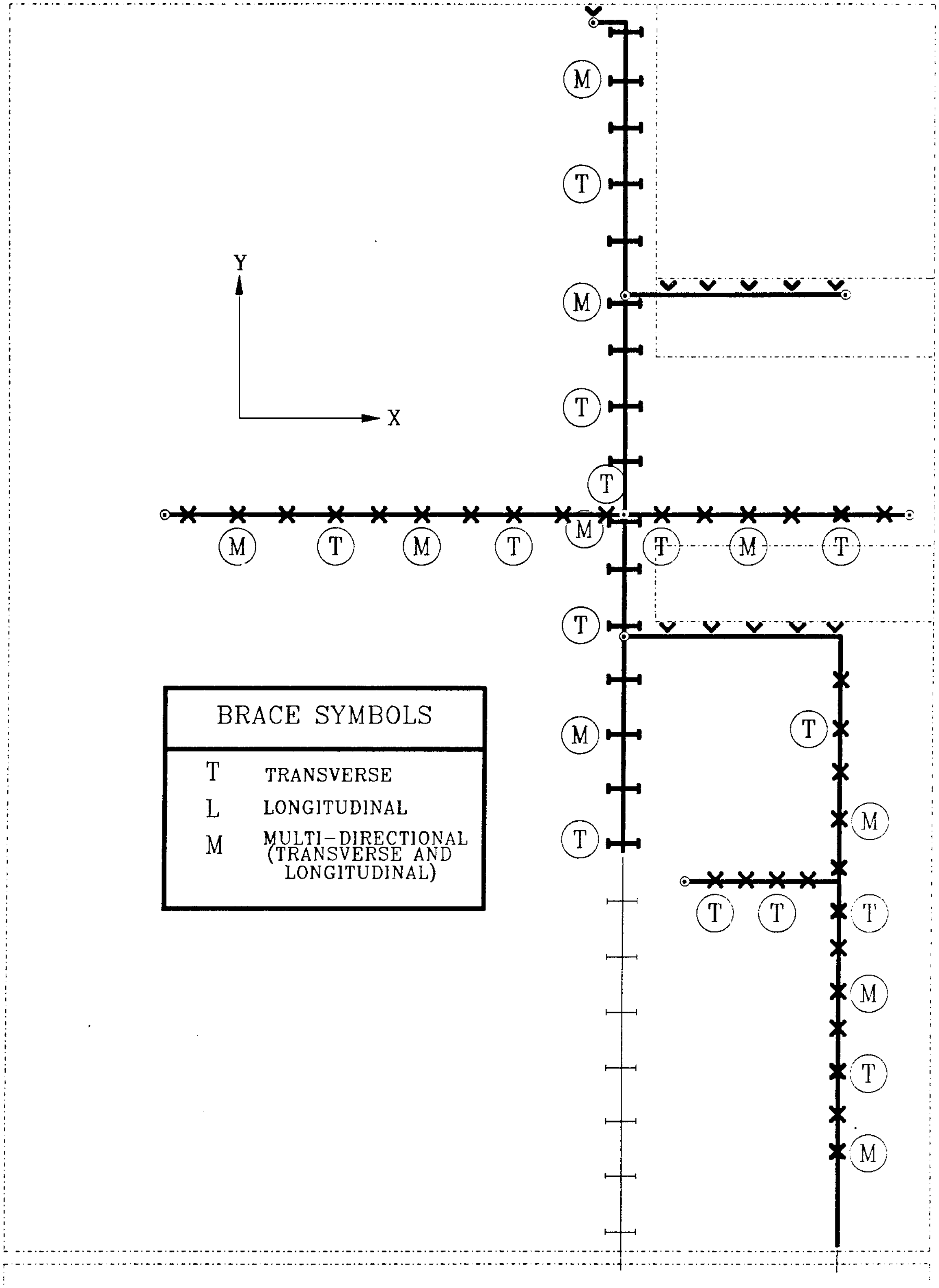


FIGURE D-4 LONGITUDINAL AND TRANSVERSELY-BRACED SCHEDULE 80 PVC PIPING SYSTEM (LTB1).

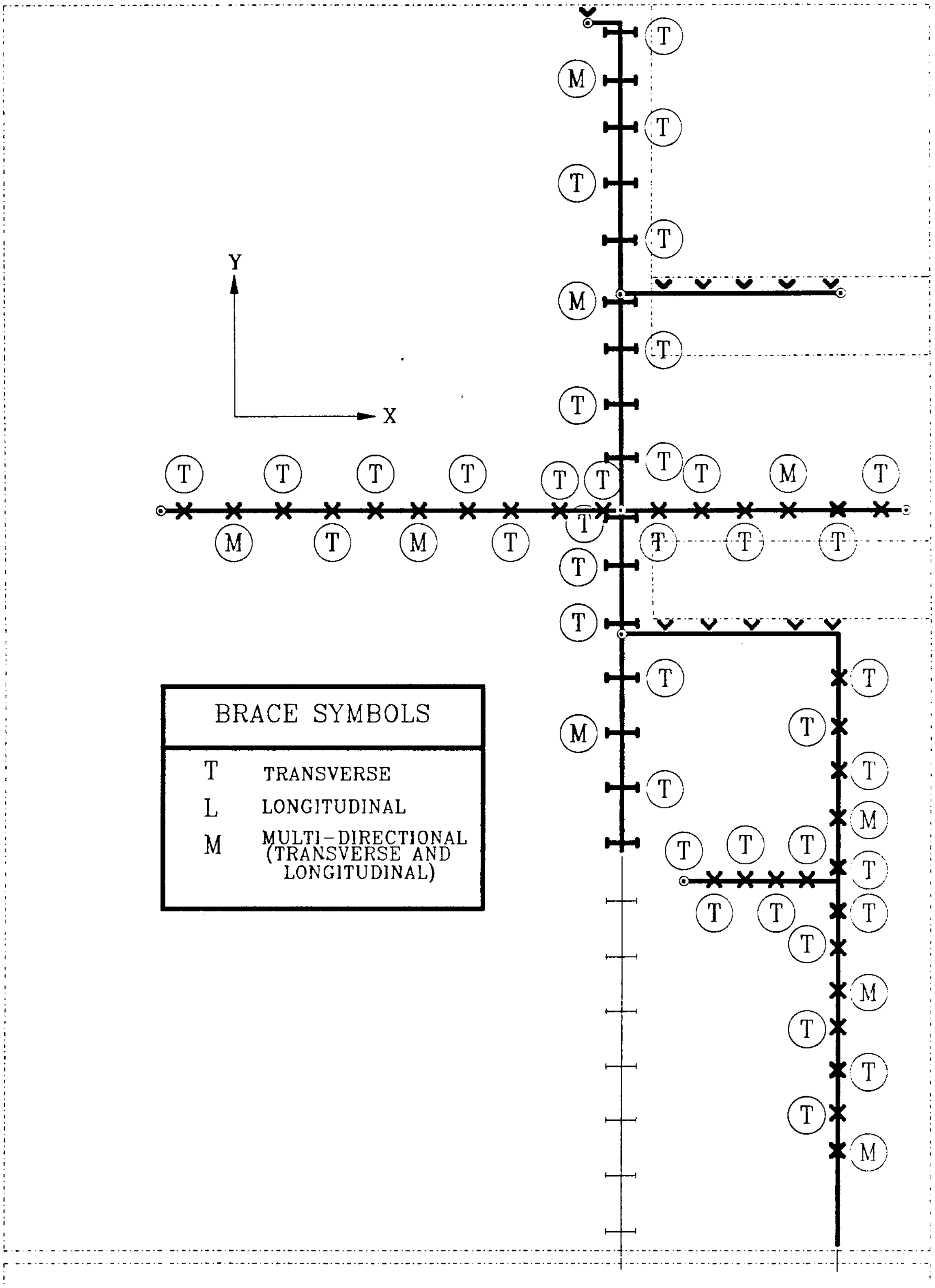


FIGURE D-5 LONGITUDINALLY AND TRANSVERSELY-BRACED SCHEDULE 80 PVC PIPING SYSTEM (LTB2).

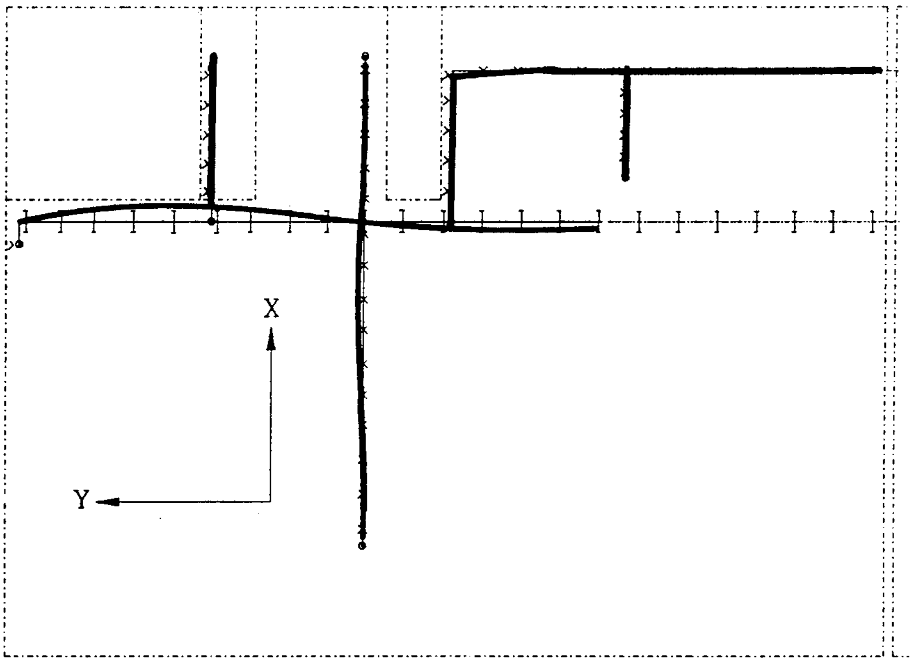


FIGURE D-6A SHAPE OF MODE NO. 1, 0.34 Hz, UNBRACED SYSTEM (UB).

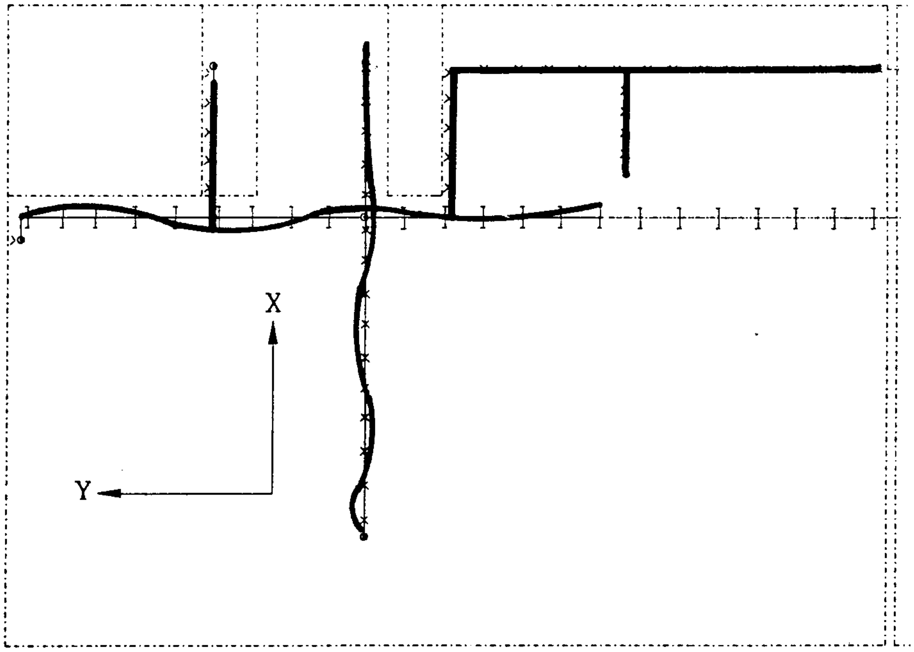


FIGURE D-6B SHAPE OF MODE NO. 8, 0.83 Hz, UNBRACED SYSTEM (UB).

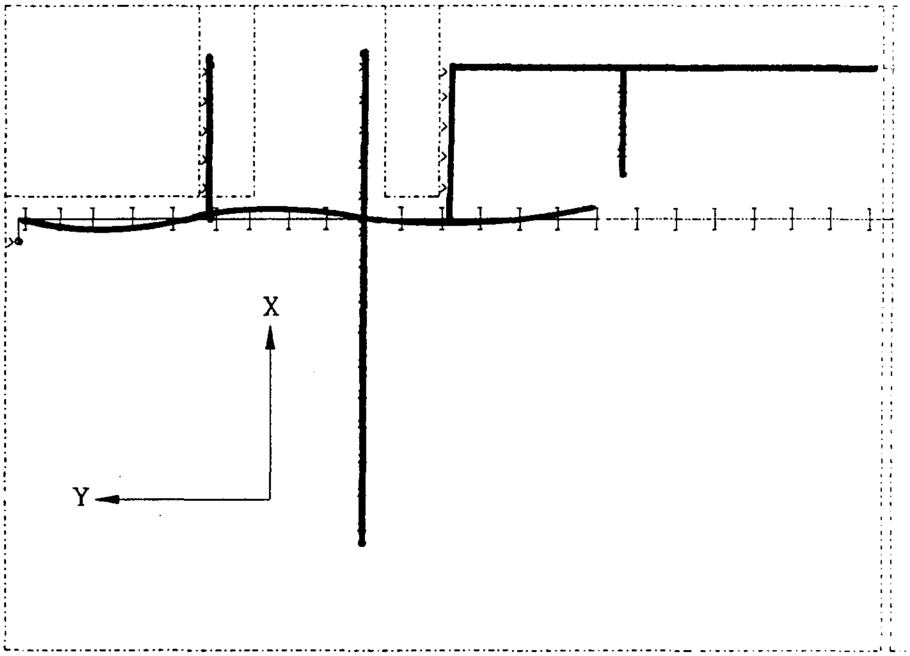


FIGURE D-6C SHAPE OF MODE NO. 5, 0.55 Hz, UNBRACED SYSTEM (UB).

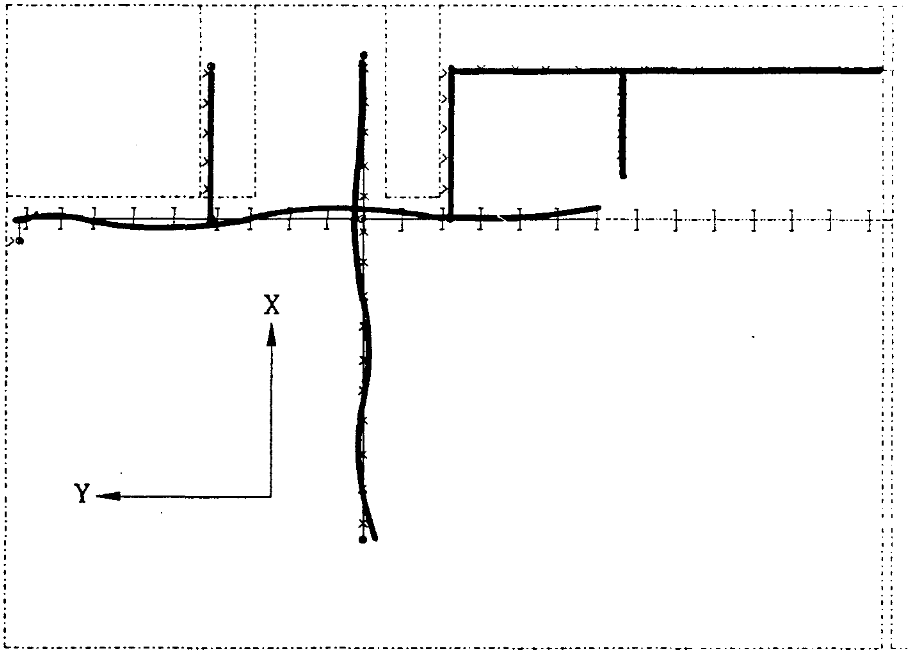


FIGURE D-6D SHAPE OF MODE NO. 7, 0.65 Hz, UNBRACED SYSTEM (UB).

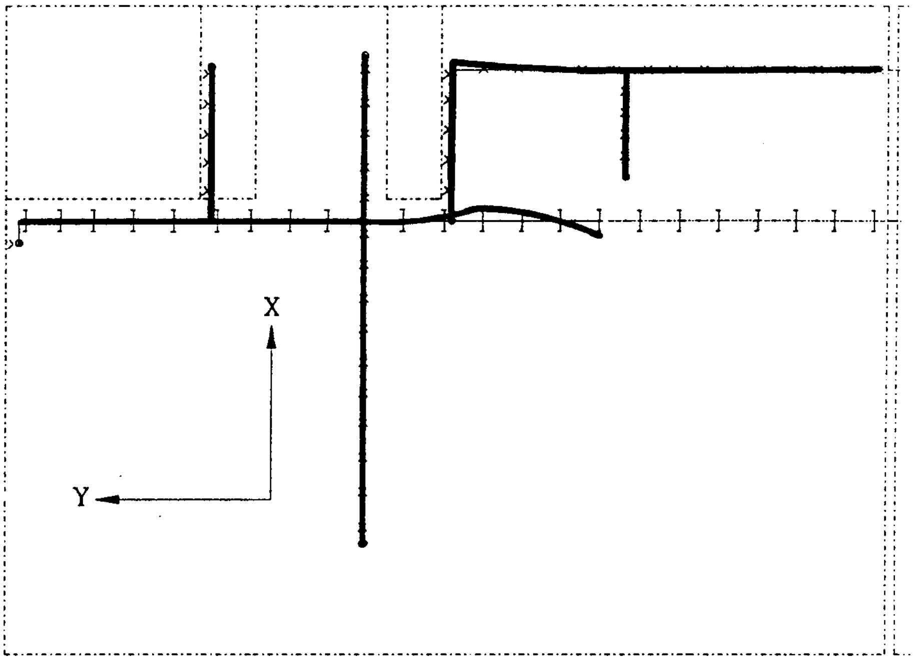


FIGURE D-6E SHAPE OF MODE NO. 26, 2.30 Hz, UNBRACED SYSTEM (UB).

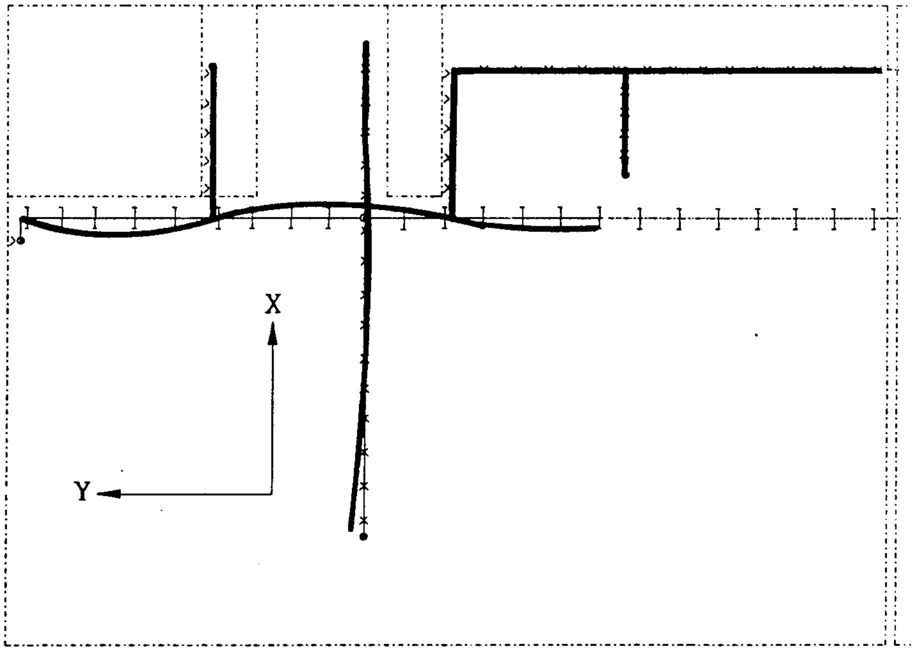


FIGURE D-6F SHAPE OF MODE NO. 4, 0.46 Hz, UNBRACED SYSTEM (UB).

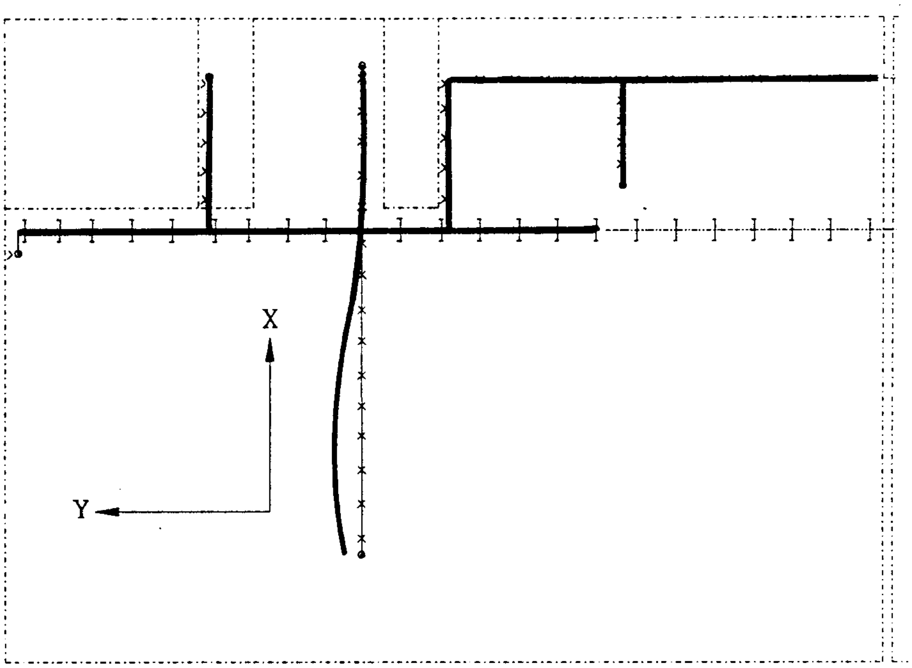


FIGURE D-6G SHAPE OF MODE NO. 2, 0.38 Hz, UNBRACED SYSTEM (UB).

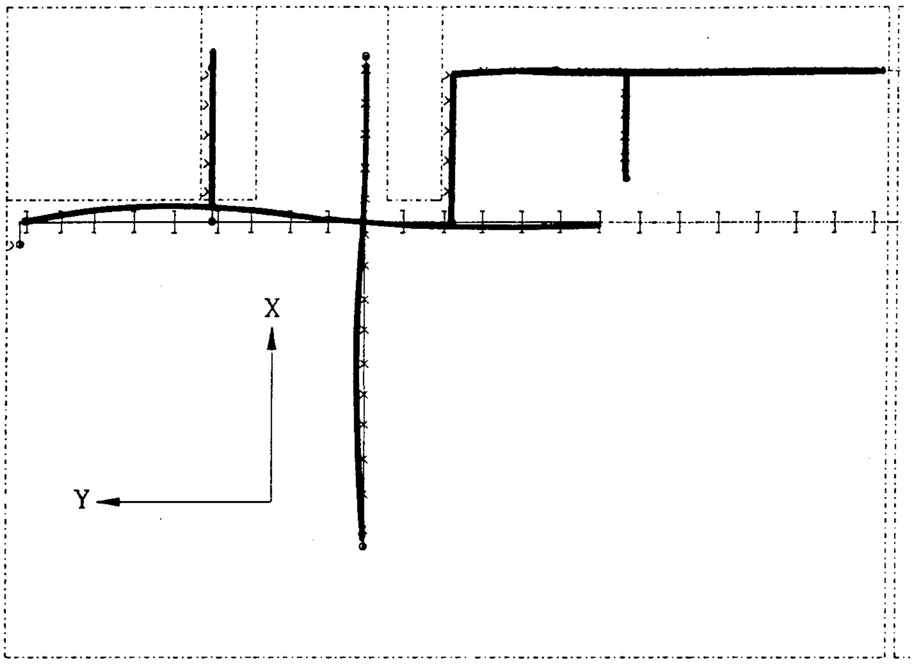


FIGURE D-7A SHAPE OF MODE NO. 1, 0.37 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

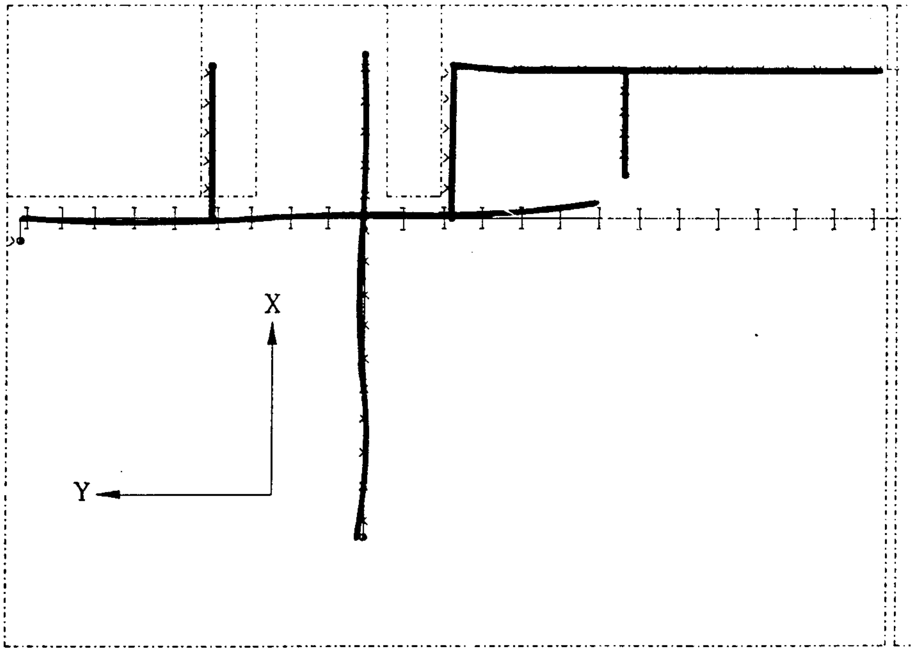


FIGURE D-7B SHAPE OF MODE NO. 4, 0.56 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

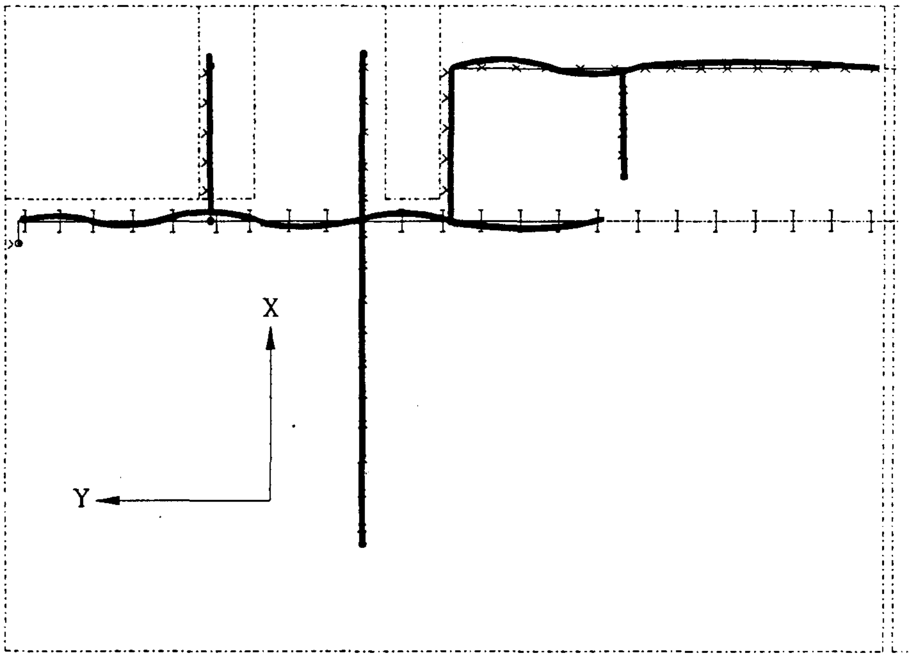


FIGURE D-7C SHAPE OF MODE NO. 29, 2.90 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

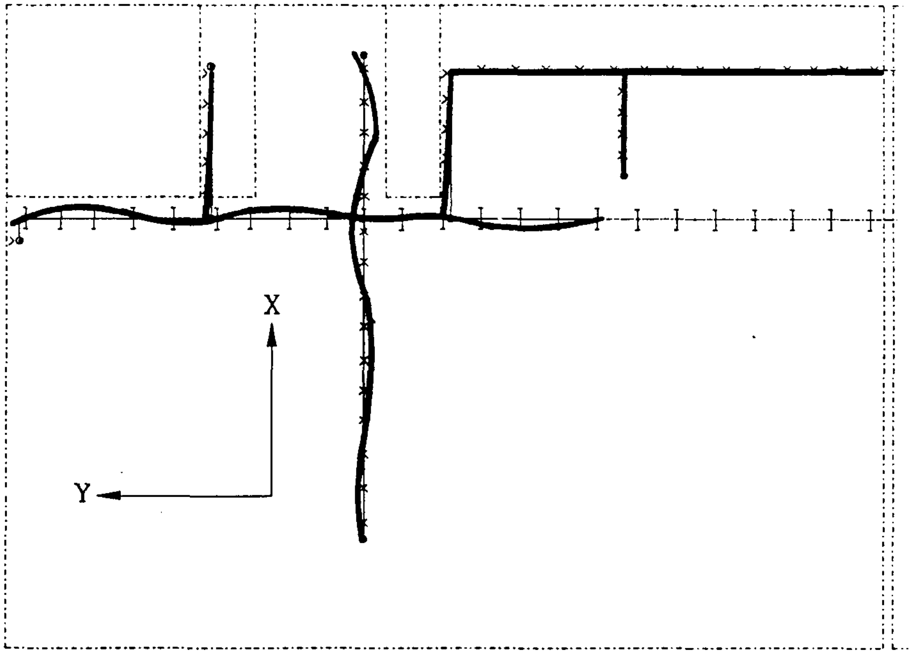


FIGURE D-7D SHAPE OF MODE NO. 25, 2.55 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

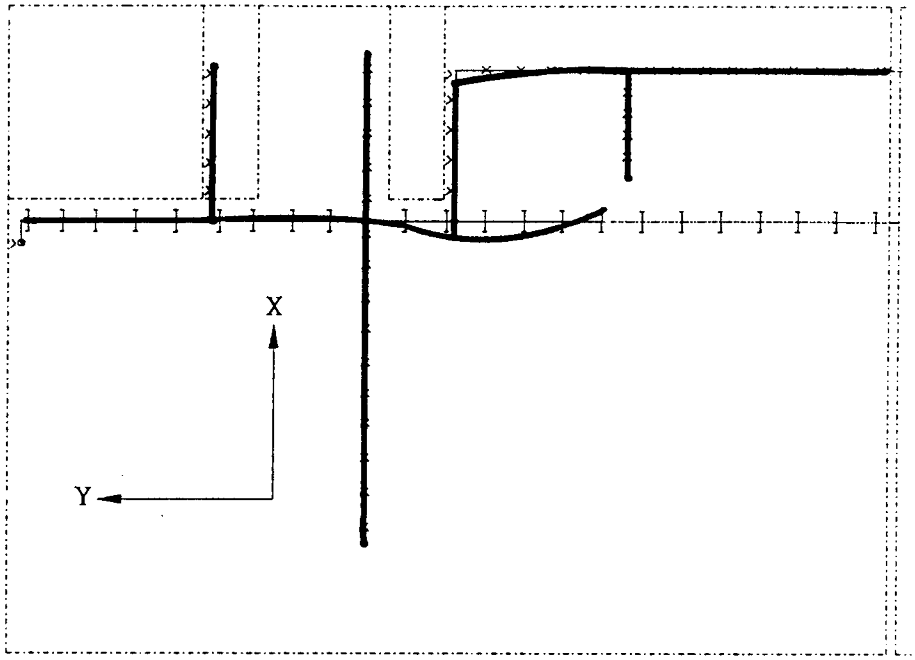


FIGURE D-7E SHAPE OF MODE NO. 23, 2.30 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

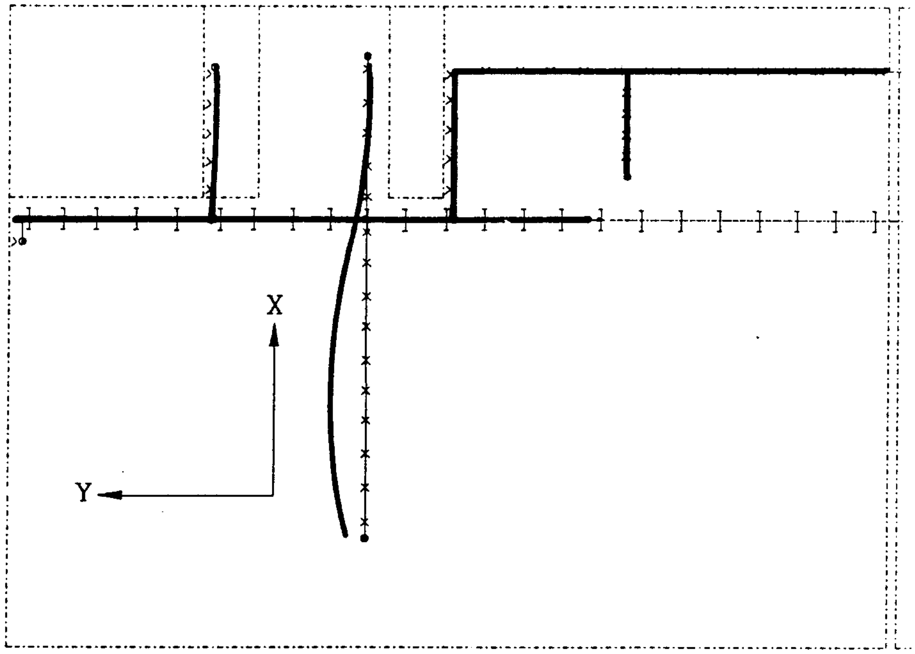


FIGURE D-7F SHAPE OF MODE NO. 2, 0.38 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

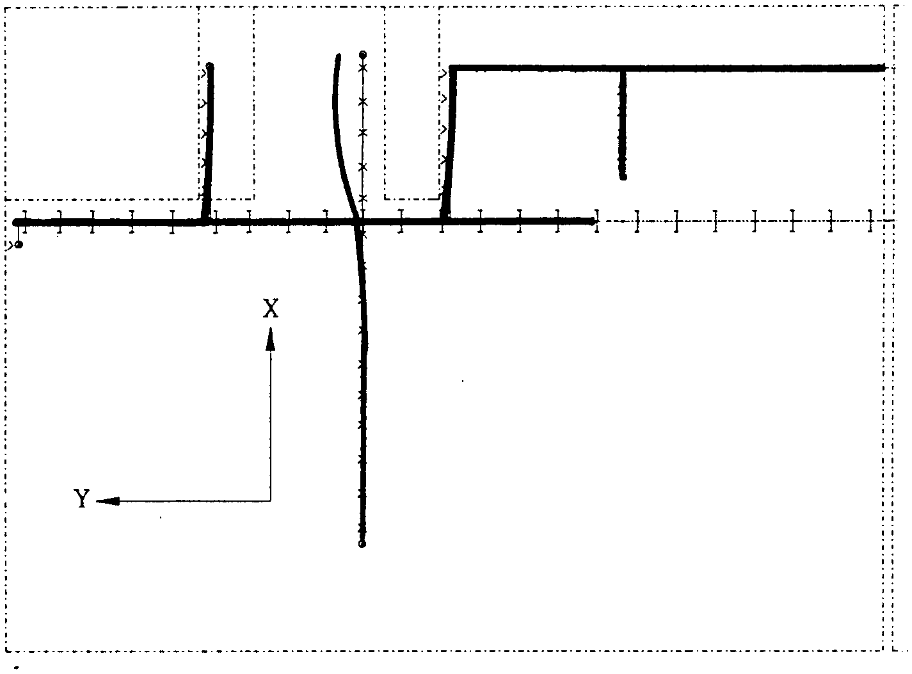


FIGURE D-7G SHAPE OF MODE NO. 9, 0.95 Hz, LONGITUDINALLY-BRACED SYSTEM (LB).

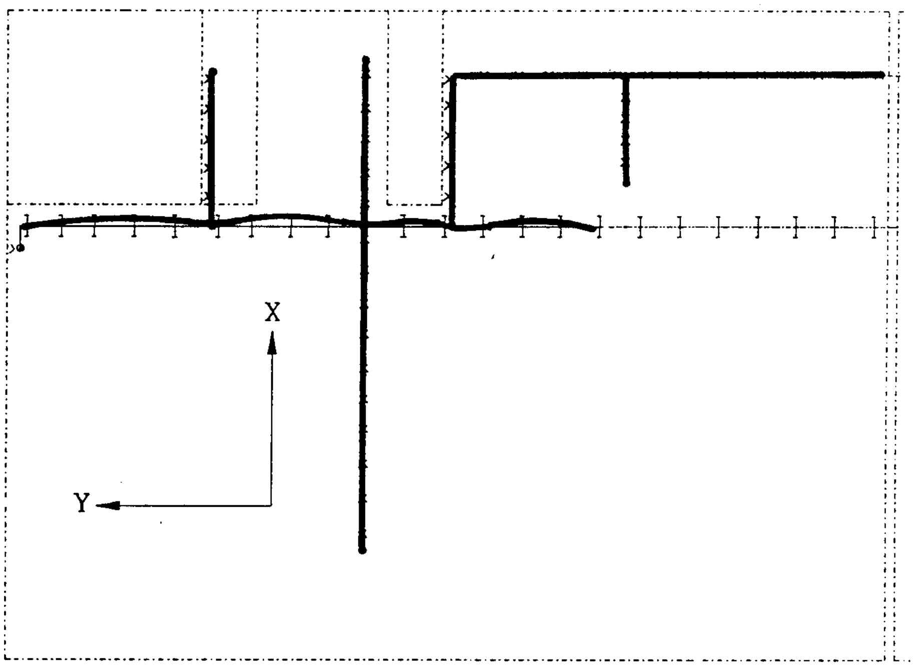


FIGURE D-8A SHAPE OF MODE NO. 24, 4.22 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

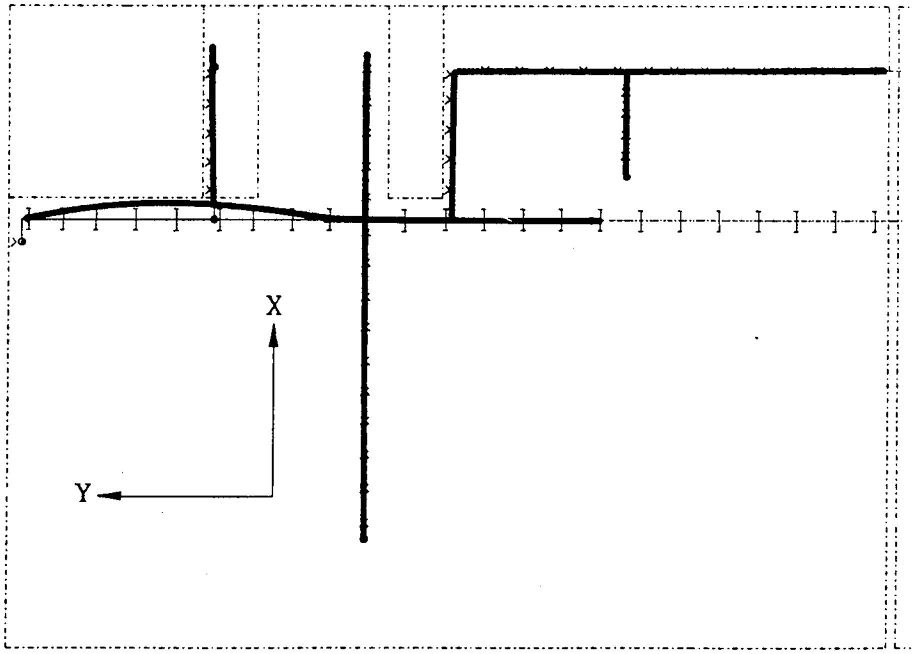


FIGURE D-8B SHAPE OF MODE NO. 45, 15.00 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

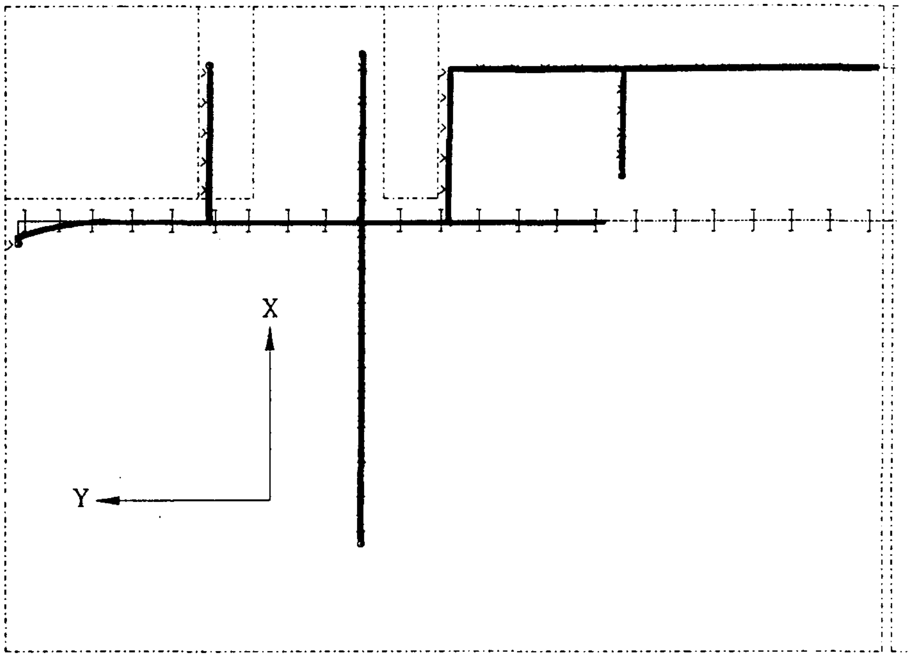


FIGURE D-8C SHAPE OF MODE NO. 28, 12.20 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

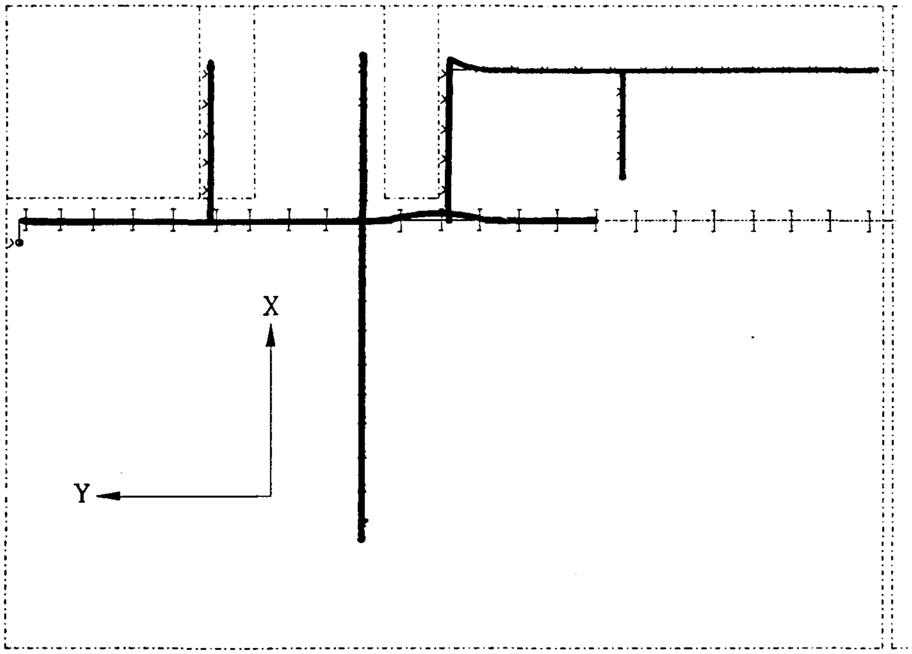


FIGURE D-8D SHAPE OF MODE NO. 27, 10.90 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

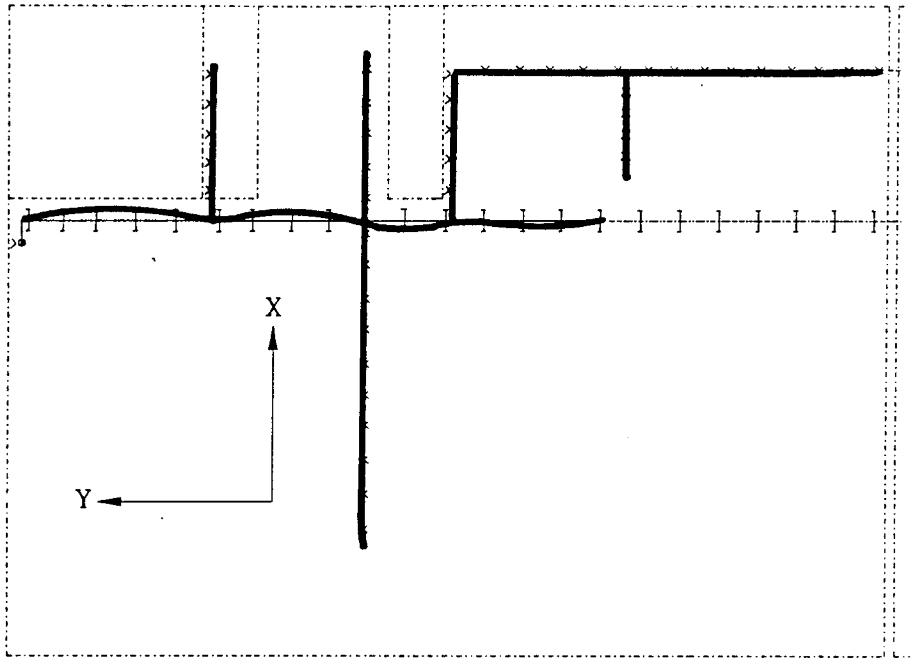


FIGURE D-8E SHAPE OF MODE NO. 23, 4.03 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

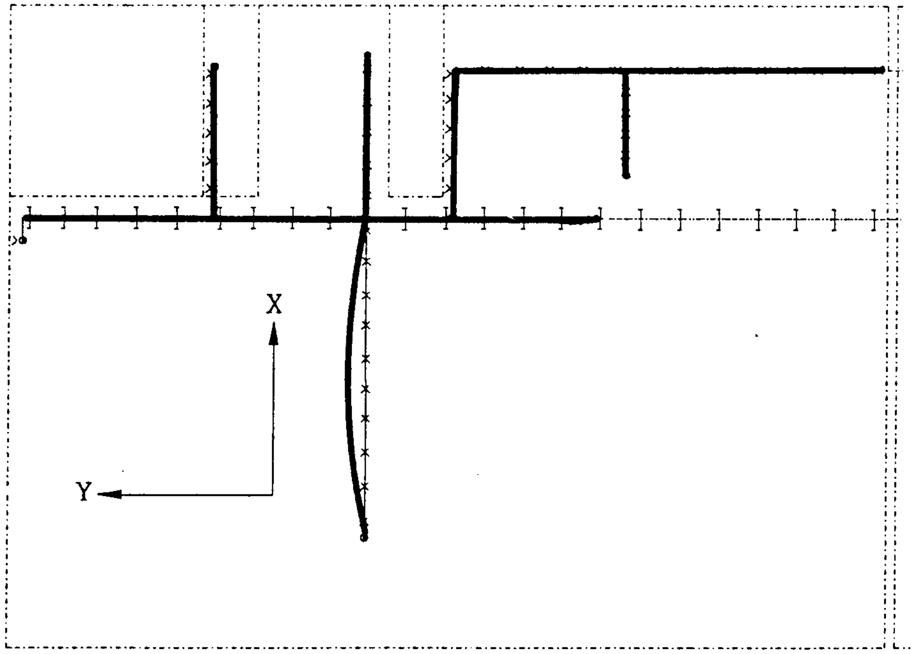


FIGURE D-8F SHAPE OF MODE NO. 19, 3.54 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

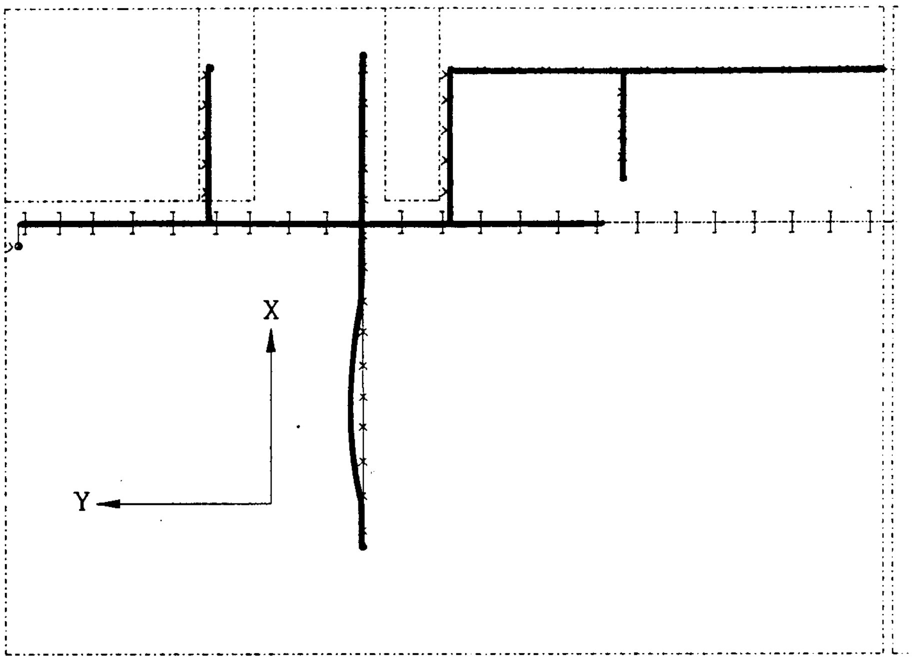


FIGURE D-8G SHAPE OF MODE NO. 41, 14.60 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

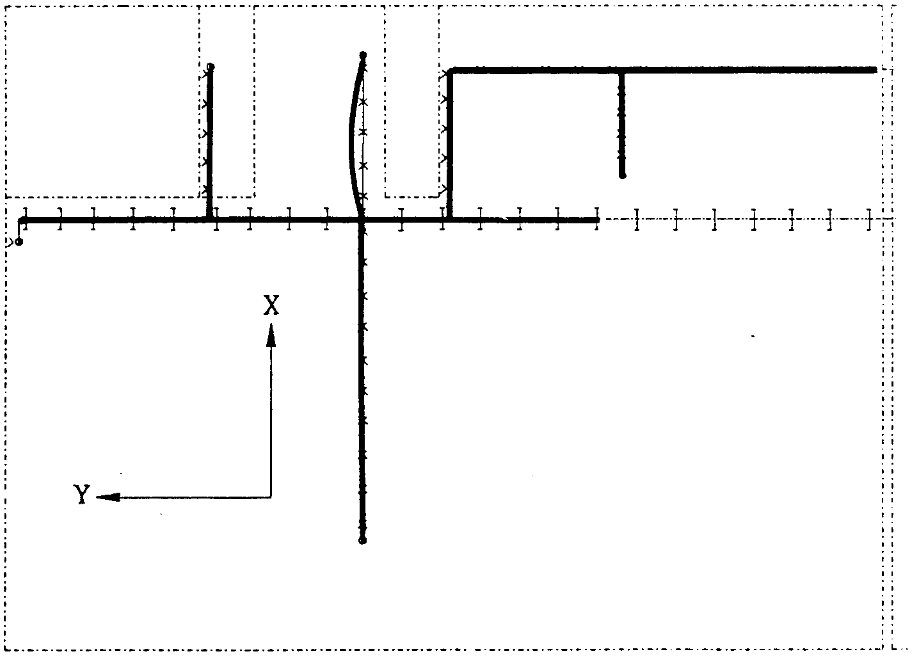


FIGURE D-8H SHAPE OF MODE NO. 18, 3.52 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB1).

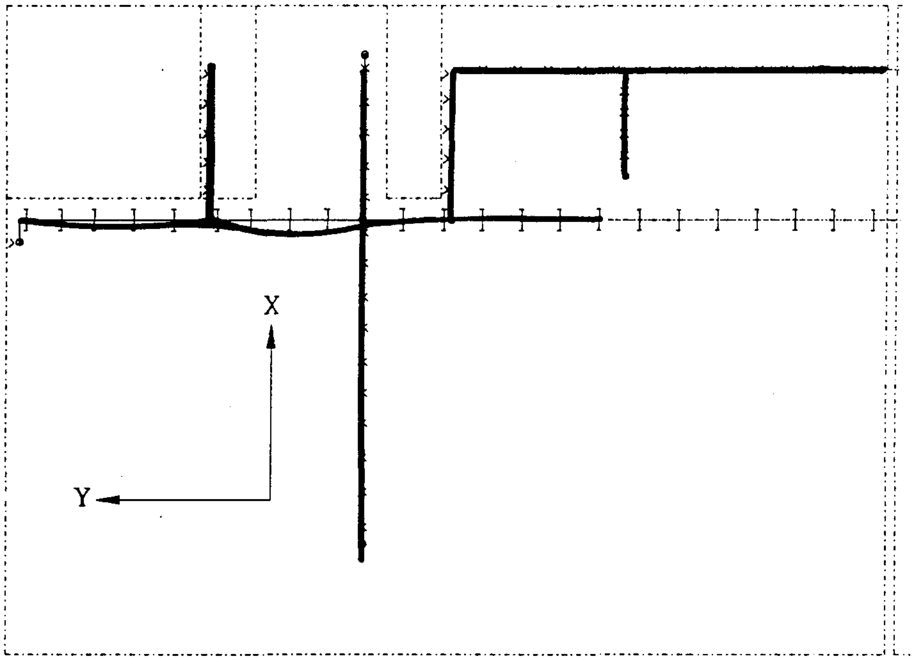


FIGURE D-9A SHAPE OF MODE NO. 10, 14.20 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

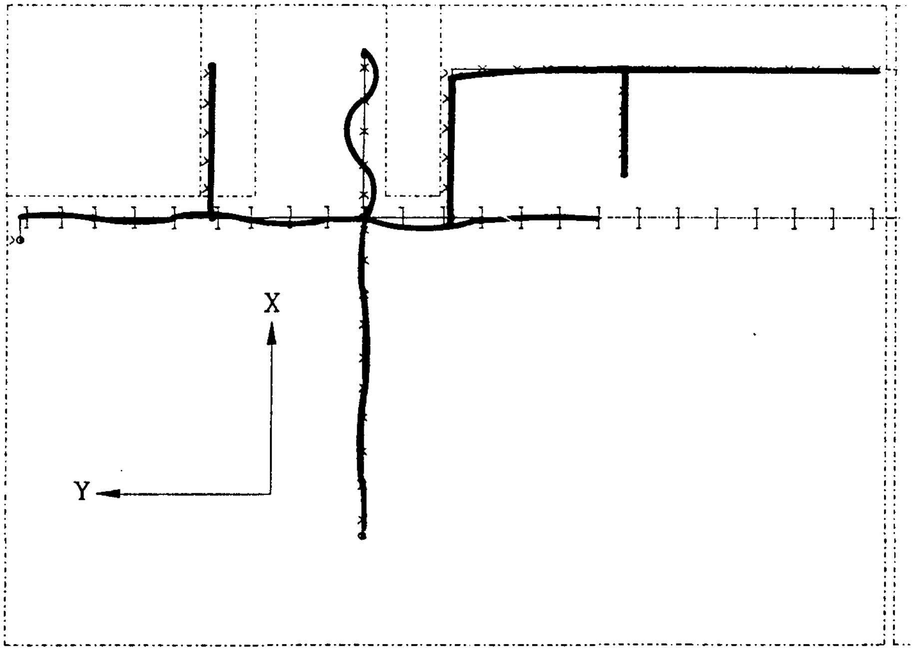


FIGURE D-9B SHAPE OF MODE NO. 23, 14.40 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

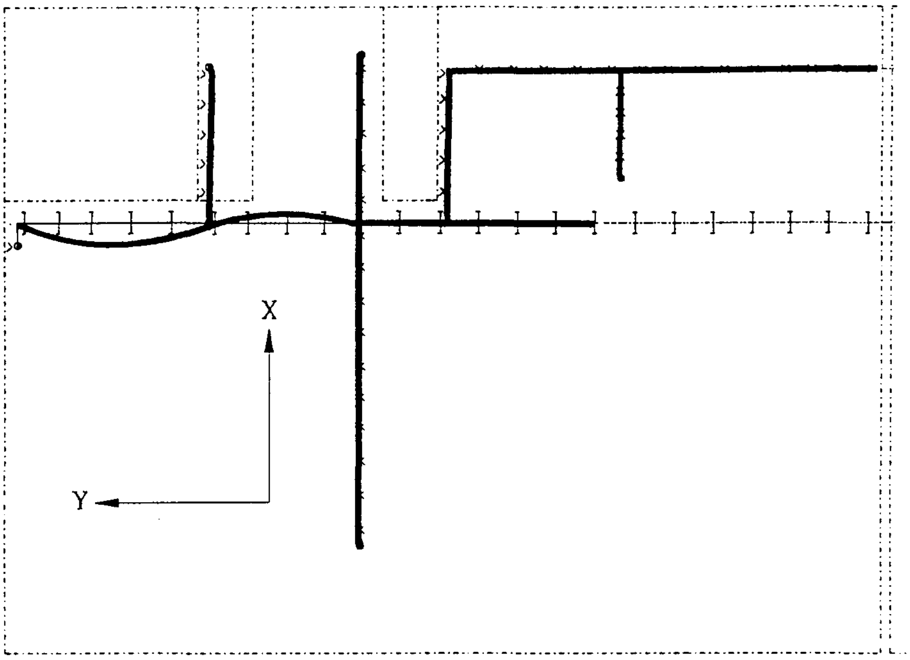


FIGURE D-9C SHAPE OF MODE NO. 7, 14.16 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

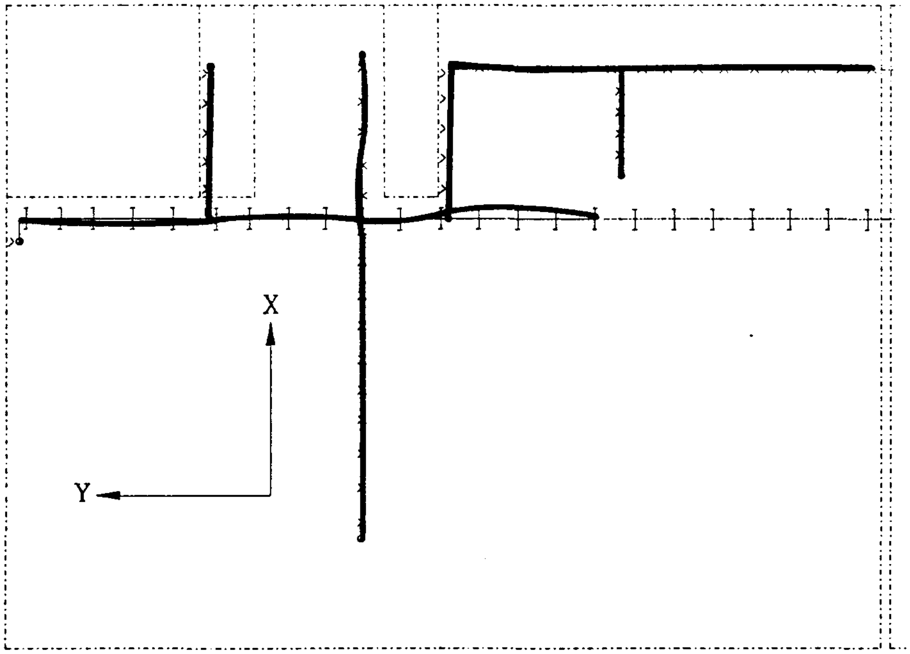


FIGURE D-9D SHAPE OF MODE NO. 18, 14.25 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

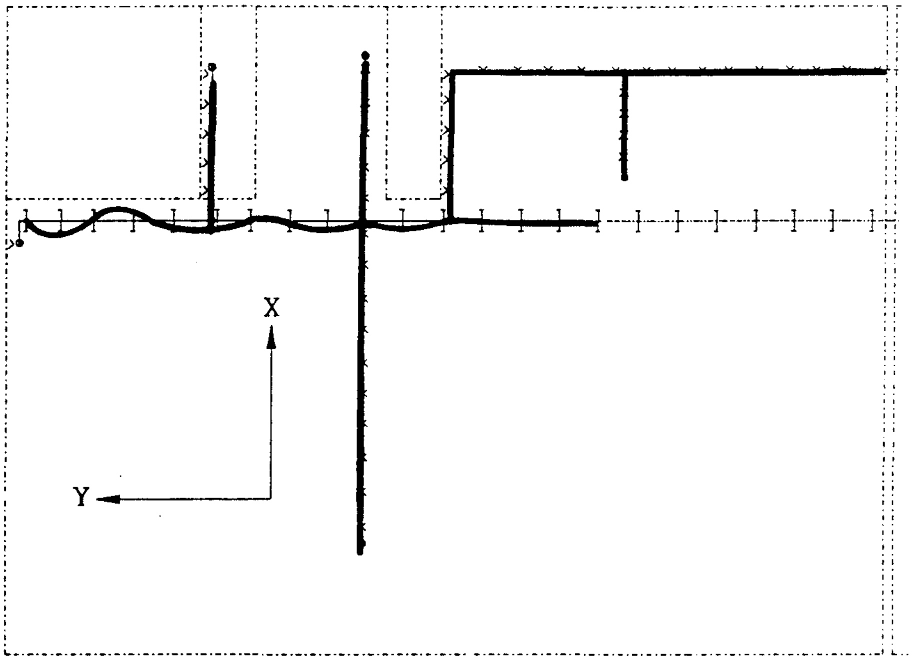


FIGURE D-9E SHAPE OF MODE NO. 26, 14.50 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

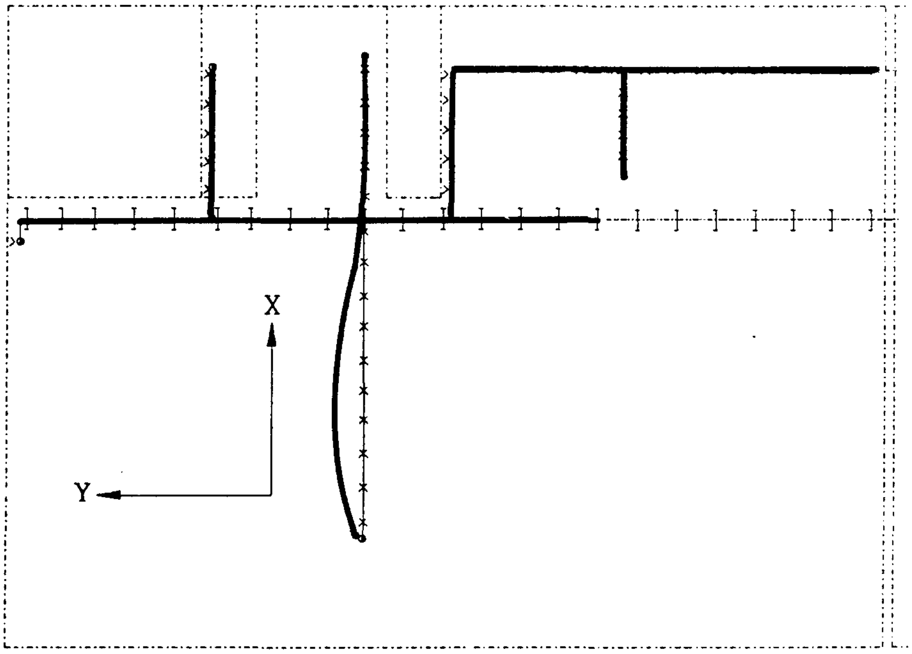


FIGURE D-9F SHAPE OF MODE NO. 5, 14.15 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

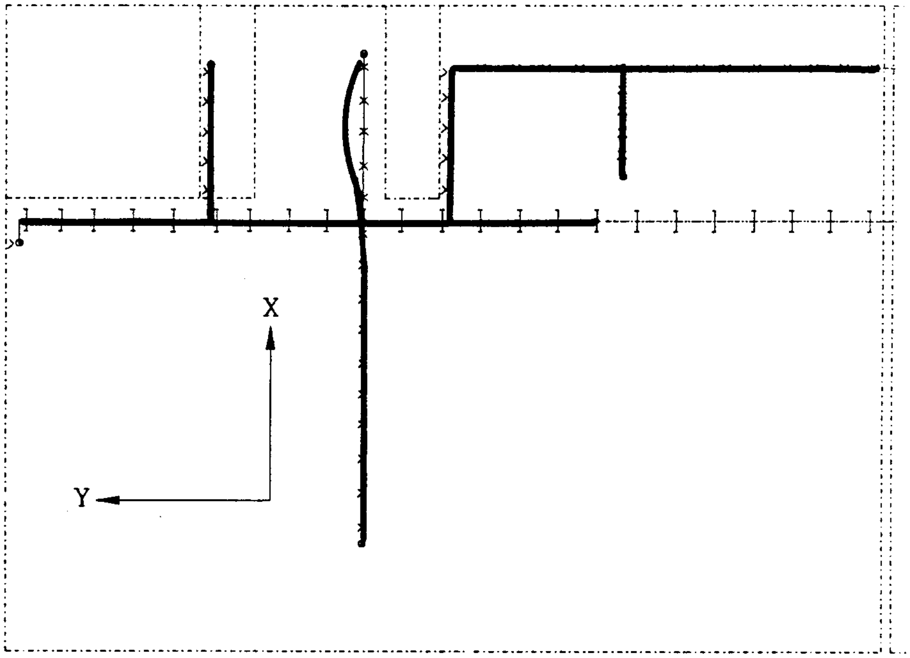


FIGURE D-9G SHAPE OF MODE NO. 13, 14.20 Hz, LONGITUDINALLY AND TRANSVERSELY-BRACED SYSTEM (LTB2).

APPENDIX E

SEISMIC ANALYSIS OF STEEL AND PVC PIPING SYSTEMS WITH ENERGY-DISSIPATIVE BRACES

E.1 Purpose and Objectives

The purpose of the work contained in Appendix E is to examine the seismic response of complex steel and PVC piping systems restrained using energy-dissipative braces. The purpose of the work is to evaluate the potential benefits of installing damped (energy-dissipative) braces on piping containing hazardous materials.

The objectives of Appendix E are summarized below:

1. Examine peak bending stresses at selected locations on the steel and PVC system models (with energy-dissipative braces) for upper-floor vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 7 (0.4g EPGA).

2. Compare and contrast peak piping system bending stress determined for the steel and PVC piping systems (with energy-dissipative braces) with the peak bending stresses previously calculated in Appendices C and D for conventional bracing schemes.

E.2 Description of Models

The basic piping system models and the energy-dissipative bracing schemes are described in the following sections.

E.2.1 Steel and PVC Piping System Models

The same basic Schedule 40 steel and Schedule 80 PVC piping system models described in Sections C.2.1 and D.2.1, respectively, are used in Appendix E.

E.2.2 Seismic Bracing Schemes

Figure E-1 shows the Schedule 40 Steel piping system and Figure E-2 shows the Schedule 80 PVC piping system with a combination of conventional and energy-dissipative seismic braces. In essence, braces have been located approximately in accordance with the LTB1 scheme (i.e., longitudinal plus transverse bracing at every other gravity support). Conventional (rigid or semi-rigid) braces are used for longitudinal restraints and for transverse braces needed to protect piping at points where the piping is rigidly connected to the structure (e.g., at walls, etc.). Energy-dissipative (flexible and damped) braces are used for transverse restraint of piping supports for which the pipe is otherwise free to displace (i.e., away from points where the pipe is held rigidly). The energy-dissipative braces were modeled with very soft springs which would displace approximately 10 inches laterally under the full tributary weight of the pipe.

E.3 Description of Analyses

Analyses where performed as described in Section C.3 except that the 20%-damped response spectra shown in Figure 3-2 are used to define the seismic vibration environment.

E.4 Summary of Results

E.4.1 Modal Analyses

The results of the modal analyses are summarized in Table E-1 for both steel and PVC piping systems and plots of the shapes of dominant modes (i.e., modes with significant participation) are shown in Figures E-3 and E-4 for the steel and PVC systems, respectively.

For both the steel and PVC piping systems, the dominant mode in the X-direction (i.e., response perpendicular to the mainline supported on trapeze hangers) is about 1 Hz and represents global displacement of the piping as shown in Figure E-3A for the steel system, and in E-4A for the PVC system. Peak lateral displacements for this mode are about 3-4 inches for vibratory motion corresponding to NEHRP/ATC-3 Map Area No. 7. Since the frequency of the dominant mode falls below the fundamental-mode of the building, displacement response is similar for piping attached to the ground and piping attached to upper-floors.

E.4.2 Response Spectrum Analysis

The results of the response spectrum analysis are summarized in Table E-2 for both steel and PVC systems. As shown therein, peak seismic bending stresses are very low, averaging approximately one-half of the stress limit permitted for Category A (extremely hazardous) piping systems.

TABLE E-1

SUMMARY OF MODAL ANALYSIS RESULTS FOR COMPLEX STEEL AND PVC PIPING SYSTEMS WITH ENERGY-DISSIPATIVE BRACES

Direction/ Dominant Mode[1]	Steel Piping System			PVC Piping System		
	Mode No.	Frequency (Hz)	Participation[2]	Mode No.	Frequency (Hz)	Participation[2]
X 1st	1	1.18	58.5	2	1.06	35.8
X 2nd	11	4.30	12.0	4	1.14	10.3
X 3rd	16	7.90	9.3	26	2.90	10.0
X 4th	8	3.18	4.5	51	15.70	7.0
X 5th	14	5.86	2.2	47	12.20	6.9
X RIGID		>20	13.5		>20	30.0
Y 1st	2	1.34	3.3	1	1.05	3.4
Y 2nd	5	2.07	1.5	8	1.36	1.9
Y 3rd	26	10.75	1.1			
Y 4th						
Y 5th						
Y RIGID		>20	94.1		>20	94.7

1. A dominant mode is defined as having at least 1% participation in the direction under consideration.

2. Participation is defined as the percentage of total mass acting in the direction under consideration.

TABLE E-2

SUMMARY OF PEAK SEISMIC BENDING STRESSES FOR COMPLEX STEEL AND PVC PIPING SYSTEMS WITH ENERGY-DISSIPATIVE BRACES SUBJECTED TO UPPER-FLOOR VIBRATORY MOTION CORRESPONDING TO NEHRP/ATC-3 MAP AREA NO. 7

Piping Segment (Support Type)		Steel System Stress[1]	PVC System Stress[1]
No.	Description		
1	6" Diameter Main Line (on Trapeze Hangers)	5.9	0.48
2	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	6.2	0.21
3	3" Diameter Branch Line (on Long Rod Hangers)	5.0	0.30
4	3" Diameter Riser (from 1 to 3)	5.0	0.85
5	3" Diameter Branch Line (on Short Rod Hangers)	6.7	0.40
6	3" Diameter Riser (from 1 to 5)	3.2	0.46
7	3" Diameter Branch Line (on Long Rod Hangers, restrained at wall)	5.6	0.58
8	3" Diameter Branch Line (on Short Rod Hangers, restrained at wall)	2.6	0.22
9	1" Diameter Feeder Line and Riser to Equipment	7.3	0.32
10	2" Diameter Branch Line (on Short Rod Hangers)	3.6	0.35

1. Basic allowable tensile stress for ASTM A53 steel pipe is 12 ksi based on a minimum yield strength of 30 ksi and an ultimate strength of 48 ksi and the allowable hydrostatic design (tensile) stress for ASTM D1785 PVC pipe at 73^{o}F is 1.0 ksi (i.e. ASME B31.9, Ref. 20).

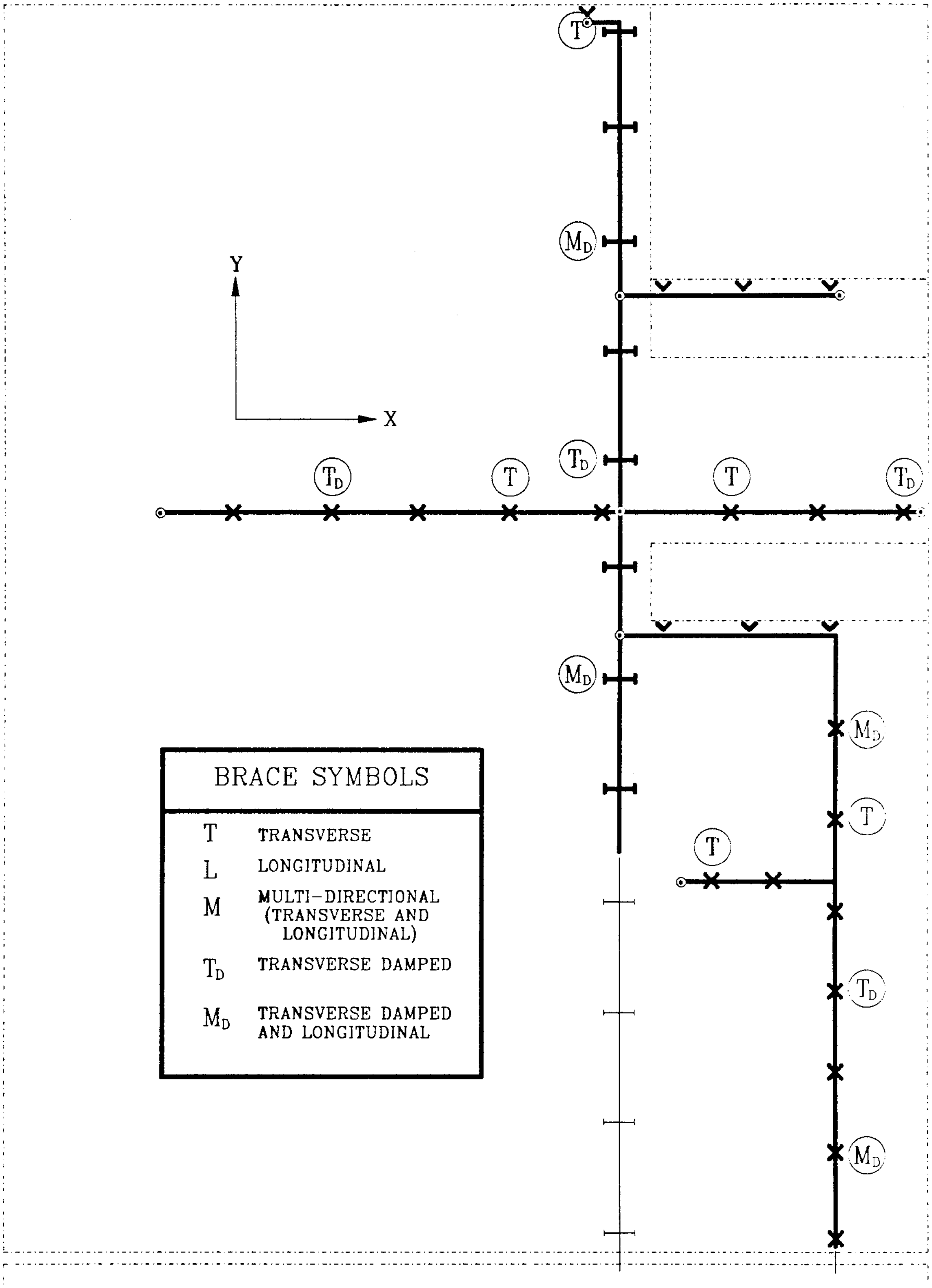


FIGURE E-1 **SCHEDULE 40 STEEL PIPING SYSTEM BRACED WITH ENERGY-DISSIPATIVE BRACES.**

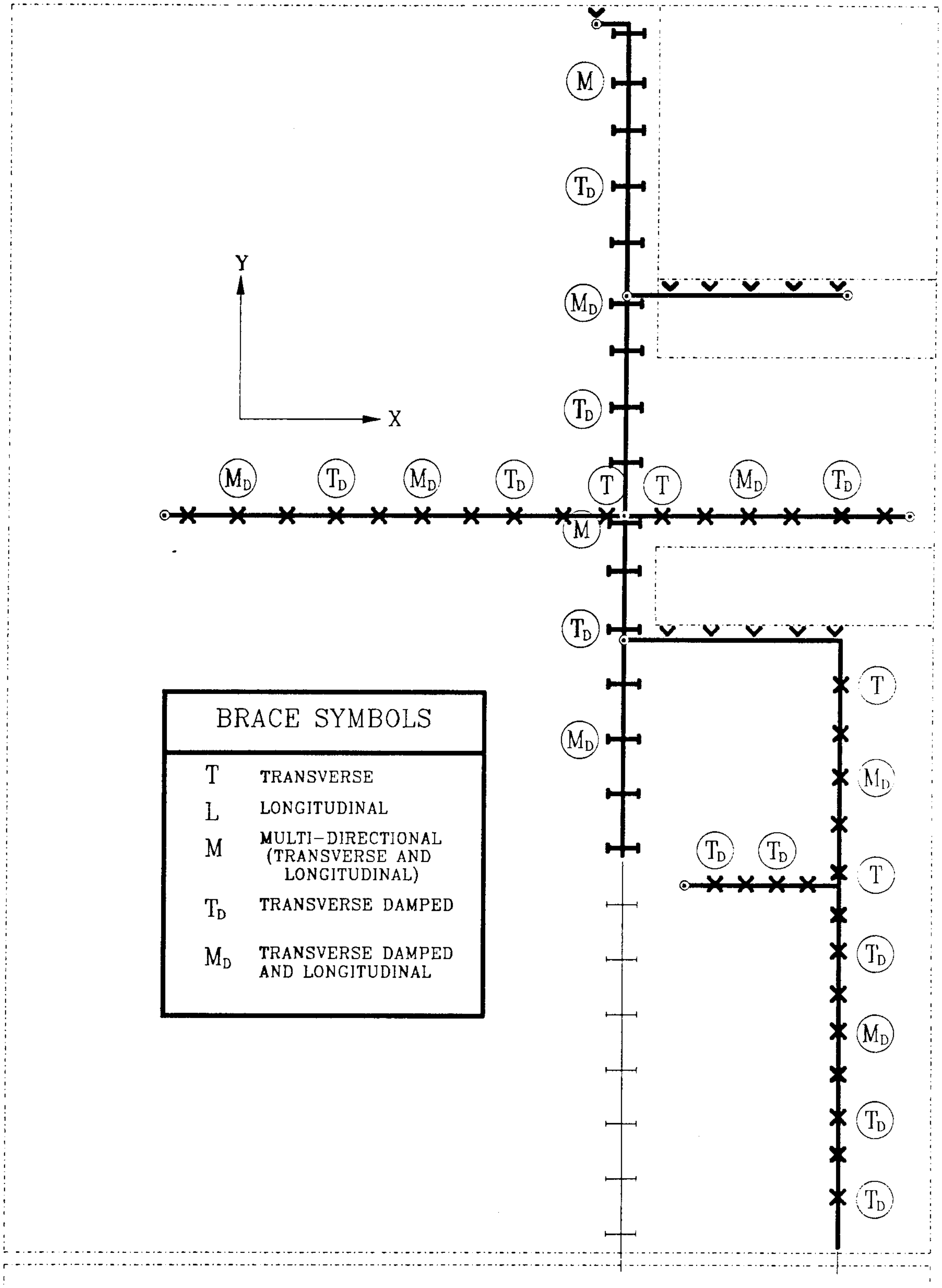


FIGURE E-2 SCHEDULE 80 PVC PIPING SYSTEM BRACED WITH ENERGY-DISSIPATIVE BRACES.

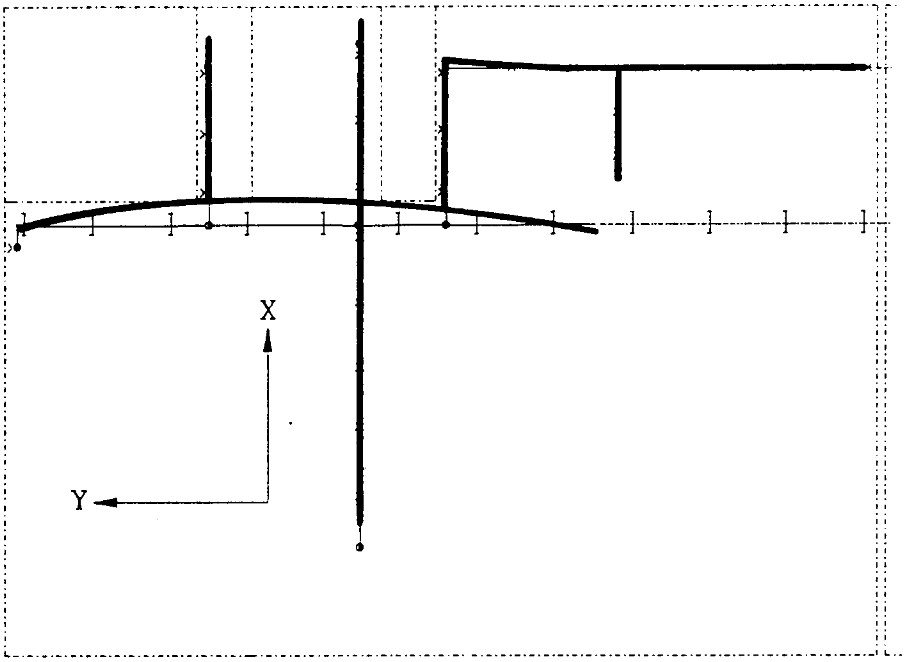


FIGURE E-3A SHAPE OF MODE NO. 1, 1.18 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

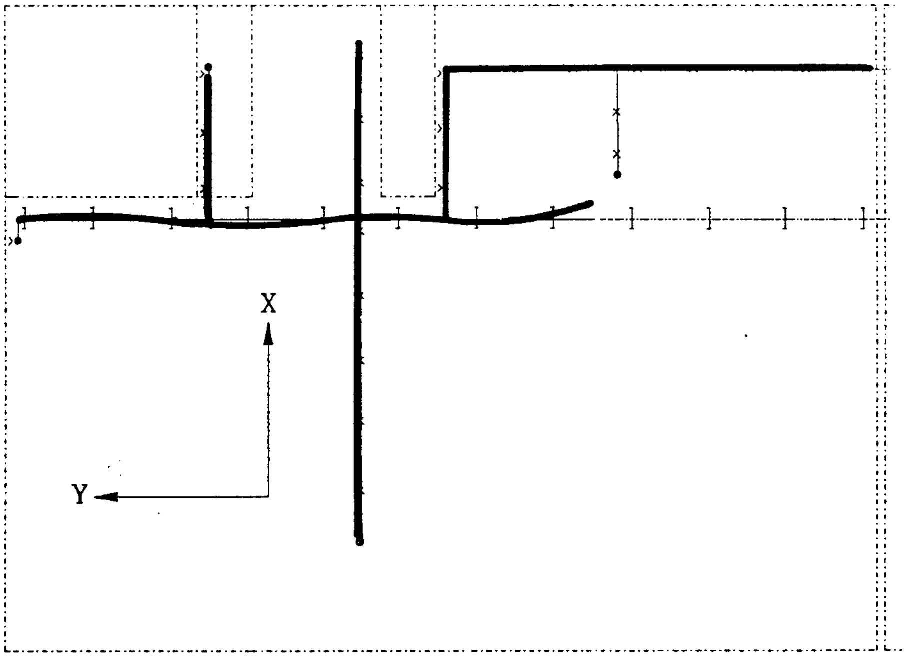


FIGURE E-3B SHAPE OF MODE NO. 11, 4.30 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

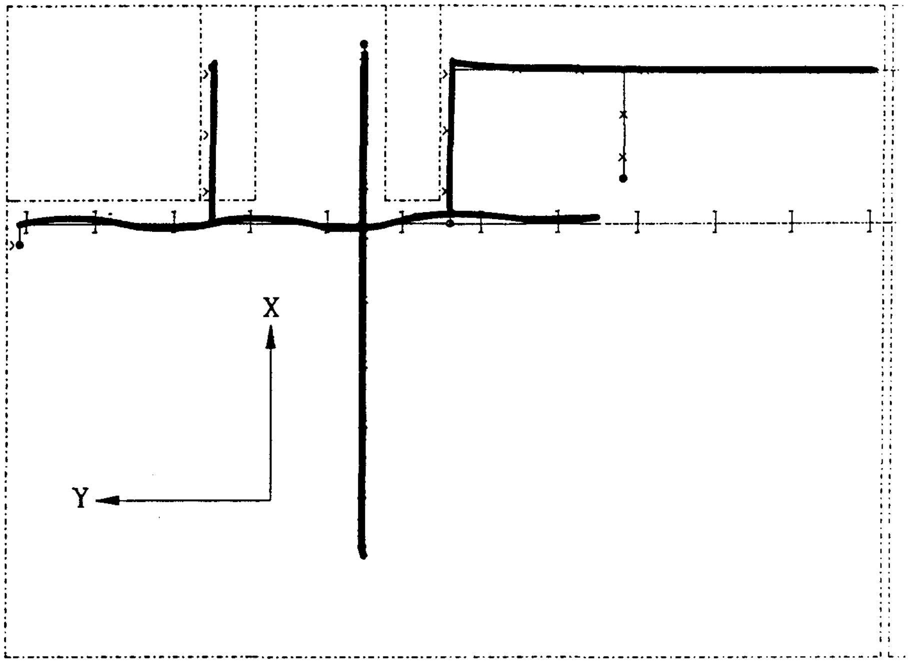


FIGURE E-3C SHAPE OF MODE NO. 16, 7.90 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

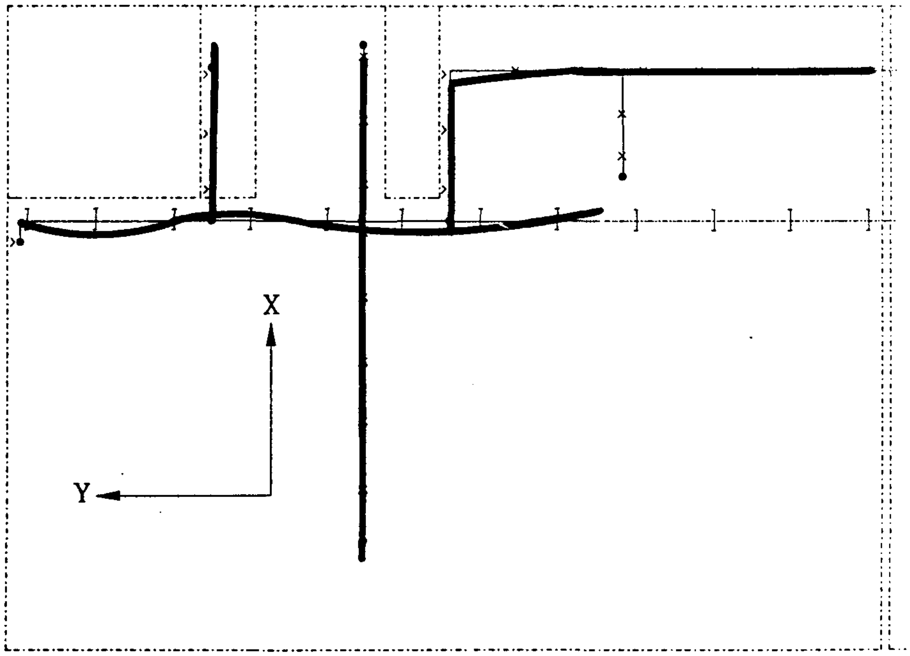


FIGURE E-3D SHAPE OF MODE NO. 8, 3.18 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

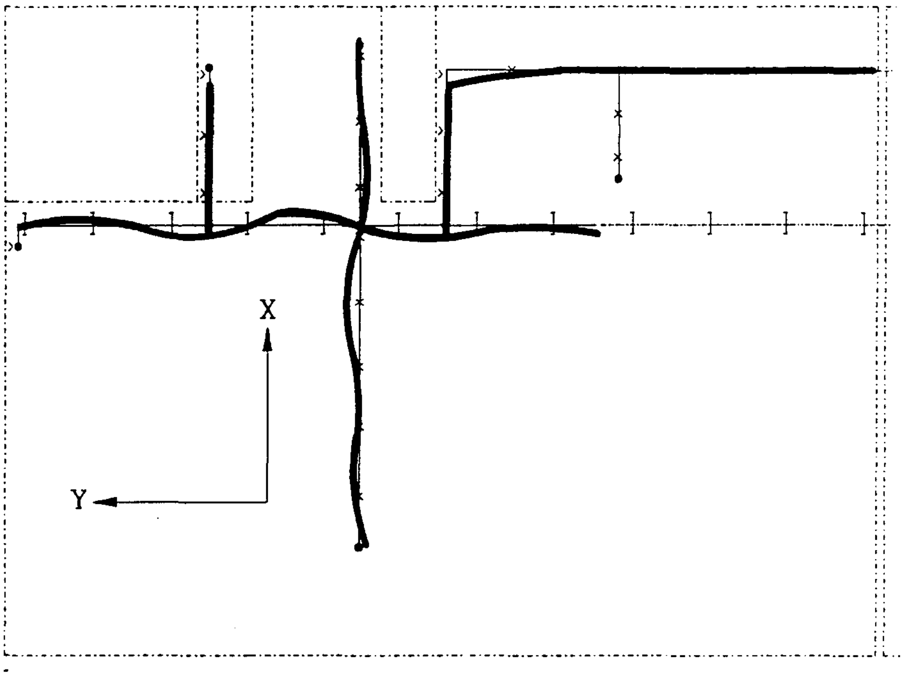


FIGURE E-3E SHAPE OF MODE NO. 14, 5.86 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

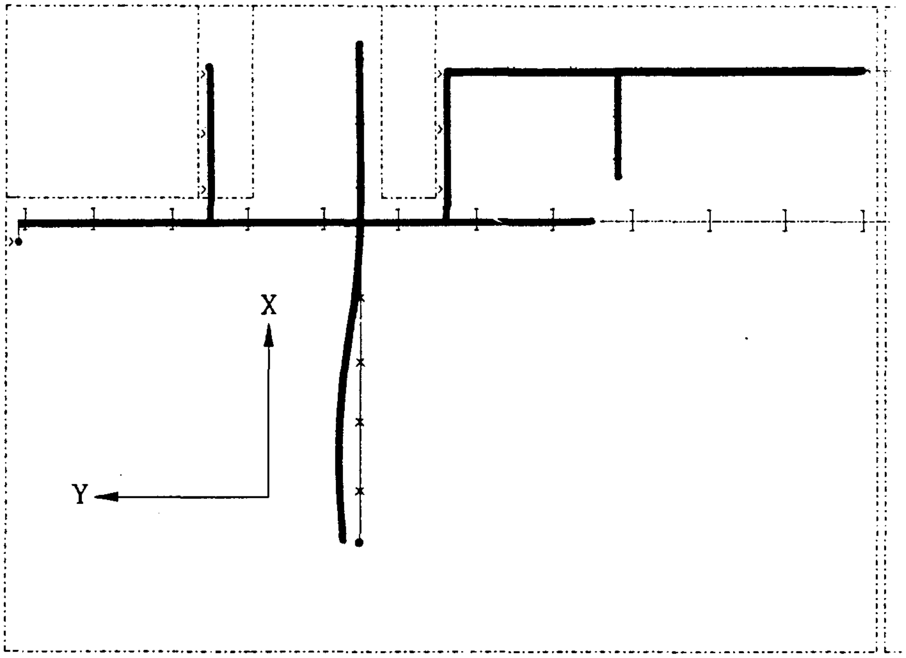


FIGURE E-3F SHAPE OF MODE NO. 2, 1.34 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

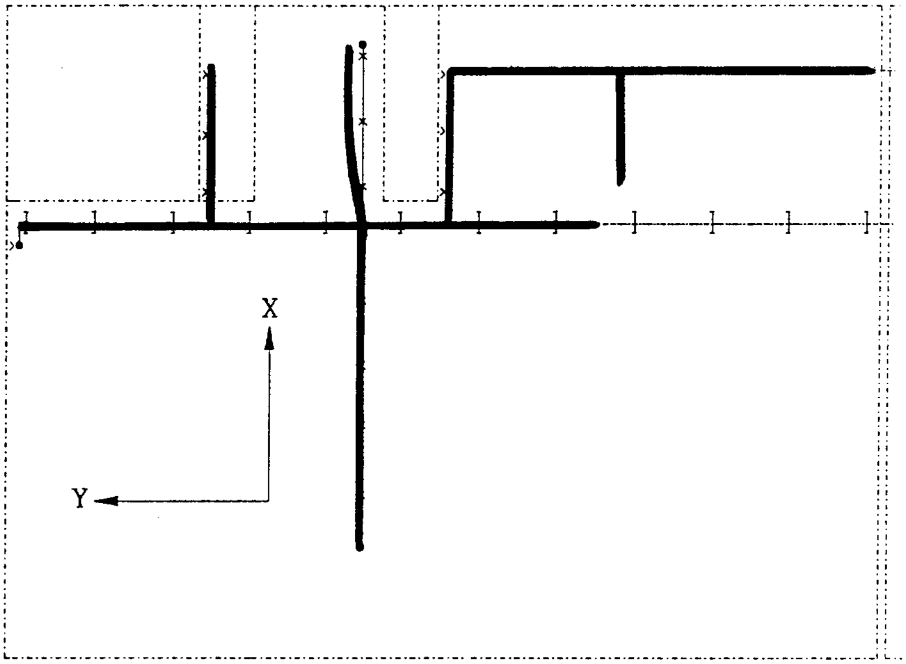


FIGURE E-3G SHAPE OF MODE NO. 5, 2.07 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

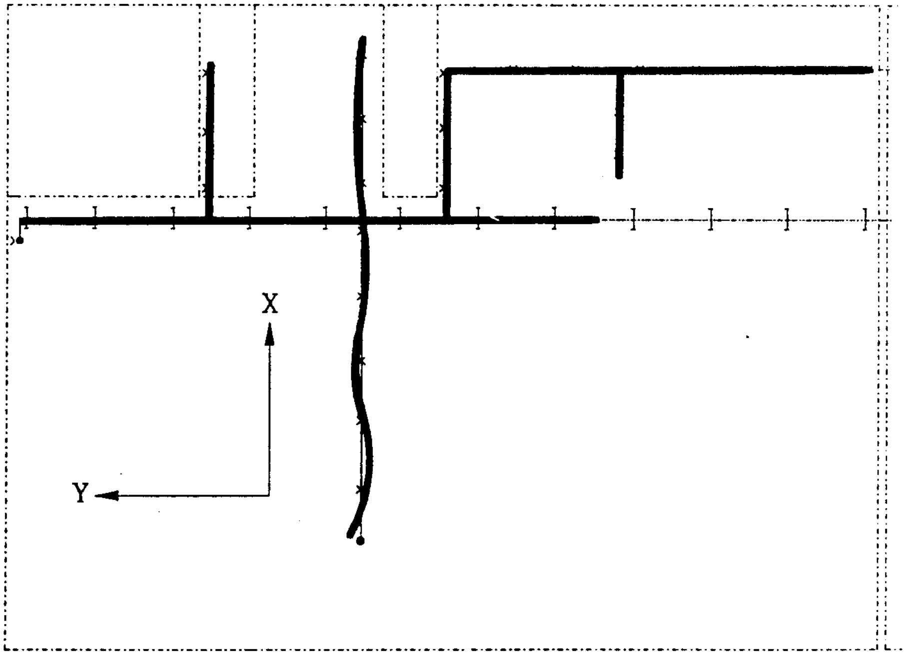


FIGURE E-3H SHAPE OF MODE NO. 26, 10.75 Hz SCHEDULE 40 STEEL SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

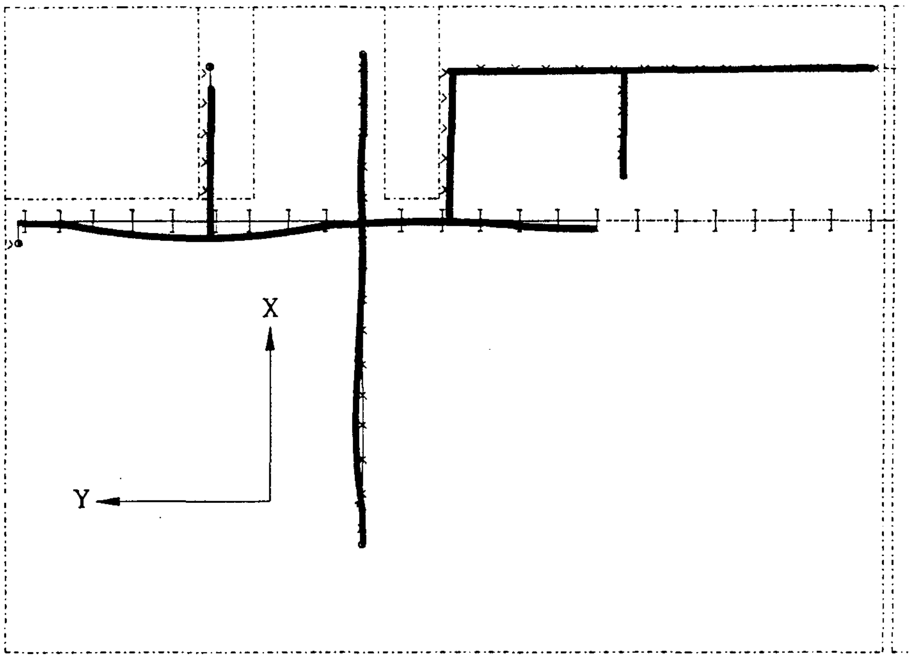


FIGURE E-4A SHAPE OF MODE NO. 2, 1.06 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

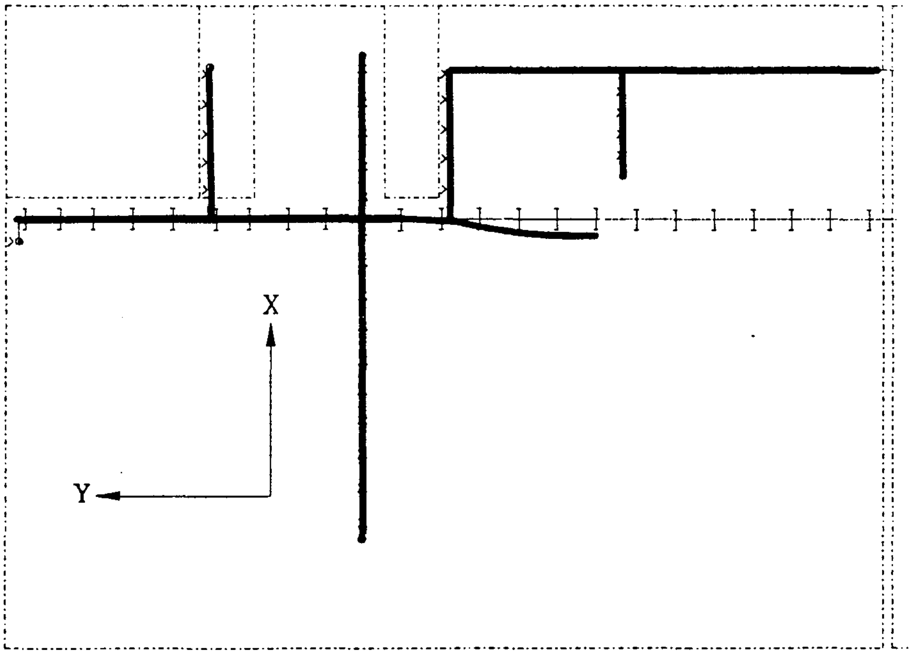


FIGURE E-4B SHAPE OF MODE NO. 4, 1.14 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

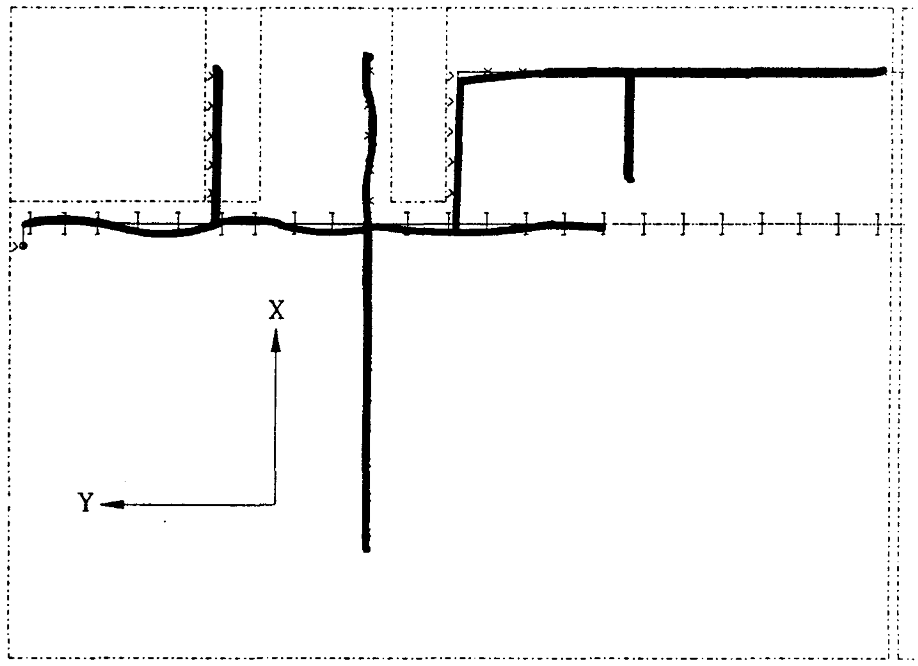


FIGURE E-4C SHAPE OF MODE NO. 26, 2.90 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

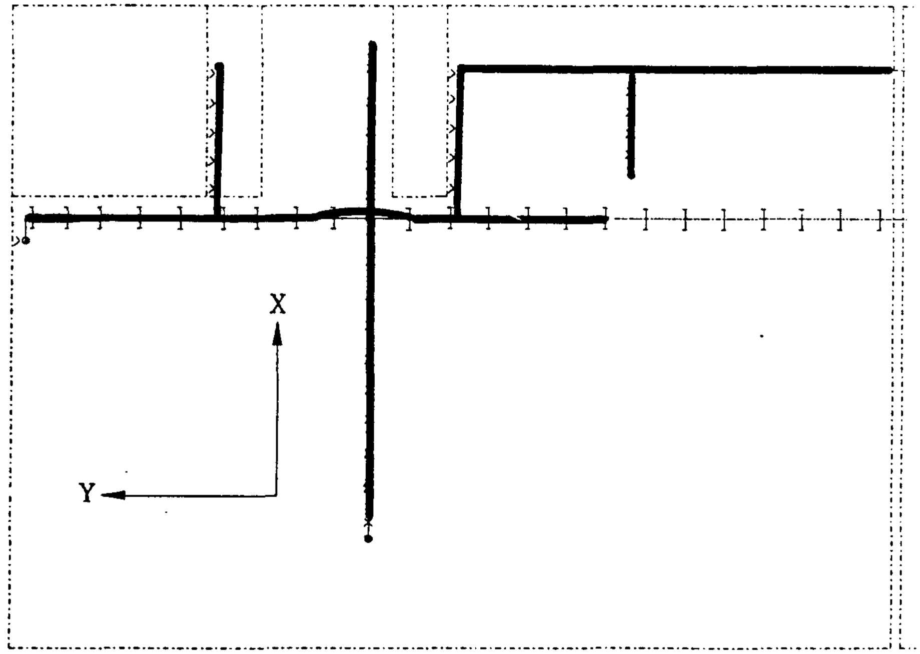


FIGURE E-4D SHAPE OF MODE NO. 51, 15.70 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

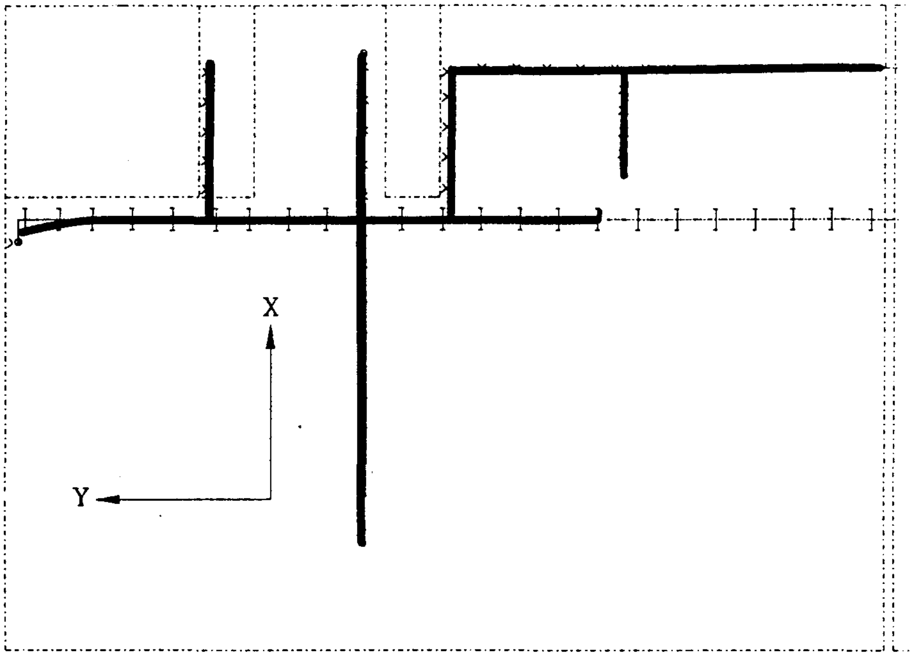


FIGURE E-4E SHAPE OF MODE NO. 47, 12.20 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

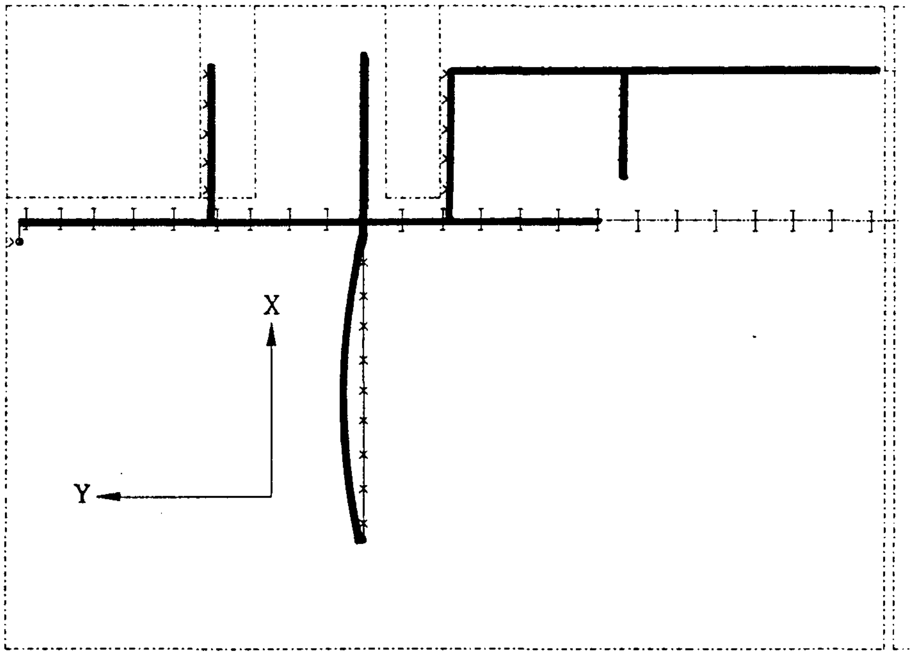


FIGURE E-4F SHAPE OF MODE NO. 1, 1.05 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.

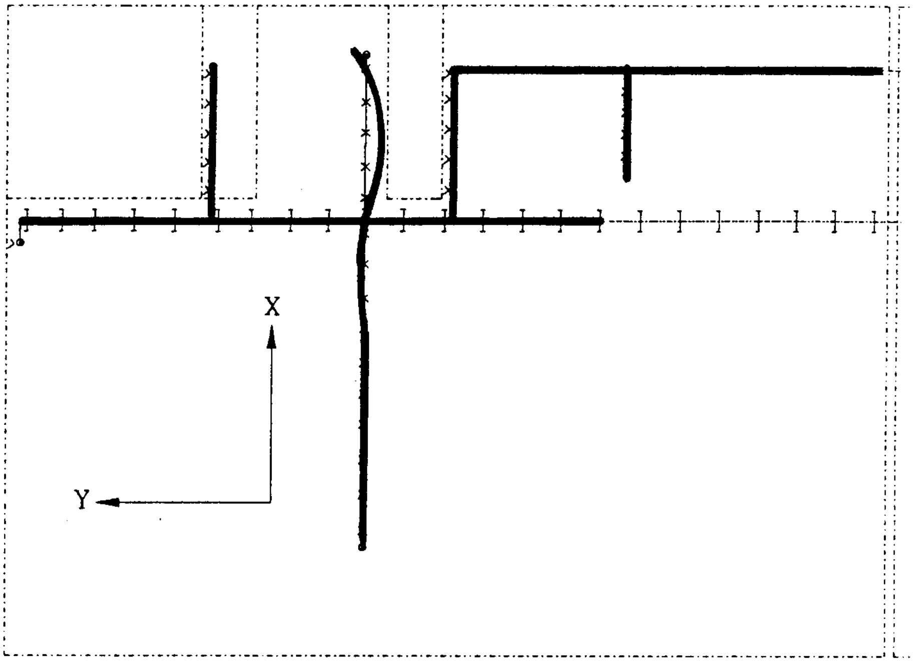


FIGURE E-4G SHAPE OF MODE NO. 8, 1.36 Hz, SCHEDULE 80 PVC SYSTEM WITH ENERGY-DISSIPATIVE BRACES.