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Review Notes of 3-6-24.

1)There are boxes like this one throughout the document that contain Code references to help with review. These will be removed before final publication.

2)Sections that are place-holders are marked [INCOMPLETE]. Yellow highlights are used to identify recent notes and changes that need some review.

3)Stress and stress case nomenclature is being resolved and at this point there will be small inconsistencies as stress equations are converted to directional (in, out, tor, ax).

4)[tony] be sure that where Sy is defined that it is clear if it means the hot, cold or average value.

ASME B31E Working Draft Update of 3/6/2024

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1 PURPOSE

This Standard provides recommendations for the seismic design of above-ground piping systems in the scope of the ASME B31 Piping Codes. If adopted by the individual B31 Code section, these may become requirements of that section.

1.1 Scope

This Standard applies to above-ground, metallic piping systems in the scope of the ASME B31 Code for Pressure Piping (B31.1, B31.3, B31.4, B31.5, B31.8, B31.9, B31.11). The recommendations in this Standard are valid when the piping system complies with the materials, design, fabrication, examination, testing, and inspection requirements of the applicable ASME B31 Code section. Minimum seismic design loads and load cases are intended to be taken from ASCE 7-2022 or later, or any comparable standard. Seismic evaluation procedures change regularly as new methods are introduced. The reader must be aware of latest developments, in particular where soft soil, liquefaction or new calculation methods involving probabilities are used that reduce required supporting. This can be particularly true for large D/t pipe, configurations subject to elastic follow-up, or pipe otherwise sensitive to plastic deformation.

Recent emphasis is on the underestimation of support displacements due to elastic solution procedures, seismic anchor and other relative support motions along with underestimated in-structure excitation.

It has been recognized that fatigue damage, inelastic analysis and system instabilities may not be adequately controlled using elastic analysis of only primary and occasional loads. This standard permits the capable user of performing any appropriate analysis while also providing additional, simple-to-use guidelines for possible fatigue damage, redundancy, instability and redistribution of loads due to inelasticity.

1.2 Terms and Definitions

active components: components that must perform an active function, involving moving parts or controls during or following the earthquake (e.g., valves, valve actuators, pumps, compressors, and fans that must operate during or following the design earthquake).

ASD (stress): Allowable Stress Design associated usually with primary and occasional loads and a yield or tensile based limit with a single safety factor based on experience.

ASD (strength): Allowable Strength Design associated usually with sustained and occasional loads. Loads can be factored based on experience, but a single safety factor (Ω) is used to separate the resistance and the load. See also LRFD.

axial seismic restraint: seismic restraint that acts along the pipe axis.

Critical piping: piping system that must remain leak tight or operable (see definitions) during or following the earthquake. (Ref. sect. 3.2.2.)

design earthquake: the level of earthquake for which the piping system is to be designed for to perform a seismic function (position retention, leak tightness, or operability) or is otherwise designated as critical by the owner.

ductile piping system: in the context of this Standard for seismic qualification, ductile piping system refers to a piping system where the piping, fitting, and components are made of material with a minimum elongation at rupture of 15% at the temperature concurrent with the seismic load.

ductility response factors: usually R, R_p, R_μ, R_{po}, F_μ, or any factor used to represent energy dissipation or reduced mechanical response due in part to inelastic response not included in the analysis. When inelastic response is included in an analysis, displacements, strains and loads transmitted to structures can be greater. The pipe stress analyst is responsible for communicating the correct load origins and magnitudes to the structural engineer.

*equivalent lateral force method (ELF):*an approach using factored accelerations and a single assumed mode shape to multiply the weight of each element in a piping system for use in a linear elastic seismic load case.

free-field seismic input: the ground seismic input at the facility location.

in structure seismic input: the seismic excitation within a building or structure, at the elevation of the piping system attachments to the building or structure.

*Impulse:*dynamic displacement or force element that can be defined by a characteristic triangular waveform and duration. Seismic forces and displacements can be made up of a large number of impulses of differing magnitudes and durations occurring repeatedly at differing periods for the earthquake duration. Soft soils tend to have long impulse durations and therefore can cause greater displacement and damage. Site soil specification is a key element of an accurate analysis.

lateral seismic restraints: seismic restraints that act in a direction perpendicular to the pipe axis and in the horizontal plane.

leak tightness: the ability of a piping system to prevent leakage to the environment during or following the earthquake. Leak tightness is controlled by satisfying fatigue and rupture requirements and controlling loads on bolted connections and couplings. Generally two levels of leak tightness can be identified by leak rate and whether gas or liquid is the leaking media. Appendix 9 identifies these rates and provides allowable loads on flanged joints and couplings to limit emissions to acceptable levels.

LRFD: Load and Resistance Factor Design is a probabilistic design method introduced around the 1980's mainly used for primary, sustained and occasional loads, but can be used for any load and resistance function, i.e. fatigue, ratcheting, creep, etc. Load factors and separation constants (β) are based on standard deviations associated with random variables describing any aspect of the solution. Variables (e.g. seismic loads) associated with larger standard deviations have a bigger impact on the load factors. Calculations involving probability and optimization are performed by the governing committee and load factors used to guarantee a minimum probability of failure are published in the applicable standard.

military grade shock tests: military grade shock tests in accordance with MIL-DTL-901E are required for some couplings or other couplings and can be considered a short term dynamic load whose displacement, overload and leakage assessment can be evaluated by the criteria in this standard once the load has been characterized.

noncritical piping: piping system other than critical piping that nevertheless must meet the requirements for position retention during and after a seismic event, i.e., a noncollapsing end state but with potentially significant damage. (Ref. sect. 3.2.2.)

nonseismic piping: piping whose failure during a seismic event is acceptable to the owner and jurisdictional authority which need not be designed for seismic loadings.

operability: the ability of a piping system to deliver, control (throttle), or shut off flow during or after the design earthquake.

overstrength: usually represented by the variable Ω_o, and for strength design of piping components using B_2 or SSI stress indices, is the load or displacement beyond the twice elastic slope load (ASME III Appendices II, or B31J App. D). Overstrength can be defined for individual component or for the overall system. For individual components, when the load exceeds the twice elastic slope collapse load, further displacement should not cause a reduction of load capacity. (The exception is bend in-plane closing. Typical piping layout and redundancy prevent bend in-plane closing from causing complete loss of system load capacity.) (See ASCE 4 XX.XX for strain based overstrength limits.)

position retention: the ability of a piping system not to fall or collapse in case of the design earthquake.

Seismic anchor motion: seismic anchor motion (SAM) is a reversing dynamic load that is due to relative motion between pipe supports that develops from varying building displacements that occur during a seismic event. These building displacements are input at the pipe support/building interface. Piping system stresses produced by SAM effects are secondary (displacement controlled) in nature.

seismic design: the activities necessary to demonstrate that a piping system can perform its intended function (position retention, leak tightness, operability, or a combination) in case of the design earthquake.

seismic function: a function to be specified by the engineering design either as position retention, leak tight- ness, or operability.

seismic interactions: spatial or system interactions with other structures, systems, or components that may affect the function of the piping system.

seismic response spectra: a plot or table of accelerations, velocities, or displacements versus frequencies or periods.

seismic restraint: a device intended to limit seismic movement of the piping system.

seismic retrofit: the activities involved in evaluating the seismic adequacy of an existing piping system and identifying the changes or upgrades required for the piping system to perform its seismic function.

seismic static coefficient: acceleration or force statically applied to the piping system to simulate the effect of the earthquake.

target displacement: the inelastic maximum seismic displacement expected from a static or dynamic analysis that does not require the use of response modification or ductility factors.

nonuniform piping system: piping system interconnected with: a)varying lengths of large diameter and short diameter pipe, b)short, small diameter branches between opposing large diameter pipe subject to movement, c)pipe subject to elastic follow-up, and d)small diameter pipe anchored closely to large diameter pipe.

uniform piping system:used to refer to an integrally welded piping system of uniform strength and ductility that extends between two or more anchors with intermediate supports. Uniform piping systems are not subject to damage by large ground motion seismic inertial events.

zero load bumper: supports to address the uncertainty that exists with large motion seismic events, or with other difficult to evaluate reversed dynamic loads. Zero load bumpers are designed with gaps equal to the maximum anticipated seismic movement and are intended to minimize possible system instability, provide redundancy, overstrength, and assure that calculated displacements are sufficiently accurate.

1.3 Required Input

The Standard user should compile all of the following data, recognizing that minimum load standards may change from version-to-version and that it is the user's responsibility to be sure that commercial software satisfies the requirements for the applicable Code year.

(a) The scope and boundaries of piping systems to be seismically designed or retrofitted.
(b) The applicable ASME B31 Code section.
(c) The classification of piping as critical or noncritical, and the corresponding seismic function (position retention for noncritical systems; degree of leak tightness, operability, or both for critical systems).
(d) The free-field seismic input / ground motions (commonly in the form of accelerations) for the design earthquake at the geographic location of the facility and for the applicable soil conditions.
(e) The responsibility for developing the in-structure seismic response spectra, where required.
(f) The operating conditions concurrent with the seismic load and the determination and application of response modification factors per 3.2.3.
(g) The responsibility for qualification of the operability of active components, where required.
(h) The responsibility for the evaluation of seismic interactions and the recognition that the solution method used may underestimate displacements in which case engineering judgment or additional analyses are required to determine that sufficient flexibility is available where displacements at supports may be out-of-phase or not wholly included in the analysis.
(i) The responsibility for as-built reconciliation of construction deviations from the design documents.

2 MATERIALS

2.1 Applicability

This Standard applies to all metallic piping materials listed in the applicable ASME B31 Code section.

2.2 Retrofit

The seismic retrofit of existing piping systems shall take into account the condition of the system and its restraints. The retrofit evaluation shall take into account accumulated (strain) damage.

As part of the seismic retrofit, the piping system shall be inspected to identify defects in the piping or its supports and current and anticipated degradation that could prevent the system from performing its seismic function.

Although different criteria may be permitted for seismic retrofit of building structures such as in the ASCE 41 Code, *Seismic Rehabilitation of Existing Building Structures*, the intent of this B31E standard is that the same stress criteria apply to new designs as for retrofit projects. See API-579 / ASME FFS-1, Fitness for Service, for additional information for FFS criteria other than seismic.

3 DESIGN

3.1 LIMITATIONS OF APPLICABILITY

3.1.1 Large D/t and small Diameter Pipe

This Standard applies to piping having a cross-section D/t ratio of 50 or less unless seismic induced occasional stresses remain elastic and/or circumferential support or local thickening is applied to assure that plane sections remain plane.

Piping where the $D/t > 50$ can be subject to shell buckling, overstrain or an underestimate of displacements due to local stresses. Small bore pipe where $D_o < 1.5$ in. may experience large rotation and stress stiffening where relative displacements are high with respect to the diameter of the pipe. Larger pipe experiences plastic bending, while small bore pipe undergoes a transfer of bending to membrane stresses and can experience a significant increase in axial load for a relatively small rotation.

3.1.2 Nonmetallic Piping

Nonmetallic pipe supporting and pressure effects are considerably different than those effects for metallic piping. Sections for non-metallic piping, loads, displacements and supporting are under development.

3.2 SEISMIC DEMAND, GROUND MOTION INPUT

3.2.1 Seismic Demand Input Source

The seismic demand ground motions to be applied to any piping system, whether contained within a building structure or as an independent standalone system, are specified by the applicable jurisdiction's specified building code, which in the US is generally based on the International Code Council's (ICC) model International Building Code (IBC). These either adopt or reference with changes the structural design criteria document ASCE/SEI 7, Minimum Design Loads and Associated Criteria for Buildings and Other Structures (hereafter referred to as ASCE 7).

ASCE 7, which is referenced in most B31 sections, defines earthquake spectral response acceleration parameters at 0.2-second short period (S_{DS}) and 1-second-long period (S_{D1}) at geographical locations using either the US Geological Survey's (USGS) Seismic Design Geodatabase which is available through the USGS Web Service or, as of the 2022 edition of ASCE 7, the ASCE 7 hazard tool online.

The ASCE7 design response spectrum is also provided as a multi-period 5% damped response spectrum. For locations where the multi-period response spectrum is not available, or where the analyst desires, the two-period response spectrum may be used.

The ASCE 7 design earthquake is specified as having 10% probability of exceedance within 50 years, or a 475-year return period. The more severe maximum considered earthquake (MCE) is specified as having 2% probability of exceedance in 50 years, or a return period of 2475 years. For comparison, the design basis event for commercial nuclear plants has a return period of 10,000 years (i.e., the seismic demand for industrial structures is much lower than for nuclear plants.) For B31 piping in the US, the ASCE 7 design level seismic demand, (S_{DS} and S_{D1}) input is appropriate for determining piping system response.

The S_{DS} and S_{D1} acceleration parameters are used to either develop design response spectra for dynamic analysis, to develop input for time history analysis, or to calculate equivalent static forces such as in ASCE 7 Ch. 13. The commentary of ASCE 7 provides background and rationale associated with each of these approaches. It should also be noted that the maximum considered earthquake (MCE) may be selected by the owner as the design basis event if warranted by risk and hazard considerations. An example of such design is the new San Francisco – Oakland Bay Bridge, but this would be rare for industrial projects.

To determine the specific loads to be applied to particular piping systems and their supporting elements and structures based on these ground motions, decisions must be made by the owner and designer considering hazard assessments, business priorities, etc. They must also comply with the requirements of the local Authorities Having Jurisdiction (AHJs).

3.2.1.1 Source Input Height Amplification and other influences

The seismic loading applied to piping systems inside buildings or structures must account for the in-structure amplification of the free-field ground accelerations by the structure. The in-structure amplification may be determined on a simplified basis based on the ASCE 7 Chapter 13 Height Amplification Factor, equation 13.3-5, Input Amplification = $1 + 2.5(z/h)$ or by a facility-specific dynamic evaluation, where z is the height of the support attachment point to the pipe above ground and h is the roof height. In-structure response spectra can also be developed through detailed modeling of the building structure, simplified modeling of the building structure, or by verifying that the building behaves in a rigid manner relative to the pipe. Where small and large connected piping systems interact in the same or different building structure, adequate flexibility must be provided as discussed in sect. 3.4.1.1- *ductility review*.

When sensitive equipment (rotating or non-rotating), hose, refractory or glass lined components, etc. where little to no overstrength exists, in-structure loadings might be higher than loads computed using response modification factors in ASCE 7 equation 13.3-4. In this case the user should consult sect. 3.2.3 – *response modification factors* to assure that appropriate design loads are considered.

Measurement devices, large actuators, threaded connections, relative support movement, configurations sensitive to elastic follow-up, cantilevered systems (no redundancy) and large differences in d/D can also result local sensitivities.

Site specific soil irregularities, proximity to fault lines, independent foundations and local liquefaction may all influence resultant seismic loading. Designers are urged to evaluate the local site conditions carefully. Softer soils can increase peak load spike duration inducing more significant primary load behavior.

Underestimated displacements at supports, while historically not resulting in the collapse of piping systems, may result in interference, loss of fatigue life or damage due to ratcheting where high membrane stresses due to pressure exist.

Maximum venting conditions possible during an earthquake (e.g., internal pressure during choked flow conditions) should be included in the simulation if applicable. (Ref. App. 4).

3.2.1.2 Damping

System damping reduces the magnitude of the earthquake input accelerations in linear analyses. The damping value for piping system design may be taken as 5% of critical damping.

3.2.2 Critical vs. Noncritical Piping, Seismic Risk Category

It is the owner's responsibility to ensure that the appropriate criticality designation is assigned to a piping system that must meet seismic design requirements, and that the appropriate analytical method be selected for qualifying that piping system. Table 3.2.2 relates the B31E criticality designation to the ASCE 7 Table 1.5-1 Risk Category.

3.2.2.1 ASME B31 Critical Piping

When ASME B31.9 piping systems leak after seismic events considerable damage can be done to both the building and its ability to provide critical services. B31.9 defines critical piping for seismic design as shown in section 1.2 of this standard, essentially requiring a leak-tight, operable end state following the specified seismic event. This is considered a similar requirement for many piping systems in B31.3, B31.1, B31.12, B31.4 and B31.8 services where some degree of leak tightness must be maintained to avoid ancillary damage. This standard endorses that definition, noting however that the definition does not provide unambiguous correlation to ASCE 7, which is needed since supporting structures must comply with the structural Code. See sect. 3.8 for more details.

3.2.2.2 Other Requirements for Critical Piping

Displacements due to underestimated dynamic displacements or elastic follow up can result in fatigue or local failure and leakage at flanged joints due to bolt stretch, poor installation practices or torsion when small systems are loaded by the movements of large surrounding pipe. The guidelines in Appendix 9 can be used to evaluate the necessary high tightness or low tightness requirements of flanged joints in critical systems.

For steam and other high pressure gas systems where leakage is not visible or audible (acoustic sensors) the user must exhibit considerable care when restarting high pressure gas facilities after seismic events. In some cases, the alternating moments may result in leakage only during the event.

3.2.2.3 ASCE 7 Risk Category Applied to Piping

In ASCE 7, the risk category (RC) of the system is established in conformance with ASCE 7 Table 1.5 therein based on "Use or Occupancy of Buildings and Structures." The owner or designer is permitted to redefine aspects of the 3.2.2 classification as necessary. Recommended alignment with this standard is provided in Table 3.2.2 below.

Table 3.2.2 Risk Category Alignment

ASCE 7 Table 1.5-1 Risk Category	ASCE Risk Category relationship to B31E
I	Noncritical Piping
II	Owner or designer to select as applicable.
III	Critical Piping
IV	Critical Piping

The user of this standard should recognize the potential for stored energy release, the release of hazardous or toxic substances, the presence of high pressures or damaging amounts of water or other liquids, and the possibility of an owner designated "essential facility" which could be due to business imperatives, unique national infrastructure, etc. A "critical piping" classification may be used for any circumstance.

3.2.2.4 ASCE 7 Importance Factor Applied to Piping

Given the risk category / criticality designation, ASCE 7 assigns a structural and component importance factor, I_e and I_p respectively, that are used as multipliers on the force applied to the structure. The values range from 1.0 for RC I and II, 1.25 for RC III, and 1.5 for RC IV /

Critical. ASCE 7 commentary explains that the concept of importance factor related to structural design does not directly correlate to the same end states in components such as pressure piping.

Even though it does not directly correlate to a piping end state, the importance factor is required for structural design and it is recommended that it be applied to the piping input demand (seismic accelerations). This will ensure that the associated pipe supports and structures to which piping is attached are designed appropriately and in accordance with the structural code. If it is not applied directly to the piping, the structural designer must ratio the piping loads and displacements transmitted by the piping designer by the appropriate importance factor.

3.2.3 Response Modification Factors Applied to B31 Piping for Static and Dynamic Loading

B31 calculated stresses utilize elastic nominal behavior while recognizing that local overstrain (some plastic straining) can exist for both primary[1], secondary and expansion stresses. The use of ASCE 7 or ASCE 4 inelastic energy absorption factors, ductility factors, response modification factors, etc., such as F_μ, R, R_μ, R_{po} or R_p, to reduce seismic loads because of system ductility not included in the elastic model must be used with the appropriate Categories and solution methods described in Tables 4, 4a, 3.3.2, and 3.3.2-1 herein.

When Category 1 and 2 allowable stresses in Table 2 and Table 4 are used (a) below must be satisfied. When Category 3 allowable stresses in Table 2 and Table 4 are used both (a) and (b) below must be satisfied.
(a) additional ductility requirements must be satisfied per sect. 3.4.1.1, and
(b) response modification factors R, R_μ, R_{po} or R_p and F_m must be redced as described in Tables 4a.

<footnote 1> primary stress allowables are formulated so that after the component is loaded to the allowable load and then unloaded, the component will return to its original shape, permitting a small amount of inelastic strains.

Allowable stresses for Category 1 and for Category 2 piping in section 3.4 follow historical precedent and will underestimate elastic stresses, support loads and displacements. These calculated support loads and displacements must be adjusted using engineering judgment, and various adjustments described herein, to avoid underdesign of supports and pipe interference with other pipe, critical electrical relays or other control systems. Good engineering judgement in terms of layout and ductility must be provided.

Unlike Table 2 Category 1 and Category 2 critical piping, all Category 3 piping is intended to produce accurate displacements, forces and stresses. There is no need to adjust support loads and displacements when ductility factors are set to unity. See Eq. 12 and Tables 2 and 4a.

$$R_p = R = R_\mu = R_{po} = F_\mu = 1.0 \qquad \text{Eq. 12.}$$

Where in-structure loads or relative displacements may be significant for any Category, the user is encouraged to either:
1)Follow the guidelines in Sect. 3.4 Table 3.
2)Perform a ductility review per 3.4.1.1.
3)Use experience to be sure that sufficient flexibility and support loadings are present near equipment anchors and close supports.
4)Include structural models in the analysis.
5)Consider the AZ Method in Table 3 as a method to evaluate the relative displacements at supports adjacent to anchors.
6)Include models of the structure in the analysis.
7)Include flexibilities of the structure in any static analysis as described elsewhere herein, (sect. XX).
8)Perform a dynamic modal analysis with approximate or actual models of the structure and supports. (See simplified structural models described herein, (sect. XX).
9)Consider performing an inelastic analysis per sect. 3.3.2.3.1.

The allowable stress basis is described in Table 4.

Table 4: Sect 3.4 Table 2 Allowable Stress Basis[1]

Category	
1 (0.9Sy)	Analysis has historical, over-conservative basis. Loads and displacements can be underestimated. Stresses are underestimated based on ductile pipe and structure behavior not included in the simulation. Post-analysis result evaluations must verify system ductility and relative displacement capability by inspection. Ductility factors are used per the applicable Code, e.g. ASCE 7.
2 (2.0Sy)	Intermediate basis. Underestimated stresses are permitted to have higher allowable stresses consistent with ductile piping systems. The user must apply ductile design guidance per 3.4.1.1. Ductility factors are used per the applicable Code, e.g. ASCE 7.

3 $(4.0Sy)^2$	Stresses are not artificially reduced using ductility factors. Higher allowable stresses are permitted. Displacements and support loads are more accurately predicted. Ductility and relative support movements must be checked. Simplified inelastic behavior and component analysis is optionally provided and may be used as a verification tool for the results from all other Categories.

[1] Sy is the material yield strength when the seismic or reverse dynamic event occurs.
[2] Allowable stresses are not used for inelastic analysis design points. See Appendix XX for strain and rotation allowables.

Table 4a: Sect 3.4 Table 2 Ductility Factors[1]

Category	
1	R_p , R , R_μ , R_{po} : As specified by applicable design Code, i.e. ASCE 7. For B31 distribution systems (piping), usually greater than 1.0.
2	R_p , R , R_μ , R_{po} : As specified by applicable design Code, i.e. ASCE 7. For B31 distribution systems (piping), usually greater than 1.0.
3	$R_p = R = R_\mu = R_{po} = F_\mu = 1.0$

[1] a small amount of ductility is included in the Category 1 analysis while an increased amout is permittedin Category 2 and 3 analysis due to the short term, strain limited dynamic nature of seismic and reverse dynamic loads covered by this standard.

ASCE 4 and ASCE 43 use a similar concept of energy absorption / ductility factors, therein called F_μ, which varies by desired limit state (post-event outcome). F_μ = 1 is equivalent to R_p = 1. (See ASCE 43-19.)

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The horizontal seismic design force shall be calculated as

$$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] \qquad (13.3\text{-}1)$$

F_p is not required to be taken as greater than

$$F_p = 1.6 S_{DS} I_p W_p \qquad (13.3\text{-}2)$$

and shall not be taken as less than

$$F_p = 0.3 S_{DS} I_p W_p \qquad (13.3\text{-}3)$$

where

F_p = Seismic design force;
S_{DS} = Spectral acceleration, short period, as determined in accordance with Section 11.4.5;
I_p = Component Importance Factor as determined in accordance with Section 13.1.3;
W_p = Component operating weight;
H_f = Factor for force amplification as a function of height in the structure as determined in Section 13.3.1.1;
R_μ = Structure ductility reduction factor as determined in Section 13.3.1.2;
C_{AR} = Component resonance ductility factor that converts the peak floor or ground acceleration into the peak component acceleration, as determined in Section 13.3.1.3; and
R_{po} = Component strength factor as determined in Section 13.3.1.4.

3.2.4 Seismic Demand Load Factors Applied to Piping (1.0E)

For B31 and ASME III analysis of seismic and other reversing dynamic loads, when using the design response acceleration parameters from ASCE 7 Chapter 11 to calculate inertial loadings the load factor for earthquake loads (E) in load case combinations should be 1.0 for all categories of seismic strength-based loading to align with B31 and ASME III strength based resistance using the stress indices SSI or B_2. Where ASCE 7 recommends point-in-time factors of 0.75, for load cases including both seismic, wind or other occasional loadings those factors shall be used without change.

3.2.5 Allowable Stresses

Experience has shown that inertial load failures do not occur for uniform piping systems where ductility and flexibility is included inherently in the design, i.e. weld neck flanges, vs. threaded connections. Issues can arise when larger piping systems are attached to inflexible smaller pipe that is improperly supported or where relative movement between supports is not accounted for. These issues are usually resolved either by inspection, experience or an inelastic analysis where redundant behavior and elastic follow-up can be evaluated and shown to be within expected limits.

Sect. 3.4 Table 2 and Table 4a provides increased allowable stresses along with ductility design recommendations to permit a more appropriate seismic or reverse dynamic load evaluation. (See Rodabaugh [12].)

Section 3.4 Table 2 guidelines are used with stresses computed using equations 7a-7e, or 8a-8e.

Seismic loads, or other reverse dynamic loadings can cause low cycle damage due to fatigue or ratcheting. Equations 9a-9e can be used with the allowable equations XX thru XX to evaluate the cumulative damage due to fatigue and ratcheting.

These collective approaches are believed to provide relief to designers subject to thermal loadings where snubbers must otherwise be used to restrain seismic loads without inducing thermal stresses. Fewer restraints should be needed and when used with gapped bumpers to control seismic displacements, economic piping systems with a low probability of failure can be designed in high seismic areas.

3.3 DESIGN METHOD

The method of seismic design may be as given in Table B-3.2.1 of B31.9, except that Design by Analysis is required for all critical piping. Otherwise the method selection depends on:

(a) the classification of the piping system (critical or noncritical)
(b) the magnitude of the seismic input
(c) the pipe size
(d) owner/designer preference

In all cases, the designer may elect to seismically design the pipe by analysis, in accordance with para. 3.3.2.

3.3.1 Design By Rule

Where design by rule is permitted in Table 1, the seismic qualification of piping systems may be established by providing lateral seismic restraints at a maximum spacing given by the following:

(a) For U.S. Customary units

$$L_{max} = \text{the smaller of } 1.94 \times \frac{L_T}{a^{0.25}} \text{ and } 0.01 \times L_T \times \sqrt{\frac{S_y}{a}}$$

a = peak spectral acceleration, largest in any of the three directions, including in-structure amplification, g
L_{max} = maximum permitted pipe span between lateral seismic restraints, ft
L_T = reference span, the recommended span between weight supports, from ASME B31.1, Table 121.5 (reproduced in Table 2), ft
S_Y = material yield stress at operating temperature, psi

(b) For SI units

$$L_{max} = \text{the smaller of } 1.94 \times \frac{L_T}{a^{0.25}} \text{ and } 3.33 \times L_T \times \sqrt{\frac{S_y}{a}}$$

a = peak spectral acceleration, largest in any of the three directions, including in-structure amplification, g
L_{max} = maximum permitted pipe span between lateral seismic restraints, m
L_T = reference span, the recommended span between weight supports, from ASME B31.1, Table 121.5 (reproduced in Table 2), m
S_Y = material yield stress at operating temperature, MPa

The maximum span L_{max} between lateral seismic restraints for steel pipe with a yield stress S_Y = 35 ksi (238 MPa), in water service, for several values of lateral seismic acceleration a, is provided in Table 2. Longer spans can be developed for gas and vapor service.

3.3.2 The maximum permitted span length L_{max} should be reduced by a factor of 1.7 for threaded, brazed, and soldered pipe.

Table 1 Seismic Design Requirements, Applicable Sections

	Noncritical Piping		Critical Piping	
Acceleration	NPS (DN) ≤ 4 (100)	NPS (DN) > 4 (100)	NPS (DN) ≤ 4 (100)	NPS (DN) > 4 (100)
$a \le 0.3\ g$	NR section 4 (interactions)	NR section 4 (interactions)	DR para. 3.3 (rule) para. 3.6 (mech. joints) para. 3.7 (restraints) section 4 (interactions)	DA para. 3.4/3.5 (analysis) para. 3.6 (mech. joints) para. 3.7 (restraints) para. 3.8 (components) section 4 (interactions)
$a > 0.3\ g$	NR section 4 (interactions)	DR para. 3.3 (rule) para. 3.6 (mech. joints) para. 3.7 (restraints) section 4 (interactions)	DA para. 3.4/3.5 (analysis) para. 3.6 (mech. joints) para. 3.7 (restraints) para. 3.8 (components) section 4 (interactions)	DA para. 3.4/3.5 (analysis) para. 3.6 (mech. joints) para. 3.7 (restraints) para. 3.8 (components) section 4 (interactions)

a = peak spectral acceleration, largest in any of the three directions, including in-structure amplification, g
DA = design by analysis
DR = design by rule
NPS = nominal pipe size, in.
NR = explicit seismic analysis is not required, provided the piping system complies with the provisions of the applicable ASME B31 Code section, including design for loading other than seismic

Table 2 Maximum Span, ft (m), Between Lateral Seismic Restraints for Steel Pipe With a Yield Stress of 35 ksi (238 MPa), in Water Service at 70°F (21°C)

	Maximum Span, ft (m)					
NPS (DN)	L_T, ft (m)	0.1 g	0.3 g	1.0 g	2.0 g	3.0 g
1 (25)	7 (2.1)	24 (7.2)	18 (5.4)	13 (3.9)	11 (3.3)	9 (2.7)
2 (50)	10 (3)	34 (10.2)	26 (7.8)	19 (5.7)	16 (4.8)	13 (3.9)
3 (80)	12 (3.6)	41 (12.3)	31 (9.3)	23 (6.9)	19 (5.7)	15 (4.5)
4 (100)	14 (4.2)	48 (14.4)	37 (11.1)	27 (8.1)	22 (6.6)	18 (5.4)
6 (150)	17 (5.1)	58 (17.4)	44 (13.2)	32 (9.6)	27 (8.1)	22 (6.6)
8 (200)	19 (5.7)	65 (19.5)	50 (15)	36 (10.8)	30 (9)	25 (7.5)
12 (300)	23 (6.9)	79 (23.7)	60 (18)	44 (13.2)	37 (11.1)	30 (9)
16 (400)	27 (8.1)	93 (27.9)	70 (21)	52 (15.6)	44 (13.2)	35 (10.5)
20 (500)	30 (9)	103 (30.9)	78 (23.4)	58 (17.4)	48 (14.4)	39 (11.7)
24 (600)	32 (9.6)	110 (33)	84 (25.2)	62 (18.6)	52 (15.6)	42 (12.6)

3.3.9 Guidelines given in 3.4.1 Table 2 should be used with Design by Rule approaches. A ductility review per 3.4.1.1 by analysis or engineering judgement should be conducted. along with the following steps (1) through (6).

(1)The piping system should be evaluated to be sufficiently flexible to accommodate the differential movement of attachment points to the structure or the movement of equipment or headers to which the piping is attached. This evaluation may be achieved by calculating the predicted seismic plus concurrent loads movement of the structure, equipment, or header to which the pipe is connected, and verifying that the pipe spans have sufficient flexibility to sustain these movements. Guidelines for relative movements between supports are given in para.3.4.1 Table 3, and are provided in ASCE 7 Table 15.7-1.

(2)The distance between seismic restraints should be reduced for pipe spans that contain heavy in-line components.

(3)Unrestrained cantilevered pipe should be evaluated on a case-by-case basis.

(4)The effect of seismic restraints on the expansion and contraction flexibility of the piping system must be verified in accordance with the design rules of the applicable ASME B31 Code section.

(5)The designer should identify degradation in the piping or its supports and future anticipated degradation that could prevent the system from performing its seismic function.

(6)Straight pipe runs longer than three times the span of Table 2 should be restrained longitudinally.

3.3.2 Design By Analysis

The user must select the analysis method and the allowable stress category to be used for a Design by Analysis solution. There are four analysis methods and 3 allowable load categories to select from. The allowable stress categories are described in Table 2, and the analysis methods are described in Table 3.3.2 below.

Table 3.3.2 Analysis Methods

	Method Description
1	Equivalent Lateral (and Vertical) Force Method. Static analysis. Use of elastic material models. May use any of Table 2 Category 1,2 or 3 allowables and appropriate ductility factors per Table 4a.
2	Same as 1 except may use inelastic material models, ductility factors equal to unity, and limits based on stability, elemental rotations, strains and equivalent inelastic stresses. (See Appendix).
3	Modal Dynamic Analysis (See Appendix 1)
4	Nonlinear Transient Dynamic Analysis. (See Appendix XX.)

Attributes of each analysis method are presented in Table 3.3.2-1.

Table 3.3.2-1 Analysis Method Attributes

1	Static analysis accurate when weight-based lateral (and vertical) loads define main seismic response. Use of ductility factors can result in underestimates of displacements and forces. (Users must assure the presence of ductility by inspection or additional analyses.) Elastic-only behavior may also result in excessive loads or incorrect distributions of forces and moments where small diameter and large diameter portions of the piping systems interact. Static analysis is considered the most economic evaluation method, typically used with ductility factors (see Tables 2 and 4a.), and with allowable stresses from Sect. 3.4 Table 2 Category 1 or 2.
2	Static analysis with inelastic modeling as described in Appendix 6. Ductility factors are set to unity. Results are considered the most accurate static results available; loads are redistributed, redundancy is verified and elastic-followup is incorporated. First order system instability and push-over can be determined. Results can also be used to determine system overstrength.
3	Modal dynamic methods includes accurate influence of mode shapes and structural behavior when modeled. Inelastic analysis can be performed using target displacements and adjusted spectra beyond the scope of this standard. (See Appendix 6). Complete structural models or simplified structural models as described in sect. XX can be implemented.
4	Nonlinear transient dynamic analysis is considered the most accurate analysis method but is the most difficult to apply. Analysts capable of performing this analysis may do so following guidelines in ASCE 7 Chapter 16 and ASCE 4, 41 or 43 as applicable.

3.3.2.1 Linear Response Spectrum Modal Dynamic Analysis (Method 3)

Linear response spectrum (RS) dynamic modal analysis of piping is a valid B31 design approach and may be used in developing loads and stresses in piping for comparison with B31 limits. As stated in section 3.2.3 however, the use of structural response modification factors to effectively reduce the magnitude of the input spectrum is only permitted if the results are to be assessed in accordance with the provisions of Sect. 3.4.1 Table 2 Category 1.

There are many considerations for performing appropriate RS dynamic analysis and this B31E Standard does not purport to serve as a comprehensive guide for doing so. Commentary at the end discusses some of the issues, and the ASME BPVC Section III Appendix N, Section 1223 provides requirements for nuclear piping, which may be useful to the B31 designer.

See also Appendix 1 for additional information regarding modal and directional combinations.

3.3.2.2 Equivalent Static Load Analysis (ELF)

The equivalent lateral force procedure (ELF) of ASCE 7 Chapter 13 is often used to evaluate minimum required seismic loads from ASCE 7 Equation 13.3-3. In high seismic zones, the user is encouraged to use Section 3.4.1 Table 2 allowable stress categories 2 or 3 and assure that ductility and displacements are appropriately considered per 3.4.1.1.

ASME BPCV Section III Appendix N, N-1225, *Simplified Dynamic Analysis* provides an acceptable equivalent static load approach using the peak of the response spectrum, (which is 1 g in high seismic Western US locations), and accounts for support spacing.

3.3.2.3 Advanced Analysis Methods

ASME BPVC III Appendix N, para. N-1222 provides acceptable approaches for both linear and nonlinear time history seismic analysis methods, while ASCE 7 Chapter 16 provides requirements for nonlinear time history analysis of building structures. The user able to perform these calculations is permitted to do so.

3.3.2.3.1 Inelastic Solutions and Target Displacements

Nonlinear transient, nonlinear static, inelastic and target displacement solutions offer improvement in load and displacement behavior modeling and can be far superior to equivalent lateral force (ELF) models of seismic events. These methods may not be familiar to all designers but guidelines are provided in Appendix 8 and in ASCE 41. Analysts are urged to become more familiar with these methods as they can improve displacement and stress predictions and help identify support locations and gaps assuring that seismic movements remain within anticipated bounds while minimizing support loads. Where a nonlinear or target displacement solution is used all of the following should be considered:

a)The owner or their representative should approve use of any advanced analysis.

b)Any advanced analysis method used should be reviewed by an independent third party,

c)Users of piping systems with cantilevered elements in either the vertical or lateral directions are encouraged to perform push-over analysis to determine the system proximity to global instability.

3.3.2.4 Steps for Design By Analysis Methods

General Steps for each Analysis Method and Category are Described in Table 3.3.2-2 below:

Table 3.3.2-2 General Steps for Analysis[1,3]

Mtd[2]	Cat	(Note 2)
1	1	1)Prepare elastic model
		2)Compute seismic or reversed dynamic loads per established guidelines using ductility factors greater than 1 as appropriate.
		3)Establish primary plus occasional load cases as described in the applicable minimum load guideline using ductility factors > 1 as per Table 4a.
		4)Compute stresses per left hand side of Eq. 7e, or 8e.
		5)Compare calculated stress from 7e or 8e to right hand side allowable using So = 0.9Sy per Table 2
		6)Perform ductility review per 3.4.1.1
1	2	Perform identical steps 1 thru 6 above using ductility factors per Table 4a and include the ductility review per 3.4.1.1, except compare the calculated stress from Eq. 7e or 8e to the corresponding right hand side allowable using So = 2.0Sy per 3.4.1 Table 2.
1	3	Perform identical steps 1 thru 6 above using ductility factors per Table 4a and including the ductility review per 3.4.1.1, except compare the calculated stress from Eq. 7e or 8e to the corresponding right hand side allowable using So = 4.0Sy per 3.4.1 Table 2. Perform fatigue and ratcheting calculations per 3.4.2.
2	3	1)Prepare elastic model. Include inelastic point springs (per Appendix).

		2)Compute seismic or reversed dynamic loads per established guidelines using ductility factors equal to 1.0.
		3)Establish primary plus occasional load cases as described in the applicable minimum load guideline.
		4)Use manual iterations or permit commercial programs to find the converged solution using inelastic springs in Appendix ().
		5)Evaluate inelastic rotation, strain or inelastic stress limits per Appendix (). When inelastic rotation = 0.0, members are within allowables.
		6)Perform ductility review per 3.4.1.1.
3	1	1)Prepare elastic model for dynamic modal analysis.
		2)Develop spectra with ductility factors from Table 4a and specify spectrum cases and mode contributions.
		3)Calculate stresses using the left hand side of Eq. 7e or 8e as applicable, with the result compared to the right hand side using So = 0.9Sy per 3.4.1 Table 2.
		4)Perform ductility review per 3.4.1.1
3	2	Perform all steps of Method 3 allowable Category 1 except use ductility factors per Table 4a and compare calculated stress using Eq. 7e or 8e to the right hand side allowables using So = 2Sy per 3.4.1 Table 2.
4		Prepare detailed report describing loading, model and boundary conditions and solution approaches and model validation. Submit to owner and designer for approval. Conduct the analysis as defined in the approved report.

[1] for each calculation evaluate leak tightness per App 10.
[2] Mtd-Method of analysis, Cat – Allowable stress category from Table 2.
[3]When Sy is identified as an allowable, it should be taken at the operating temperature.

3.3.2.5 Other Analysis Considerations

< space reserved >

3.4 SEISMIC PIPE STRESS LIMITS

Seismic load failure mechanisms addressed in this Standard are listed in Table 1 below:

Table 1 – Seismic Load Failure Mechanisms

1	Nonseismic load combination per existing Code	
2	Loads due to pressure weight and seismic	Collapse, displacement, excessive strain
3	SAM Loadings	Collapse, displacement, excessive strain
4	Fatigue Contribution due to Seismic Loading	Thru-wall crack
5	Ratcheting due to Seismic Loading	Thru-wall crack
6	Local Loads (Shear, plus bending/axial)	Local Cracking
7	Flange High or Low Tightness Leakage	Leak rate per App(10)

Piping systems are historically resistant to inertial, displacement limited seismic loading and so larger allowable stresses can be permitted. (See Rodabaugh Ref. 7.)

Some components stressed to greater than 4/3 Sy in most cases[1] do not offer increasing resistance to displacement because twice elastic slope limits have been exceeded. In these instances where elastic models are used support loads and stresses can be artificially high while displacements are artificially low. Ductility load corrections given in ASCE 7 (load reduction) are introduced in most static and dynamic analysis to calibrate stress results so that successful systems are not rejected. When inelastic behavior per Table 3.3.2 Method 2 is considered, load reduction factors are not required.

Calculated stresses compared to given allowables are intensified stresses. For fatigue life determination the stress intensification factors - SIFs(i) in B31J, Table 1-1 shall be used. For primary, sustained or occasional stresses, intensification should be incorporated in the stress evaluation by use of sustained stress indices (sustained stress multiplication factors) in B31J, Table 1-1.

For Sect. III evaluations, B_2 intensifiers can be used for primary, sustained or occasional stresses and the allowable stresses given in Table 2 used in place of S_h in NCD-3652 Equation (8), NCD-3653.1 Equation (9a) and Equation (9b), and in place of S_h in para. NCD-3655 (3). See Appendix 11.

When sect. 3.4.1 Table 2 allowable stresses are used, ductility requirements must be satisfied and their evaluation included in the stress and support load reports.

The ASME III B_2 factor used herein can be taken as 1.5 times the SSI found in B31J-2017 or later versions except for straight pipe where B_2 = SSI = 1.0.

B_2 indices where needed may be defined with respect to the directional SSI indices from B31J Table 1-1, and stresses computed per equations 9a-9e.

Axial loads and stresses, F_{ax}, F_{ax}/A are not used in all Codes but are included in the equations given here since axial loads may be more significant in seismic and other reverse dynamic events and where elastic followup may occur..

Elastically calculated stresses cannot be used at points where inelastic rotations or strains are nonzero. See Appendix xx for evaluation of these points.

Primary loads, sustained loads, occasional loads, limit loads and other overloaded conditions are most often defined in terms of single direction load amplitudes. The equivalent lateral force F_p computed in ASCE 7 Chapter 13 Eq. 13.3-1 is the amplitude of the static applied seismic load. For fatigue evaluations requiring ranges, the statically calculated stresses due to F_p should be doubled. This factor is already included in Equations 9a through 9b.

Load responses computed from modal dynamic analyses are also usually amplitudes and cause displacements that act first in one direction and then in the opposite direction. Modal stress responses must be doubled to be used in a fatigue evaluation using ranges.

Thermal, fatigue, and some dynamic loadings are identified in terms of load ranges. Rotating bar, older fatigue test results and allowables in VIII-2 Part 5 are often given in terms of the stress amplitude.

This Standard addresses fatigue in terms of stress ranges.

Ratcheting involves two stress components. A varying component (seismic) as a range, and the primary component, (pressure) as a constant nonvarying load amplitude, generally given for piping by a stress that is a nonintensified function of (PD)/(2T)[1]. Any intensification should be applied to transform the nominal stress (PD)/(2T) into a local membrane stress.

<footnote 1> for non-creep conditions.

Displacement ranges due to inertial seismic loads, relative displacements at supports and seismic anchor movements (SAMs) can contribute to overload and to fatigue and may be evaluated using any method in Table 3.3.2 and any allowable stress category in Sect. 3.4.1 Table 2.

When para. 3.4 Table 2 Category 2 or Category 3 allowables are used the fatigue damage must be evaluated using 3.4.2(1) and 3.4.2(2) below. If operating conditions involving thermal and other stress ranges are not available, (1) may be used alone to evaluate fatigue damage due to seismic or other reversing dynamic loads.

3.4.2(1) gives a stand-alone calculation for fatigue damage due to seismic or other reverse dynamic events.

3.4.2(2) compute r_i for use in the B31 Code Equation 1d cumulative damage calculation permitting seismic damage to be summed with the damage due to other cyclic loading.

3.4.1 Stress Limits for Primary, Sustained and Occasional Loads

Higher allowable stresses are permitted if the user assures that ductile detailing is employed, fatigue is avoided and at the highest allowed stress levels some nonlinear evaluation of the system may be employed to verify results . Three categories of allowable stresses are provided:

Table 2 – Allowable Stress and Displacement Categories[7, 8, 9, 10]

	Stress Allowable Categories[5]	**[4] Allowable Stress Basis (S_o)**	**E mult**	**Table 15.7-1 Factor**
1	Category 1: Elastic rules with ductility stress reductions and displacement increases.[3]	**0.9 Sy**	**1.0**	**1.0 Cd**
2	Category 2: Elastic rules, plastic detailing and displacement verification recommended.[2, 3]	**2 Sy**	**1.0**	**1.0 Cd**
3	Category 3: Model verification, plastic detailing and displacement verification required. Fatigue and ratcheting per Eqs. 7 or 8 and 9. Inelastic behavior per App.X may be used for overstressed locations and verification.	**4 Sy (Note 6)**	**1.0**	**1.0 Cd**

Notes

[1] bend opening.

[2] users can apply category 3 inelastic guidelines to category 2 analyses to assure that excessive inelastic behavior does not occur in high seismic load categories. (Inelastic analysis can be used with Category 2 or Category 3 allowable stresses.)

[3] increased displacements should be evaluated per ASCE Chapter 13 or using guidance provided herein, (sect. XX). Fatigue calculations are required.

[4] Fatigue calculations should be performed when an elastically calculated stress range due to seismic loading is in excess of 150,000 psi, or calculated strain ranges are in excess of 1%.

[5] Example stress calculations are given in Appendix 11.

[6] When behavior is inelastic, the allowable is based on rotation, and unless otherwise identified, 5 deg. (0.08 radians) is the maximum relative rotation permitted. (See Appendix XX.)

[7] Sy is the yield stress for the condition being evaluated.

[8] If the designer is concerned about the a lack of redundancy, elastic follow-up, or system instability then the Table 2 Category 3 inelastic analysis per Appendix 6 can be performed in addition to any of the Category 1,2 or 3 evaluations.

[9] If used for a Sect.III NC/ND seismic or reverse dynamic load evaluation using B_2 indices, the “Allowable Stress Basis” can be multiplied by 1.5. The additional requirements of Table 2 should also be met, and the guidelines of Appendices 5 and 6 should also be satisfied. Sect.III equation guidance is provided in Appendix 10.

[10] Table 2 Category 2 and 3 allowables may only be used when (a) and (b) below are satisfied:

(a)the system studied has been shown elsewhere to satisfy all weight,

pressure and other sustained loads, and any thermal (expansion) or other operating loads excluding seismic or reverse dynamic loads per the B31 or Sect. III Code of choice.
(b) Seismic or reversing dynamic loads must have an estimated number of cycles less than 500.
(c)seismic and non-reversing dynamic loads are of short impulse duration and are displacement limited.

3.4.1.1 Ductility Review

Where ductility factors given in Table 4a are greater than 1.0 an engineering review of results is required by an engineer experienced in seismic evaluations. The engineer by either calculation or judgment should review the following items along with the layout of the piping system and be sure that sufficiently ductile behavior will occur during an earthquake.

1)flexibility of piping in between supports attached to vessels or structures that are essentially rigid with respect to grade.

2)flexibility of piping in between supports attached to vessels or structure that experience story drift or other local displacements that may be out-of-phase.

3)large diameter and small diameter pipe interacting where large displacements are involved and elastic followup, local overstrain or guillotine separation of the smaller piping may occur.

4)rotating equipment not protected from large overloads

5)essential valves that must operate during earthquakes or emergency conditions.

6)glass or refractory lined pipe systems sensitive to local yield.

7)interference with other pipe, electrical equipment or relays.

Where ductility factors given in Table 4a are equal to 1.0 and a modal or elastic analysis is performed without inelastic verification, then all items in 3.4.1.1 should be evaluated. When an inelastic analysis is performed, then 3.4.1.1 (4),(5), and (6) should be evaluated.

For all cases where movement at structural attachment points is not included explicitly in the model, and the structure is flexible, (see para. 3.8), the "AZ Approach" or displacements in ASCE 7 Table 15.7-1 should be used to be sure that adequate pipe flexibility is provided at anchors and supports in the vicinity of those anchors so that in- or out-of-phase displacements will not damage supports, connections, the pipe or result in leakage.

The "AZ Approach" shown in Table 3 uses a single constant to describe phase aware displacements for any supporting structure, t-pole, compressor building, etc. Using Table 3, the elevation from grade (z) is divided by the constant in Table 3 that is a function of allowable category and pipe criticality. The resulting displacement is applied in a worst-case out-of-phase horizontal direction at the support and evaluated using engineering judgement or a static reanalysis of the piping in the vicinity of the support. The designer must assume that all elevated supports (supports whose elevation above grade is greater than 6.72 ft. (2m).) may move in a phase independent manner whose amplitude in the horizontal direction is given by the AZ approach.

Table 3 – AZ Approach for Out-of-Phase Static Seismic Displacements.

	Category 1 Analysis *mm.(in.)*	**Critical Piping Analysis Categories 2 and 3** *mm. (in.)*	**Non-Critical Piping Analysis Categories 2 and 3** *mm.(in.)*
1	300 (11.81)	200 (7.87)	200 (7.87)

Where gaps or bumpers are provided, the designer must provide sufficient ductility at the support so that plastic behavior is available to reduce displacements and absorb energy. Overstrength for such supports should be on the order of 2-to-3 times the calculated maximum load. Maximum loads may be calculated using zero gaps at points of interest or may be found from equation 10 below:

$$F_{max} = 3.2\, I_p\, W_p, \qquad \text{Eq. 10}$$

where W_p is the longest unsupported length of pipe from the bumper to the nearest support acting in the direction of the design seismic load.

Ductile support behavior is illustrated in Appendix 5 Fig. 5.5. Ductile supports for seismic or reverse dynamic loading can eliminate the need for snubbers, lower the cost of supports, reduce the need to stiffen attached structures and minimize the coefficient of variance (COV) associated with dynamic loadings while still accommodating thermal expansion.

3.4.2 Stress Limits for Fatigue and Ratcheting evaluation of Load Ranges

3.4.2.1 Stresses due to Fatigue

Stress ranges can be calculated to evaluate fatigue for members subject to elastic behavior using Equations 9a through 9e below:

$$S_{ax} = [\, i_a\, (2\, |F_B|/A_p\,)\,]^2 \qquad \text{Eq.9a}$$

$$S_{bi} = [\, i_i\, (2\, |M_{Bi}|\,)\,]^2 / Z \qquad \text{Eq.9b}$$

$S_{bo} = [\ i_o\ (2\ |M_{Bo}|\ )\ ]^2\ /Z$ Eq.9c

$S_{bt} = [\ i_t\ (\ 2\ |M_{Bi}|\ )\ ]^2\ /Z$ Eq.9d

$S = 2(\ S_{ax} + (S_{bi}^2 + S_{bo}^2 + S_{bt}^2)^{0.5}\ )$ Eq. 9e

The cyclic stress range found in Equation 9e can be used in para. 3.4.2.3 for fatigue and ratcheting damage evaluations.

3.4.2.2 When Ratcheting Damage should be determined.

When para. 3.4 Table 2 Category 3 allowables are used and $PDo/(2\ t) > 0.5\ Sy$, ratcheting calculations per Equation 5 should be performed and the effect of ratcheting on cumulative damage determined using the B31 Code equation (1d), (see 3.4.2.4).

P-pressure used in the ratcheting calculation. (See Appendix 4).

Do – outside diameter of the pipe. If at an intersection then the outside diameter of run pipe.

t –pipe corroded wall thickness.

Sy – yield stress in the operating condition.

3.4.2.3 Fatigue and Ratcheting Evaluations

Fatigue damage can be computed using either (1) or (2) below:

1)*life fraction:* To determine the low cycle stress range damage factor divide the number of seismic design cycles (N_{sd}) (usually 10 – to – 100) by the number of allowed cycles (N_{allow}) computed by Equation 2. The result must be less than 1.

2)*cumulative damage – fatigue:* When the seismic fatigue damage from numerous seismic cases must be combined with fatigue damage from operating and possibly other reverse dynamic loadings, select the number of seismic design cases for each seismic stress range S_i. The number of seismic design cycles N_{sd}, is usually 10 -to- 100. Compute r_i for the seismic case "i" using Equation 4 and include the term $r_i^3\ N_{sd}$ into the cumulative damage equation 3d in the applicable B31 design code. (See Eq. 1d from B31.3 below.)

Ratcheting damage can be computed using (1) below:

1)*cumulative damage – ratcheting:* The ratcheting r_i term due to a seismic event (or any large amplitude reversing load) is computed in Appendix 5.
Any number of r_i terms for seismic stress ranges, ratcheting, or any other combination of reverse or non-reversing dynamic loadings may be included in the cumulative fatigue life evaluation. It is not uncommon to include a larger number of smaller magnitude seismic events (that occur more frequently) along with a smaller number of larger magnitude seismic events that would likely only occur once. These seismic loads, when combined with any number of thermal, water hammer or relief valve stress range events can be used to determine the overall fatigue life at a given point in the piping system. This combination will be required to compute the probability of failure (P_f) for reliability evaluations, i.e. $P_f = 1 - \Phi(\beta)$, $\beta_{(estimate)} = [1 - \Sigma(N_i/N_{all\ i})]/SQRT(\ \Sigma\sigma_i^2\ )$; where σ_i is the standard deviation of the allowed cycle ratio ($N_i/N_{all\ i}$).

3.4.2.4 Fatigue and Ratcheting Damage Equations for Low Cycle Stress Ranges

$S \leq 20\ N_{sd}^{-1/3} \times 1.25(Sc + Sh)$ Eq. 1

$N_{allow} = (\ 2\ S/1895e3\ )^{-3}$ Eq. 2

$\varepsilon_{allow} = (1895e3\ /\ 2)(N^{-1/3})/E$ Eq. 3

fatigue:

$r_i = S_{occ}\ /\ S_E$ Eq. 4

ratcheting:

$r_i = C_o\ (\ 0.12\ \varepsilon_g\ /\ (2m_2)\ )^{1/3}$ Eq. 5

C_o, ε_g and m_2 are defined in Appendix 4.

S_{occ} – seismic or reverse dynamic stress range computed using Eq. 9e.

N_{sd} – number of seismic or reverse dynamic load cycles for design, usually 10 – to – 100, although for high return periods (i.e. 5 yrs), N_{sd} may be larger than 100.

r_i – see Eq. 1d below.

S_E - value in Equation 4 is the largest stress range in the cumulative damage assessment not including any seismic or reverse dynamic load range stresses.

The term r_i found in Equation 4 and Equation 5 above, for short term dynamic loading or ratcheting is included as one of the summation terms in Eq. (1d) (shown below from B31.3-2022):

$$N = N_E + \sum \left(r_i^3 N_i\right) \text{ for } i = 1, 2, \ldots, n \qquad (1d)$$

where

N_E = number of cycles of maximum computed displacement stress range, S_E

N_i = number of cycles associated with displacement stress range, S_i

r_i = S_i/S_E

S_i = any computed displacement stress range smaller than S_E

FOOTNOTE: For large seismic loads, r_i in Equation 1d associated with the seismic load will often be greater than 1 and so will account for a large number of equivalent cycles when used in Equation 1d.

Inelastic rotation limits are provided in Appendix 6 when Table 2 Category 3 allowable loads are used with an inelastic solution.

3.4.3 Pressure, Weight and Seismic Stresses[6]

Primary or sustained stresses may be calculated using the users Code of choice and the applicable nominal stress intensifiers:

1) B_2,
2) SSIs (I_a, I_i, I_o, I_t) (B31J-2023) (Ref 17) or
3) 0.75 times SIFs (0.75 i_a, i_i, i_o, i_t).

Primary and sustained Stress equations using load amplitudes are given below.

$S_{ax} = [\, I_a\,(PD/(4t) + |F_A|/A_p + |F_B|/A_p\,)\,]^2$ Eq.7a

$S_{bi} = [\, I_i\,(\,|M_{Ai}| + |M_{Bi}|\,)\,]^2/Z$ Eq.7b

$S_{bo} = [\, I_o\,(\,|M_{Ao}| + |M_{Bo}|\,)\,]^2/Z$ Eq.7c

$S_{bt} = [\, I_t\,(\,|M_{At}| + |M_{Bi}|\,)\,]^2/Z$ Eq.7d

$S = S_{ax} + (S_{bi}^2 + S_{bo}^2 + S_{bt}^2)^{0.5} < So$ (Table 2) Eq. 7e

For Sect. III NC/ND:

$S_{ax} = [\, B_{2a}\,(PD/(4t) + |F_A|/A_p + |F_B|/A_p\,)\,]^2$ Eq. 8a

$S_{bi} = [\, B_{2i}\,(\,|M_{Ai}| + |M_{Bi}|\,)\,]^2/Z$ Eq. 8b

$S_{bo} = [\, B_{2o}\,(\,|M_{Ao}| + |M_{Bo}|\,)\,]^2/Z$ Eq. 8c

$S_{bt} = [\, B_{2t}\,(\,|M_{At}| + |M_{Bi}|\,)\,]^2/Z$ Eq. 8d

$S = S_{ax} + (S_{bi}^2 + S_{bo}^2 + S_{bt}^2)^{0.5} < 1.5\, So$ (*Table 2*) Eq.8e

Z – section modulus of corroded matching pipe.

See Appendix 12 for additional Sect. III NC/ND requirements.

Equations 7a through 8e are strength based expressions including necessary safety factors and plastic section moduli and can only be used when all requirements of para. 3.4.1 is satisfied.

If response modification or inelastic energy absorption factors are applied to the piping analysis such as in ASCE 7, see Tables 4, 4a and 2 for Category 1 or Category 2 allowables.

A_p = pipe cross-sectional area, deducting corrosion/ erosion allowance but not mill tolerance

D = mean matching pipe diameter

F_{SAM} = resultant force (tension plus shear) due to seismic anchor motion

i = stress intensification factor, from the applicable ASME B31 Code section, *0.75i* cannot be less than 1

P = system operating pressure unless otherwise specified.

S = Calculated stress at event conditions for disposition.

Sy = specified minimum yield stress of the material (SMYS) at the event temperature

t = pipe wall thickness, deducting corrosion allowance but not mill tolerance of the matching pipe.

Z = pipe section modulus, deducting corrosion / erosion allowance but not mill tolerance, in^3.

M_A = moment loading on cross section due to weight and other sustained loads, in-lb (mm-M).

M_B = moment loading on cross section due to occasional loads, such as thrusts from relief/safety valve loads, from pressure and flow transients, and earthquake, in-lb (mm-N). If calculation of moments due to earthquake is required, use only one-half the earthquake moment range. Effects of anchor displacement due to earthquake may be applied. See para. 3.4.4 and para. 3.6.2.

M_C = range of resultant moments due to thermal expansion, in-lb (mm N). Also include moment effects of anchor displacement due to earthquake if anchor displacement effects were omitted from equation 2.

Push-over evaluations using simplified inelastic models as described in para. 3.4.1 Table 2 Category 3 can provide insight into model behavior and are recommended for users seeking additional model validation.

3.4.4 Seismic Anchor Motion Stress Limits

There are two types of seismic anchor motions:

1)At-grade foundation movement
2)In-structure anchor movement

When piping systems are anchored to, or supported by a structural frame at an elevation greater than 2 meters it is possible that in-structure movements will occur at the support that are relative to at-grade foundation movements.

When these structures and potential displacements are not included in the model, then relative displacements per ASCE 7 Fig. 15.7-2 or per the "AZ approach" of para. 3.4.1 Table 3 should be considered between supports at grade and the supports at elevations.

When supports or anchors at grade are sufficiently far apart with respect to seismic wavelengths there can also be relative seismic anchor movements in between fixed vessels, equipment or structures.

Maximum relative seismic anchor movements tend to occur at support separation lengths of (c)(p), where c is the speed of sound of the seismic wave and p is the period associated with that sound speed.

The magnitude of the relative displacement between supports is a function of surrounding geological properties and site preparation. Ref 14. (Paper No. 15). Calculations in Ref. 14 shows relative seismic anchor movements of 2.6 in. in a critical span length of 100 ft. which is a function of the seismic wavelength.

Independent foundations can move relative to one-another in soft soils in complex ways as seismic waves interact with local features. User must verify design values and apply judgment. Analytical tools include independent support motion modal analysis, static relative support displacements, or nonlinear transient analysis.

See para. 3.6.2 for seismic anchor movement (SAM) limits.

3.5 MECHANICAL JOINTS [INCOMPLETE]

For critical piping systems, the movements (rotations, displacements) and loads (forces, moments) at mechanical joints (nonwelded, nonbrazed, and nonsoldered joints) must remain within the failure limits (for position retention) or leak tightness limits (for leak tightness and operability) specified by the applicable code or owner. If response modification factors are applied in the analysis such as in ASCE 7 Ch. 13 (which does not address actual pipe displacement, just relative displacements between structures), displacements must be determined using the appropriate displacement amplification factors (C_d) from ASCE 7 Table 15.4-1 or 15.4-2 in accordance with, for example, ASCE 7 section 12.9.1.2 for modal analysis. Alternatively, the analysis could be run with unmodified seismic input to calculate the elastic displacement directly.
Mechanical couplings may be particularly susceptible to pressure and excessive moments.

Coupling testing procedures often do not evaluate the reduction in bending capacity at pressure. [Tony – can you go through the ASTM F1387-19 and point out these deficiencies. The latest version we reviewed was 2019.) ASTM F1387-19 IS INCLUDED IN THE COMPLETE REFERENCES ON THE WEB SITE. This standard covers clamps and couplings. Testing does not indicate that SF exists while loaded under pressure? Apply rated pressure and Mc moment as defined in Appendix 10. Tony – please verify and site sections of F1387-19.

3.6 SEISMIC PIPE STRESS LIMITS

3.6.1 Fatigue Failure Mode Stress Limits

When fatigue due to seismic inertial cyclic loads is the primary failure mode, as is the case for piping with D/t of 50 or less and design by analysis is selected by the designer, the following stress limits shall be used in lieu of the occasional load stress limits in the B31 codes. Elastically calculated longitudinal pipe stresses due to the design magnitude earthquake shall comply with the following equations for both critical and noncritical piping if no response modification / ductility / inelastic energy absorption factors are applied and if permitted by the applicable B31 code:

Stresses due to fatigue can be calculated using the following equations:

$$S_{ax} = [\ i_a\ |F_B|/A_p\ )\ ]^2 \qquad \text{Eq.9a}$$

$$S_{bi} = [\ i_i\ (|M_{Bi}|\ )\ ]^2 / Z \qquad \text{Eq.9b}$$

$$S_{bo} = [\ i_o\ (\ |M_{Bo}|\ )\ ]^2 / Z \qquad \text{Eq.9c}$$

$$S_{bt} = [\ i_t\ (\ |M_{Bi}|\ )\ ]^2 / Z \qquad \text{Eq.9d}$$

$$S_{sei} = S_{ax} + (S_{bi}^2 + S_{bo}^2 + S_{bt}^2)^{0.5} \qquad \text{Eq. 9e}$$

The peak stress range S_{sei} can be used with the Fatigue allowable Equations 1, 2 and 4, and can be used as S_{E_occ} for the ratcheting evaluation in Appendix 4.

M_b and F_b are the range of moments due to seismic or other reverse dynamic loadings. Double the moments used in equations 7a-7e and 8a-8e.

See para. 3.4.3 for terminology.

3.6.2 Seismic Anchor Motion Stress Limits

The effects of seismic anchor motion (SAM) may be conservatively included in the 7a-7e, 8a-8e or 9a-9e stress evaluations including fatigue, ratcheting and inelastic behavior.

If added in these evaluations, or included in the modal dynamic analysis then no further evaluation is required.

If not included in any prior analysis then the displacements at prescribed restraints may be analyzed separately per Table 3.3.2 Method 2, Table 2 Allowable Category 2 and ductility reduction factors set for "critical piping".

Seismic anchor movements may be in-phase or out-of-phase with other seismic loadings.

3.7 <See 3.5 for Mechanical Joints>

3.8 SEISMIC PIPE SUPPORTS

The interaction between structure, pipe and supports depend significantly on the properties of the structure. Considering that most uniform piping systems subject to inertial loads do not experience failure of any kind the effect of the structure should be evaluated for support loads, structural attachments or movement of small lines attached to the pipe or structure. When the structure is flexible, the piping designer has more to consider but can generally simplify the system as long as there are no complexities. In these cases additional flexibility and possible out-of-phase displacements should be considered.

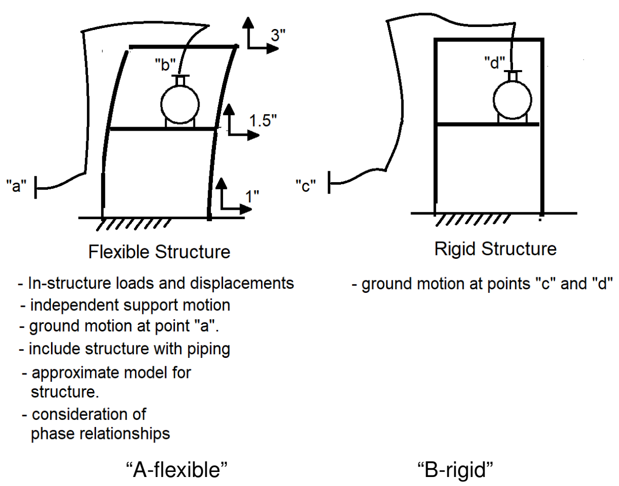


Fig. 3.8-2 Pipe and Structure Interaction

The pipe designer is responsible for transmitting appropriate loads to the structural engineer. The structural engineer will have their own procedures for dealing with seismic and other reverse dynamic loads that may be displacement limited.

Almost all structural analysis is based on ASD or LRFD strength methods, and so the structural engineer needs a strength based load and a system assumption, i.e. was the structure assumed to be rigid or flexible.

A rigid structure is one where there are no lower bound natural frequencies and the in-structure base excitation is the same as the ground excitation. There are no relative displacements for rigid structures.

A structure is considered "rigid" (Fig. 3.8-2 (B)), in ASCE 7-22 Chap. 11 if its first natural frequency is greater than 17 Hz. A structure is considered "rigid" in ASME III when its first natural frequency is greater than 33 Hz. (Ref – Joe?). Modal displacement amplitudes associated with 1g loading of rigid structures are given in Table 3.8-1.

Table 3.8-1 1g Modal Displacements for rigid structures[1]

	Frequency	Deflection (amplitude)
1	17 Hz	0.034 in.
2	33 Hz	0.009 in.

[1] Modal displacements cannot be used directly in a 3-dimensional model of the piping system, but do provide order-of-magnitude estimates of attached structural displacements.

For structures to remain rigid in high seismic zones their behavior must often be elastic. In these cases (ASME III) the structures may be considerably larger than a similar structure for a fossil power plant or refinery and when structural and piping natural frequencies align, significant in-structure loading may develop with loads well in excess of ASCE 7 equation 13.3-3.

Table 3.8-2 identifies loads that should be transferred from the piping analysis to the structural engineer.

Table 3.8-2 Loads for Structural

	Case	Loads to Structural
	Ductility factors in piping analysis are greater than 1.0	Loads from piping analysis should be multiplied by the largest of the ductility factors before being communicated to the structural engineer.
	Ductility Factors are equal to 1.0.	Loads from piping analysis can be communicated directly to the structural engineer.
	Inelastic Analysis is Performed	Loads from piping analysis can be communicated directly to the structural engineer.

For each structural support, calculated loads need not exceed F_{max} found from Eq. 10.

When structural models are not available, and the structural system contains more than four load bearing columns and is higher than 2m. the lateral stiffness can be approximated by Eq. 11 below and lower bound natural frequences estimated for any part of the structure using Dunkerley's equation outlined in Table 3.8-2 below.

Lateral Structural Stiffness = 450,000 (1.11 - z/h) (lb/in.)   Eq. 11

Below 2m if the lateral stiffness is unknown, then use 500,000 lb./in.

The natural frequency of the structure can be estimated using Dunkerley's Approach for natural frequencies. Steps for the calculation are given in Table 3.8-2.

Table 3.8-3 Dunkerley's Steps for Natural Frequencies[1,2]

Step	Action (See Fig. 3.8.1-2)
1	Estimate lateral stiffness at mass "i" using Eq. 11 or a static calculation using a model of the structure. Find the lateral stiffness $k_i = F_i / \delta_i$.
2	Perform the same calculation for all appropriate masses of concern, i = 1, … n.
3	Perform the same estimation for a lateral load at the top of the structure to find k_{top}.
4	Estimate the mass of half of the structure omitting concentrated masses at points i=1,n. This mass will be m_{top}.
5	Estimate the individual natural frequencies for masses i=1,n from: $f_i = (k_i / m_i)^{0.5}$.
6	Estimate the contribution from the mass of the structure using: $f_{top} = (k_{top} / m_{top})^{0.5}$.
7	Find the natural frequency of the structure and any "n" concentrated masses from: $f_{structure} = (1/f_1^2 + 1/f_2^2 + \dots 1/f_n^2 + 1/f_{top}^2)^{-0.5}$.

[1] when structural models are available, the lateral stiffness should be calculated by applying single point loads at the location where the mass is present and then computing the lateral displacement only to that load. The stiffness due to mass "i" is F/δ.
[2] any consistent units can be used.

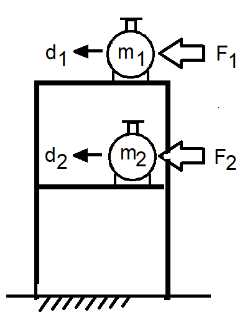


Fig. 3.8-3 Loads and Displacements for Dunkerley's Calculation of Natural Frequency. Two separate calculations for stiffness of this structure must be made, i.e. at points 1 and 2.

3.8.1 B31 Pipe Supporting Elements

The seismic load on pipe restraints and their attachment to building structures or anchorage to concrete shall be calculated by static or dynamic analysis and added to concurrent operating loads.

The seismic adequacy of seismic restraints should be determined on the basis of vendor catalogs and the applicable design method and standard, such as MSS SP-58 or MSS SP-69 for standard support components, AISC or AISI for steel members, and ACI for concrete anchor bolts. The qualification of seismic restraints must also address the prevention of buckling.

Neither vendor catalog ratings nor the MSS standards address the applicability of ASCE 7 response modification / ductility factors. It is recommended to use the load guidance from Table 3.8-2 when determining support capability. Strength safety factors of at least 1.67 are expected from commercial supports with ductility represented by an overstrength of 2-to-3. This requirement is similar to the requirement of ASCE 7 para, 15.7.10.5 for evaluation of buckling sensitive structures, and ASME VIII-2 Part 5.

3.8.2 Structural Steel Elements of Pipe Supports

Structural steel elements, anchorages, and foundations to which catalog or MSS SP pipe supports attach must generally be designed by the licensed structural engineer in accordance with ASCE 7 Chapter 15. Ch. 15 has substantially different force calculation requirements and ductility response R factors for various types of structural elements than Chapter 13 has for piping and pipe supports, and ASCE's intent in this regard is unclear. At a minimum the piping support structure designers must ensure that response modification factors are not "double booked" with forces being reduced initially for the piping and again for the support structure. Alternatively, the piping designer, particularly for critical piping, may use response modification / ductility factors of 1 for the pipe stress analysis and load / displacement calculation, and pass unmodified, elastically calculated pipe support loads to the structural engineer for their design in full conformance with ASCE 7 or other applicable structural code.

3.8.3 Non-seismic restraints

The seismic adequacy of nonseismic restraints should also be verified if they are expected to perform a function after the earthquake. For example, spring hangers should not be permitted to pull off the wall if they are necessary to support the pipe weight after the earthquake. To assess this, the displacement of the pipe must be calculated to determine if the device bottoms out and is further loaded. Such displacement calculations require the use of unity response modification factors (critical piping) or displacement amplification factors, C_d (non-critical piping).

3.8.4 Gaps

For lateral seismic restraints, a total diametric gap equal to 1⁄2 in. (12 mm) is acceptable and may be modeled linearly, i.e., as if no gap exists for dynamic loading. A gap greater than 1/2 inch total up to 0.1*D* or 2 in. (50 mm), whichever is smaller, is permitted, provided the seismic load on the support, calculated on the basis of zero gap, is multiplied by an impact factor of 2. Larger gaps or smaller impact factors may be justified by analysis or test.

3.8.4.1 Seismic supports where thermal displacements are high.

When seismic supports are located at points in the system where thermal displacements are high, snubbers may often be avoided if ductile bumpers are placed at the estimated seismic plus thermal displacements to constrain displacements beyond the estimated seismic mean as given by the 84th percentile. Loads at ductile bumpers can be estimated from Eq. 10, and in most cases, (even during seismic events), will not be used. These supports guarantee redundancy and prevent instability due to highly unpredictable long return period earthquakes.

3.8.5 Short Rods

Short rod hangers [typically less than 12 in. (300 mm) long] may provide a restoring force that tends to limit side-sway of vertically supported pipe, and may be considered as seismic restraints, provided they are designed to sustain the seismic loads and movements. To include these supports in an analysis a large rotation capability is required by the analyst. Favorable lateral resistance is a function of the rod length and will generally begin to have an influence when the rod angle exceeds 5 deg.

3.8.6 Pipe Support Stiffness Considerations

Pipe support element and structural steel stiffness shall be considered when qualifying a piping system in accordance with the B31 Codes since dynamic amplification of flexible systems (i.e., those with fundamental frequency below a rigid threshold frequency) can significantly increase loads and displacements resulting from ground motion input.

The support stiffness can be modeled into the piping analysis or the support can be designed to two deflection limits. Since ASCE 7 defines “Ridge” as 17cps.under the mass load using the design load deflection limit will envelope stiffness check. First check the deflection in the restrained direction to a 1/16” maximum for Occasional loading condition in each direction. The second check is to check the total deflection in all restrained directions to a 1/8” deflection for the maximum combined loading. Checking these two deflection limits under maximum loading conditions are met the support will be modeled as rigid in the piping analysis.

3.9 EQUIPMENT AND COMPONENTS

The seismic and concurrent loads applied by the pipe at equipment and component nozzles must be qualified as part of the seismic design or retrofit of the piping system, to a degree commensurate with the required system function, as specified in para. 1.3. However, nozzle loads provided by vendors or via standards such as API-610 (centrifugal pumps) or evaluated by means of WRC-107 / 297 / 537 require elastic load calculation that is incompatible with the use of response modification / ductility factors as in ASCE 7 Ch. 13 for piping. Therefor critical piping nozzle loads should be evaluated with these factors set to unity.

For position retention (non-collapse), it is usually sufficient to show that the piping loads on equipment and components will not cause rupture. For leak tightness (critical piping), the stress should be maintained within yield or shown not to cause fatigue ruptures (the stress limits of WRC 107 / 297 / 537 may be used). For operability, the piping loads shall be kept within operability limits established by detailed analysis, testing, or similarity to seismically qualified equipment or components.

Components with unsupported extended structures, such as valves with heavy motor operators, should be evaluated to ensure that the extended structure does not fail during a seismic event. For components with unsupported extended structures, a natural frequency check should be performed and if greater than 33 Hz, it will respond rigidly and is likely acceptable. When the natural frequency is less than 33 Hz, the component extended structure should either be stiffened as recommended by the component manufacturer or modeled to assure that any resonances with system response are adequately addressed in the design analyses.

3.10 EVALUATION OF WELDED ATTACHMENTS TO PIPING FOR SEISMIC LOADS

Should we:

- Reference WRC 448.H – Evaluation of Welded Attachments on Pipe & Elbows, Rodabaugh, et. al. (1/2000)
- Reverence the forthcoming B31W, Standard Method for the Evaluation and Design of Rectangular Attachments and Welds to ASME B31 Above -Ground Piping Systems (20xx TBD)

Application of response modification factors prohibited? Fatigue seismic allowables still ok?

…etc.

4 INTERACTIONS

Piping systems should often be evaluated for seismic interactions in congested areas. Credible and significant interactions should be identified and resolved by analysis, testing, or hardware modification. However, the determination of displacements for interaction assessments is incompatible with the use of response modification / ductility factors in ASCE 7 Ch. 13 and analyses should either be performed using Category 3 guidelines or by the use of displacement amplification factors, C_d, as previously discussed for mechanical joints (noncritical piping). (See Sect. 3.4 for a description of Category 3 factors and requirements.)

5 DOCUMENTATION

The engineering design shall specify the documentation to be submitted by the designer.

6 MAINTENANCE

The piping system should be maintained in a condition that meets the seismic design requirements for the operating life of the system. In particular, changes to layout, supports, components, or function, as well as material degradation in service should be evaluated to verify the continued seismic adequacy of the system.

7 REFERENCES

The following is a list of publications referenced in this Standard. The latest edition shall apply, unless otherwise noted.

1. U.S. Regulatory Commission Regulatory guide 1.92 – Combining modal responses and spatial components in seismic response analysis
2. Evaluation of modal combination methods for Seismic response spectrum analysis- BNL-NUREG-66410. Paper ID K4-A4-US
3. E. Rosenblueth and J. Elorduy, "Responses of Linear Systems to Certain Transient Disturbances," Proceedings of the 4th World Conference on Earthquake Engineering, Santiago, Chile, January 13–18, 1969, Volume I, pp. 185–196,.
4. On the correct application of the 100-40-40 rule for combining responses due to three directions of earthquake loading- PVP2010-25466, Jinsuo Nie, Richard J Morante, Manual J Miranda, Josh I.Braverman, Proceedings of ASME Pressure vessel and piping Conference /K-PVP conference, July 2010, Washington, USA
5. Leak Tests at Real Bolted Flange Joints – Verification of Gasket Characteristics determined with Standardized Test Procedures, R.Jastrow, E.Martens, O.Mayer, Paper #2071, 2001
6. Tightness of Bolted Flange Connections – what does that mean?, J.Bartonicek, F.Schoeckle, Paper #F06-1, 2003.
7. Background for the ASME Nuclear Code Simplified Method for Bounding Primary Loads in Piping Systems, S.E. Moore, E.C. Rodabaugh.
8. An Introduction to ASD and LRFD and Its Application to Pressure Vessels and Piping, K.Kirkpatrick, B. Millet, B. Mosher, E.Wey, F. Mejia., PVP2023-105906, 2023.
9. AISC 360-16, Specification for Structural Steel Buildings, American Institute of Steel Construction, 2016
10. ASCE 7-22, Minimum Design Loads and Associated Criteria for Buildings and Other Structures, 2022.
11. Comparison of Design Ground Motion Between Coastal California and the Central United States, Z.Wang, Frontiers of Earthquake Engineering, July, 2014. (Paper No. 13)
12. Functional Capability of Piping Systems, NUREG-1367, D.Terao, E.C. Rodabaugh. (Paper No. 11)
13. B31.9-2008 Building Services Piping.
14. Response Spectra for Differential Motion of Structures Supports during Earthquakes in Egypt, M.I.S. Elmasry, HBRC Journal, 2012, (Paper No. 15)
15. B31.1 – Power Piping
16. B31.3 – Process Piping

17. B31J – Stress Intensification Factors (i-Factors), Flexibility Factors (k-Factors), and Their Determination for Metallic Piping Components”

18. ACI 318 Building Code Requirements for Reinforced Concrete. Publisher: American Concrete Institute (ACI), 38800 Country Club Drive, Farmington Hills, MI 48331 (www.aci-int.org)

19. AISC, Manual of Steel Construction. Publisher: American Institute of Steel Construction (AISC), One East Wacker Drive, Chicago, IL 60601-1802 (www.aisc.org)

20. AISI, Specification for the Design of Cold-Formed Steel Structural Members. Publisher: American Iron and Steel Institute (AISI), 2000 Town Center, Southfield, MI 48075 (www.steel.org)

21. ASCE/SEI 7, Minimum Design Loads for Buildings and Other Structures. Publisher: American Society of Civil Engineers (ASCE), 1801 Alexander Bell Drive, Reston, VA 20191 (www.asce.org)

22. ASME B31.4, Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

23. ASME B31.5, Refrigerant Piping and Heat Transfer Components

24. ASME B31.8, Gas Transmission and Distribution Piping Systems

25. ASME B31.9, Building Services Piping

26. ASME B31.11, Slurry Transportation Piping Systems

27. Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016; Order Department: 22 Law Drive, P.O. Box 2900, Fairfield, NJ 07007-2900 (www.asme.org)

28. ICBO AC156, Acceptance Criteria for the Seismic Qualification Testing of Nonstructural components. Publisher: International Conference of Building Officials (ICBO), ICC Evaluation Service, 5360 Workman Mill Road, Whittier, CA 90601

29. MSS SP-58, Pipe Hangers and Supports—Materials, Design, and Manufacture

30. MSS SP-69, Pipe Hangers and Supports—Selection and Application. Publisher: Manufacturers Standardization Society of the Valve and Fittings Industry, Inc. (MSS), 127 Park Street NE, Vienna, VA 22180 (www.mss-hq.com)

31. ASME BPVC.III.1.NCD-2021

32. Seismic Analysis of Safety-Related Nuclear Structures, ASCE/SEI Standard 4-16.

33. PCC-1 Guidelines for Pressure Boundary Bolted Flange Joint Assembly. 2022.

34. ASME Section III Appendices.

35. Plastic Collapse of General Frames, K.McIvor, A.S.Windman, H.C.Wang, 1976

36. Evaluation of the Plastic Characteristics of Piping Products in Relation to ASME Code Criteria, E.C. Rodabaugh, S.E. Moore, 1978.

8 COMMENTARY

3.2.1 Commentary to Seismic Demand

Because ASCE 7 is specifically cited in several B31 Code sections, this standard focuses on determination of free field input / ground motion acceleration parameters as described previously as well as interpreting other key aspects for application to the seismic design of piping. Other seismic design standards do exist and will also be addressed to a lesser extent.

ASCE 7’s criteria for developing minimum seismic design loads for nonstructural components (which includes piping and pipe supports per Ch. 13) continues to evolve and significant changes were made in the 2022 edition. While the parameters have changed, the result is not much different for common B31 piping features (e.g., welded steel pipe per B31) using the equivalent lateral load approach of ASCE 7 chapter 13. Calculated loads for piping per eqn. 13.3-1 are substantially less than the minimum required value per eqn. 13.3-3 (i.e., less than $0.3S_{DS}I_pW_p$, see ASCE 7 for definitions). Thus, the minimum specified load per equation 13.3-3 governs as it did in the 2016 edition. These loads have been compared to loads developed using more common and well documented piping analysis methods such as linear dynamic response spectrum analysis and found to be much lower (Stevenson, 19xx)… and are difficult to rationalize for use in calculating pipe stress and displacements.

However, ASCE 7 is not a piping design standard and it specifically defers to the B31 piping codes for such design requirements and qualifications. ASCE 7 commentary recognizes that piping qualification per B31 or other Codes will likely result in loads different than the minimum loads specified by ASCE 7, and only requires that those loads not be less than mandated by

ASCE 7. This B31E standard ensures that minimum load structural requirement will always be met.

This B31E standard is not intended and cannot be used as a guide for performing structural design in accordance with ASCE 7 for nonstructural components (Ch. 13) or nonbuilding structures (Ch. 15). It is ultimately the responsibility of the structural engineer to determine if ASCE 7 requirements have been met and are accepted by the structural authority having jurisdiction (AHJ) per the applicable section of the building code in effect at the project site. Likewise, it is the responsibility of the piping design engineer to determine if the requirements specified by the owner have been met in accordance with the appropriate B31 Code and accepted by the applicable mechanical AHJ per the building code. Following the recommendations of this standard should ensure that the piping seismic design is acceptable to both.

3.2.23.2.4 Commentary to Critical vs, Noncritical Piping, Risk Category, Importance Factor

Critical Piping / RC IV systems are required to have a high probability of sustaining minimal damage and maintaining functionality following the design level seismic event. For piping this is interpreted as maintaining leak tightness and having minimal inelastic deformation to maintain functionality. This is the approach taken in B31.9 Nonmandatory Appendix B, B-3.4, Design by Analysis, wherein critical piping intensified longitudinal and sustained stress must meet the specified minimum yield stress (SMYS) for most materials, 1.33S, while noncritical piping can have intensified stress as high as 3S or twice SMYS, which is generally the shakedown limit for cyclic loadings, both for elastically calculated stress.

Examples of critical seismic piping could include Category M Fluid Service piping and Chapter IX high pressure fluid service in B31.3, piping under OSHA regulations for process safety management (PSM) systems in 29 CFR 1910.119 or other piping systems carrying hazardous media those definitions. In addition, any other Owner-designated system that is desired to maintain structural integrity of the piping and associated equipment and pressure vessels and have low risk of leakage following the design seismic event could be deemed critical piping. This is fundamentally an owner’s decision guided by regulatory requirements and AHJ oversight.

Lower RC structures, nonstructural components and nonbuilding structures will incur substantial damage for the design event following the rules of ASCE 7 but should not collapse. For piping this is referred to as position retention although substantial damage with large inelastic deformations should be expected to occur and leak tightness, flange integrity, vessel nozzle integrity, etc., should not be assumed. Piping that is permitted to have such an end state after the design seismic event is referred to as noncritical piping.

Piping that can be allowed to fail and has no potential for incurring consequential damage to seismic systems may be designated nonseismic piping. Such piping need not have seismic loads included in the B31 design, and if applied, this designation must be documented and approved in the design. Note however that B31 nonseismic piping may still be required to be included in the ASCE 7 structural design for loads imparted to the building. The ASME designer must work with the structural engineer and provide appropriate loads if that is the case.

Note that, similar to the equivalent lateral force equation 13.3-1 of ASCE 7, in dynamic response spectrum modal analysis, computer programs apply the importance factor to the input response spectra since it is a linear analysis. This does not mean, however, that the design spectra is amplified to the maximum considered earthquake (MCE) level, which has the same 1.5 ratio as compared to the design spectra.

3.2.3 Commentary to Response Modification Factors Applied to Piping

Complex piping systems do not respond in a strictly elastic manner to dynamic seismic loadings due to inherent support gaps and friction. In addition, under conditions of large deflections in straight pipe runs, local inelastic deformation at elbows, tees and other areas of high stress intensification likely will exist without incurring significant damage to the system or causing large permanent deformations. Both effects result in energy being dissipated during seismic shaking that reduces the actual response of the system. However, B31 piping design requirements and equations, including application of SIFs and flexibility factors, fatigue limits, buckling considerations, etc., are based on assumed elastic response of the system without accounting for energy dissipation. Thus, it is conservative to perform a purely elastic design analysis and all of the foundational work of the B31 codes is based on such elastic design principals. It is also demonstrated by EPRI and others that piping generally fails due to low cycle fatigue from its inertial response to seismic accelerations, and the stress limits in section 3.3.2.5 are in fact based on fatigue limits.

For structural design, however, ASCE 7 utilizes response modification (R) factors (2016, 2022) and ductility / strength factors (R_μ, R_{po}, 2022) to reduce the demand input by approximating the inelastic energy absorption by an amount judged appropriate by the responsible Committee while retaining the basis structural strength design load limits. These reduction factors vary by type of structural or nonstructural element and many different factors could apply to a single integrated piping system for the various types of pipe supports, connections and joints, and pressure vessel supports. The detail rationale and body of work supporting the values assigned in ASCE 7 chapters 13 and 15 is not published, and the reader is encouraged to review the commentary of ASCE 7 for more information.

ASCE 4 and 43 Nuclear Codes

The ASCE nuclear codes ASCE 4 and 43 use a similar but simplified concept of energy absorption / ductility factors, F_μ, which vary by desired limit state (i.e., end state, defined in ASCE 43 Table 1.2) from substantial damage without collapse to elastic response / operable. Essentially, this approach incorporates increasing reductions in response for higher permissible damage end states while retaining the use of the existing occasional load allowable stress equation, eliminating much of the complexity of the ASCE 7 approach.

The ASCE 4 and 43 F_μ factors are much lower than the equivalent ASCE 7 R factors up through the 2016 edition and apply to all aspects of the system uniformly, with a value of 1 when elastic response is required for the most critical systems and a maximum value of 2 where substantial damage but non-collapse is acceptable. The R factors and terminology changed in the ASCE 7 2022 edition, but the end result is the essentially the same. This ASCE 4 / 43 approach is easier to understand with the basis of elastic design in the B31 codes and is more compatible with the use of the B31 Code section occasional stress limits as published. However, if the higher, fatigue based allowable stresses of this B31E standard are applied, ductility factors of 1 should be used for the piping. It is also unclear how the different ASCE 7 R factors for support structures should be applied if following ASCE 4 and 43 approach.

It is noted that ASCE 43, section 8.2.2.4 supports the concept of using a value of inelastic energy absorption factor of one (1) for the supporting structure to generate loads on the component if the input to the component is acceleration based. This is interpreted to apply to determination of nozzle loads for qualification, but is also inconsistent with ASCE 7.

3.2.4 Commentary to Seismic Demand Load Factor (0.7 vs. 1.0E)

In the 1981 “Background for Changes” document (Ref. 7 Paper No. 5), Rodabaugh established an ASD strength approach for piping, defined by an appropriate safety factor, an implied plastic section modulus and a limit state defined by the collapse criteria in then Section VIII Div 2 (pre-2006), in the current Section III Appendices II, and used in the 2017 version of B31J App. D.

There have been three established methods used to describe required loads and methods of analysis: (Ref. 8, 9)

1)ASD Stress (working stress design, safety factors)

2)ASD Strength (limit states, safety factors)

3)LRFD Strength (limit states, load and resistance factors)

These procedures can be used for ultimate strength, service limits, fatigue, ratcheting, strain limits, etc.. The key element of the LRFD approach is that it does not use a single safety factor and so provides for possibly large variations in individual loads. As the earthquake return period gets larger for example, it becomes more difficult to predict the actual mean seismic load and so the associated coefficient of variance (COV) gets larger and the probability of failure in such an event increases.

For B31 seismic piping analysis, when using the design response acceleration parameters derived from ASCE 7 Chapter 11 to calculate inertial loadings, the load factor for earthquake loads (E) in load combinations should be 1.0 rather than 0.7 (as shown in ASCE 7 Chapter 2) for all categories of seismic loading since the allowable (resistance) for piping is based on a strength limit state.

In those cases where 0.7E has been used previously for ductile piping systems as the seismic loading for ductile piping systems, seismic loads and displacements have likely been underestimated. However, for systems designed with typical ductility and flexible supporting, it is unlikely that piping not otherwise subject to buckling or other non-ductile failures is subject to gross failure or damage from seismic events not usually experienced. When using 0.7E, underestimated loads and displacements can also be transferred to vessel, structures or equipment, and the load basis should be identified in the design with reductions in applicable limits applied.

Since 2000, the ASCE 7 values Rp, Rm, R and Rpo have often changed. See Wang (Ref. 11 Paper No.13). Damping, friction, etc., that these single constants can represent are system dependent for most piping supported off grade and can represent complex behavior. Users wishing to perform more comprehensive analyses are welcome to do so. Experience suggests that seismic evaluations conducted using 0.7E or 1.0E are already very conservative.

A further discussion of load factors are found in Appendix 10.

The use of 1.33 Sh (or 0.9Sy) as the allowable stress for operating and occasional loading is considered reasonable and potentially over-conservative with respect to stress, (see "Functional Capability of Piping Systems", Ref. 12, Paper No. 11, NUREG-1367). When evaluating the 1.33 factor in strength terms it can be considered either a reduction in the safety factor from 2 to 1.4 which is approximately the safety factor used in Sect. III for collapse of straight pipe, or the safety factor for all components in VIII-2 Art 6 for tested collapse loads prior to the 2007 VIII-2. The present (and 1980) safety factor for primary loads for branch connections and bends in piping was intended to be about 2.0. (This value is difficult to precisely identify because lower bound limit loads, for which there is no "quantitative" safety factor as there is (approximately) for calculations based on the twice elastic slope, scant testing and considerable engineering judgement were used with test data to establish SSIs and B_2 values.)

Pressure containment is the principal allowable stress design requirement for B31 piping, and the seismic effect is intended to be evaluated as an occasional service load rather than as an ultimate strength (capacity) load, albeit with elevated allowable stresses to account for the applicable failure modes. Conversely, structural design considers the seismic effect as an ultimate capacity loading as evidenced by the load factor of 1 in ASCE 7 Chapter 2 strength design load combinations. This difference is further complicated by the fact that supporting structures must be designed for both loads transmitted by the piping to the structure and other loads affecting the structure not directly related to piping. This dichotomy in design philosophy is resolved by not "factoring" the seismic demand on piping for the purposes of B31 compliance (including determination of supporting element loads) while fully complying with structural design requirements and load factors when designing supporting structures.

The phrase "factoring of loads" includes the use of the often observed β factors (Refs), unidentified "safety factors", factors on standard deviation separation (Ref), factors for "point-in-time" joint load application, and the commonly used ϕ and γ factors used to locate the point on the R=L curve that identifies the smallest distance to the origin (in an R', L' plane) to identify the highest probability of failure.

[TONY – PLEASE INCLUDE REFERENCES FOR THE ABOVE]

Most B31 code sections include an allowable stress increase factor for determining the acceptability of occasional seismic loads (e.g., 1.2Sh in B31.1, 1.33Sh in B31.3 and B31.9) or use yield strength as the piping design basis (B31.8). This B31E standard provides the commonly used sustained plus occasional load approach in the para. 3.4.1 Table 2 Category 1 allowable, considering current (and all previous) proximity to lower bound limit loads or twice elastic slope loads. The B31 occasional allowable stress increase factors appear by coincidence to be similar to the 0.7 ASD load factor on the demand side of the equation, but this relationship is circumstantial only.
Many structural related Codes (for road-side signs for example) using an allowable stress basis, (not considering the inelastic strength of the component) need to use the 0.7 factor, which is unrelated to the 1.2 or 1.33 increase in the B31 Codes on the allowable stress. For practical design reasons and because occasional loads have many characteristics that differentiate them from constant, always applied weight and pressure loading, the safety factor against strength collapse can be lower by the ratio of 2.0 to 1.5, and this is the reason for the 1.33 Sh.

3.3.2.1 Commentary to Linear Response Spectrum Analysis

[INCOMPLETE]

Chapter 13 of ASCE 7 - 2022 does not address the use of linear response spectrum (RS) modal analysis to determine loads on structures even though such an approach is provided in Chapter 12, section 12.9 for building structures and is identified as an acceptable method in Chapter 15, section 15.1.3.

RS modal analysis has been shown by Stevenson and others to provide less conservative, i.e., lower, loads than other validated equivalent lateral force procedures that do not incorporate response modification "R" factors such as in ASME BPVC III Appendix N. This is expected because RS modal analysis only applies the peak acceleration to modes in resonance with that acceleration. But it is a linear procedure and assumptions must be made for non-linear features such as how support gaps handled (e.g., treat 1/16 inch on a side as zero gap), but this approach easily accommodates low natural frequency, high flexibility, vertically sensitive, geometrically complex systems with significant potential for resonance, and it is the preferred analysis approach for many designers.

The issue of how to appropriately apply response modification / ductility (R) factors to RS analyses is unclear however, particularly when it is almost certain that different factors will be required at different points in the system, and the factors for piping are different than for pipe supports. If an R factor is applied by the piping designer in the analysis, it should be no greater than the minimum applicable R factor for any component or support in the system, and if it is applied in the piping analysis, it must not be applied again by the support or structural designer; such double dipping is not permitted and would be highly unconservative. It is noted that ASCE 7 requires separate calculations for nonstructural components having different ductility factors as discussed in their commentary.

As previously stated, ASCE 7 has been shown to produce the lowest loads of all reviewed seismic analysis procedures and this remains true with the 2022 edition since all common B31 systems remain governed by the minimum force calculations. Since this approach inherently allows significant inelastic energy dissipation and permanent deformations as an acceptable outcome, the appropriateness of uniform application of response modification / ductility factors to a linear elastic RS analysis is questionable. Note that applying any response modification / ductility factor will significantly reduce calculated displacements despite the implicit assumption of large displacements and inelastic behavior. If more realistic displacements are required, displacement correction factors, Cd in ASCE 7, must be applied to the results of analyses using modified input (see section 3.6 for further discussion).

No guidance or requirements are provided in ASCE 7 Ch. 13 for RS modal analysis of piping distribution systems. Therefore, B31E recommends the following for critical piping or piping designated as essential by the owner. In lieu of ASCE 7 Ch. 13 procedures, perform RS modal analysis using the unmodified design response spectra to perform B31 pipe code stress analysis and determine loads and displacements. With no response modification / ductility factor applied, the occasional load allowable stress limits of the B31 code sections may be increased to as high as twice yield or 3S, see section for further discussion.

For support design, apply the unmodified support reaction loads to catalog and standard pipe support hardware for qualification, and provide the unmodified loads and displacements at the piping support connection points to the structural engineer for design of structural members, anchors, embedments and foundations in full compliance with the requirements of ASCE 7. The structural engineer will likely obtain R factors from ASCE 7 Ch. 15 for the structural design, so this is a hybrid approach that meets all requirements of ASCE 7 (since the loads will always be greater than the minimum required) and the B31 Code sections. Using a more conservative approach such as this should be acceptable to both the structural and mechanical AHJs. Even if not required by the mechanical AHJ, it is the responsibility of the owner to decide whether a more conservative approach is warranted to ensure the desired end state of their systems.

Appendix 1 – Overview of Response Spectrum Method, Modal Combinations, and Directional Combinations

The intent of the code will not be to play the role of a textbook on the subject and hence the code will not offer specific guides in a “how to do fashion”. The objective of this paragraph will be to provide a high-level guideline on few technical aspects associated with response spectrum analysis. These include pointers on modal combination methods, methods for combining spatial components of seismic acceleration, comparison of static and dynamic analysis results, inclusion of missing mass effects. The directional combination approach is equally applicable for static analysis. The technical details behind the various combination methods can be found in References [1],[2] and [3].

A response spectrum analysis is a plot of maximum response quantities (displacement, velocity, acceleration etc.) as a function of frequency or time period. As the response spectrum plot shows only the maxima, there is no information on phase relationships between the individual modes. A typical example of a narrow band acceleration response spectrum is shown below.

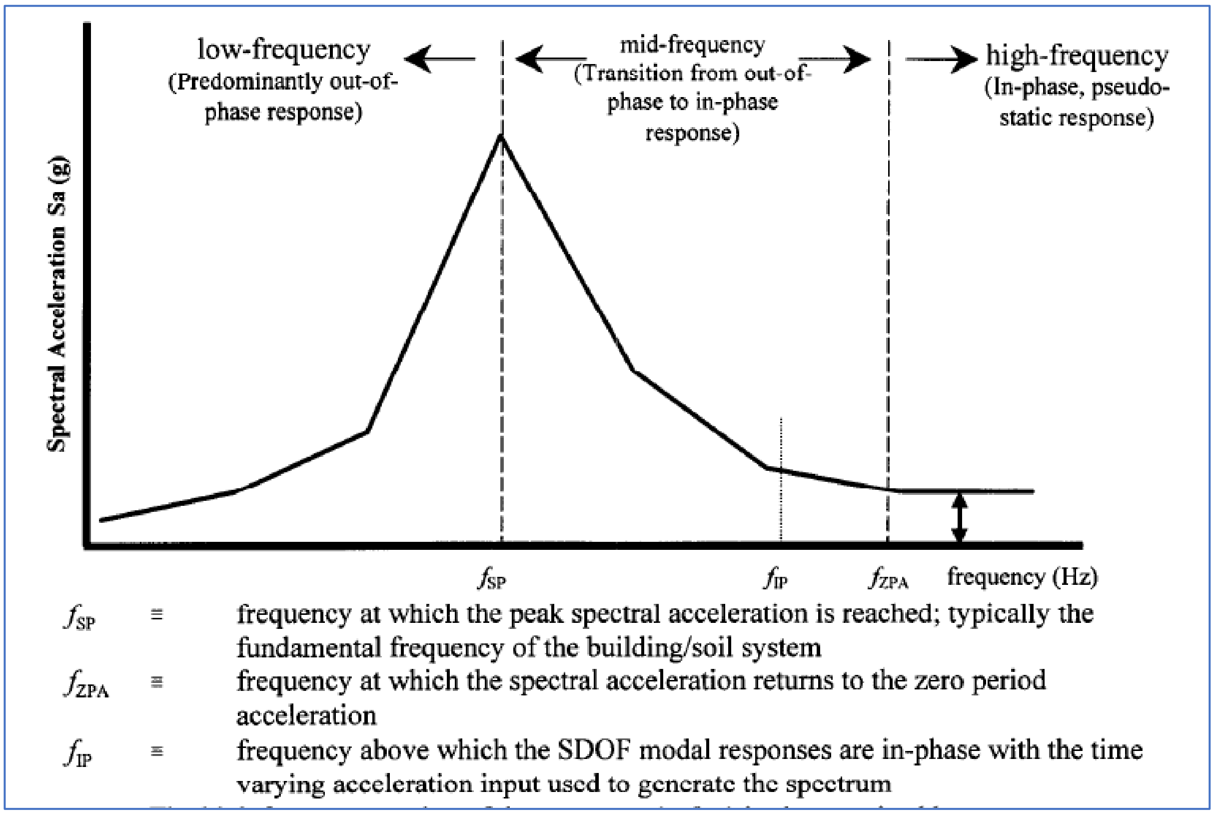


Figure 1-Narrow band acceleration response spectrum (from Reference [2])

The high frequency region of the spectrum ($>f_{ZPA}$) is characterized by no amplification of the peak acceleration of the input time history. A SDOF oscillator having a frequency ($>f_{ZPA}$) is accelerated in-phase and with the same acceleration magnitude as the applied acceleration, at each instant in time. A system or component with fundamental frequency ($>f_{ZPA}$) is correctly analysed as a static problem subject to a loading equal to mass times ZPA. This concept can be extended to the high frequency ($>f_{ZPA}$) modal responses of multi-modal systems or components. The mass not participating in the amplified modal responses (i.e., “missing mass”) multiplied by the ZPA is applied in a static analysis, to obtain the response contribution from all modes with frequencies ($>f_{ZPA}$).
In the low-frequency region of the spectrum ($<f_{SP}$) the modal responses of SDOF oscillators are not in-phase with the applied acceleration time history, and generally are not in-phase with each other. These are designated “out-of-phase” modal responses.

In the mid-frequency region ($f_{SP}\ to\ f_{ZPA}$), it has been postulated that the peak SDOF oscillator modal responses consist of

two distinct and separable elements. The first element is the out-of-phase response component, and the second element is the in-phase response
component. It is further postulated that there is a continuous transition from out-of-phase response to in-phase response. If $f_{IP} < f_{ZPA}$can be defined, then the mid-frequency region can be further divided into two sub-regions: $f_{SP} < f < f_{IP}$ and $f_{IP} < f < f_{ZPA}$.

For any response spectrum analysis, a key element is combination methods for Modal and spatial components. Another aspect is how missing mass has to be accounted for. For combination methods the key aspects of different approaches should be understood to the engineer. The various approaches can be broadly classified into three groups –

1. Where there is no correlation between individual modal responses, that is, they are statistically independent. The square root of squares or SRSS approach belongs to this group.
2. There is correlation between individual modes as long as they are within a band, for e.g. natural frequencies within 10% difference w.r.t each other. NRC Group, NRC 10%, NRC Double sum combination, Rosenbleuth double sum combination, Complete quadratic combination (CQC) etc. belong to this group. It is to be noted that the modal correlation factors have their derivations using theory of random vibrations.
3. Methods which separate modal responses into in-phase and out-of-phase components; The examples of such methods are Lingley-Yow, Hadjian and Gupta methods.

It is important for the engineer to understand the strengths, weaknesses and applicability areas of the various combination methods. An engineer is also often constrained by the limitations of the software that he or she is using.

Directional combination (equally applicable for Response spectrum and static analysis)

The SRSS procedure for combining the responses to the three components of an earthquake motion is based on the consideration that it is very unlikely that the maximum response for each of the three spatial components would occur at the same time during an earthquake. The other popular method is 100-40-40 rule.
The 100-40-40 percent rule was originally proposed as a simple way to estimate the maximum expected response of a structure subject to three-directional seismic loading for response spectrum analysis. Several researchers have compared the results of the 100-40-40 spatial combination with the SRSS spatial combination. Generally, findings indicate that the 100-40-40 combination method produces higher estimates of maximum response than the SRSS combination method by as much as 16 percent, while the maximum under-prediction is 1 percent.
The 100-40-40 procedure is as follows:
Let R_1, R_2, R_3, be the maximum responses of a piping system caused by each of the three earthquake components calculated separately, such that

$$|R_1|>|R_2| > |R_3|$$

The maximum seismic response attributable to earthquake loading in three orthogonal directions is given by the following equation:

$$R = (1.0|R_1| + 0.4|R_2| + 0.4|R_3|)$$

A point to note, maximum responses in stress may be different from maximum responses due to pipe support reactions and hence, for piping systems 100-40-40 rule should include this combination for all three orthogonal directions.

The below is a recommendation to apply the 100-40-40 rule.

$$R_{100,40,40}=100\%R_{EW}+40\%R_{NS}+40\%R_V$$
$$R = max\{R_{100,40,40}; R_{40,100,40}; R_{40,40,100}\}$$

Reference [4] can be referred to for additional guideline on the issue of application of 100-40-40 rule.

All methods utilized to combine seismic responses of individual modes obtained from the response spectrum method can provide only approximate representative maximum values, which are not exact in the sense of a time history method. Historically, time history method, applying either modal superposition or direct integration, has been used as a benchmark for gauging the degree of accuracy of these combination methods. Based on requirement of computational source and constraints in commercial software, time history analysis is difficult to perform for piping systems

For users of Eurocode-8, for modal combinations, SRSS method is recommended for modes whose time periods are within 90% of each other. For modes whose time periods do not meet this requirement, CQC approach should be used. For directional combination, both SRSS and 100-30-30 rule is recommended in Eurocode 8.

Some recommendations on Response spectrum and Time history analysis

- Modal mass participation in each orthogonal horizontal directions of response shall be at least 90%.
- ASCE-7 -22 refers to scaling of results of Dynamic analysis in section 12.9.1.4.1 In the words of this standard

> *12.9.1.4.1 Scaling of Forces* Where the calculated fundamental period exceeds $C_u T_a$ in a given direction, $C_u T_a$ shall be used in lieu of T in that direction. Where the combined response for the modal base shear, V_t, is less than 100% of the calculated base shear, V, using the equivalent lateral force procedure, the forces shall be multiplied by V/V_t, where V is the equivalent lateral force procedure base shear, calculated in accordance with this section and Section 12.8, and V_t is the base shear from the required modal combination.

While the stated requirement is for building structures, the same analogy can be used for piping systems, i.e. the total restraint loads in the two horizontal directions computed using modal combinations (Response spectrum or Time History analyses) if less than 100% of the value calculated using equivalent static analysis, the result shall be modified in line with section 12.9.1.4.1 of ASCE 7-22. The applicable equation in this case , for equivalent static analysis will be equation 13.3-1 of ASCE 7 -22.

For users referring to Eurocode, a factor analogous to R factors of ASCE-7, 22 is “q” or behavior factor. Users can select appropriate “q” factor for piping systems from relevant sections of EN1998-1, EN1998-2 and EN1998-4. However, use of “q” factors greater than 1.0 should be used with caution, keeping in view the notes regarding allowable stress for piping systems and use of R factors from ASCE-7 in paragraph (XXXX).

Appendix 1 References

37. U.S. Regulatory Commission Regulatory guide 1.92 – Combining modal responses and spatial components in seismic response analysis
38. Evaluation of modal combination methods for Seismic response spectrum analysis- BNL-NUREG-66410. Paper ID K4-A4-US
39. E. Rosenblueth and J. Elorduy, “Responses of Linear Systems to Certain Transient Disturbances,” Proceedings of the 4th World Conference on Earthquake Engineering, Santiago, Chile, January 13–18, 1969, Volume I, pp. 185–196,.
40. On the correct application of the 100-40-40 rule for combining responses due to three directions of earthquake loading- PVP2010-25466, Jinsuo Nie, Richard J Morante, Manual J Miranda, Josh I.Braverman, Proceedings of ASME Pressure vessel and piping Conference /K-PVP conference, July 2010, Washington, USA

Appendix 2 – LRFD and Variations in Seismic Load and Calculation Accuracy

[INCOMPLETE]

	Basis		Notes
ASD	Stress	Yield	Post-yield behavior is not considered. Mean load should be multiplied by 0.7.
ASD	Strength (service)	~ 1.4 Yield (lower bound limit, twice elastic slope, …), service criteria, Ωo>1	Post-yield behavior considered, there is still some overstrength when R = L; design based on single safety factor.
LRFD	Strength (service)	~ 1.4 Yield (lower bound limit, twice elastic slope, …), service criteria, Ωo>1	Post-yield behavior considered, still some overstrength when R=L; design based on standard deviation of resistance and each individual load. Resistance and load factors established to estimate minimum β.
ASD	Strength (ultimate)	Tensile/Ultimate Stress Limit	
LRFD	Strength (ultimate)	Tensile/Ultimate Stress Limit	

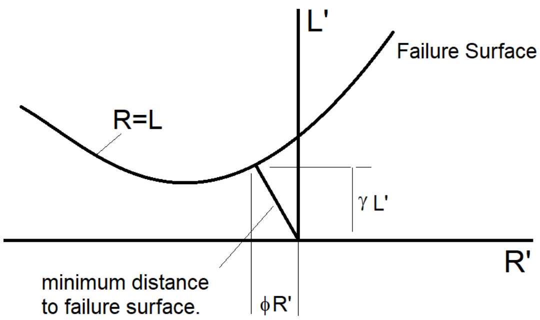


Fig. 2-1 Load and Resistance Factors and Failure Surface in Standard Deviation Space (R’, L’)

Items influencing load and resistance factors appearing in load combinations: ϕ, γ, z

1	load and resistance factors (Fig. 2-1 above), to find minimum probability of success. Based on standard deviation of resistance and each load case.	
2	Combination factors for “point-in-time” when loads might act at the same time, i.e. the factor for wind and seismic loads acting together is 0.75.	
3	Factor reflecting the difference between stress and strength determination.	

LRFD (strength), ASD(strength),

The references here would be very useful and will help people understand what is being done here and where these numbers come from.

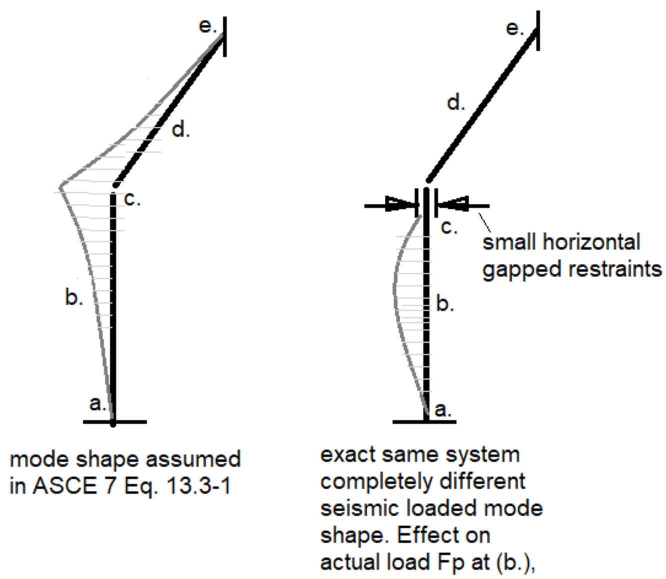
References [] through [] are NEHRP documents intended to explain the basics of earthquake designing as implemented in ASCE 7 and has it has changed since the 1980’s. Adjustments in load and probability definitions can improve the designers ability to judge the integrity of any one solution.

NEHRP ___ describes how earthquake, water hammer, and other reverse dynamic loads can have different effects on structures than wind or hurricane force loads. They also describe and quantify how long return period earthquakes can have high levels of uncertainty that must be designed for. NEHRP also describes how significant design issues through the years have been dealt with by the implementation of ductility, load, overstrength and displacement coefficients not accounted for in the typical analysis approaches.

Adjustments have to be made for differing site coefficients that can have significant impacts on ground movement and that have only recently been evaluated.

ASCE 7 Chapter 13, non-structural support loads have relatively tight lower and upper bound limits in high seismic zones. These limits tend to reflect the fact that seismic inertial loads haven't damaged piping systems, while relative displacements close to fixed supports not accounted for in designs have. (See failure distribution table).

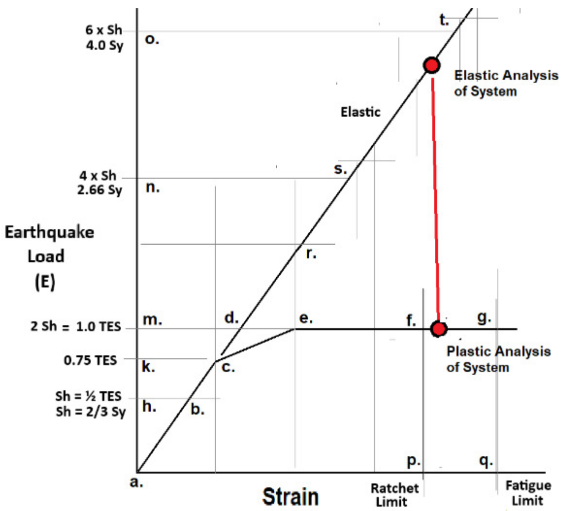
Large ductility coefficients were developed to reduce seismic loadings in cases where some plasticity, damping and the short term nature of the dynamic loading reduced displacements. Factors are also incorporated to improve the accuracy of the static loading models that assume first mode distributions of displacements that are a function of only the elevation. The applied loads are off by 1.43 times when comparing participation factors for vertical pipe that is free at the top with vertical pipe that is guided at the top as shown in the figure below:



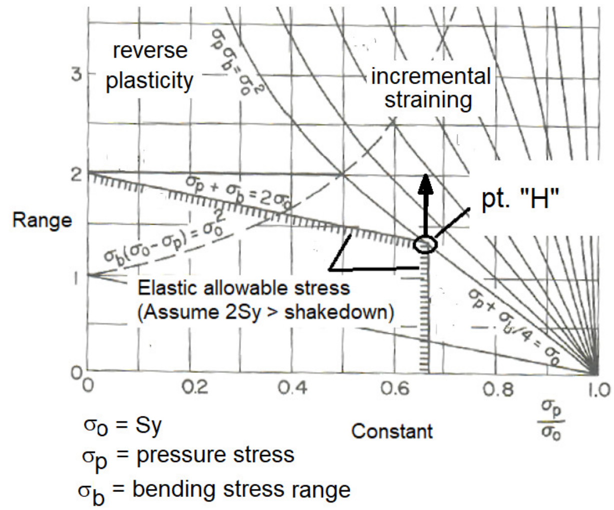
Some of the first improvements in building design technologies involved recognizing the improvements that can arise by replacing safety factor design with load and resistance factor design. It is not so much that the load and resistance factors are important but rather that the coefficient of variance is included in the acceptance calculation for each critical resistance or load property. With this information, designers can satisfy requirements by focusing on significant loads or critical properties. Several examples are given in the simple IQD models below.

Appendix 3 –Cumulative Fatigue Damage

[INCOMPLETE]



A5-Fig. 1



A5-Fig. 2 (Bree Diagram)

In A5-Fig. 2, a constant pressure stress producing a primary stress of 2/3 Sy and a bending stress of 1.3 Sy will put point "H" within the elastic allowable stress and on the edge of the incremental strain line. If there is an increase in the stress range in excess of about 1.3Sy (range) then the increase will produce some plastic ratcheting at one or both ends of the stress range. Where stresses are local, i.e. with bends and branch connections, as the strain increments continue there may be a secondary "shakedown" effect that reduces the ratcheting incremental strain to zero. Ratcheting in a complex stress state with Bauschinger effects adjusting the yield surface and Chabauche material models needed to produce accurate ratcheting strain increments through a majority of the component life is difficult to predict, and for this reason conservative approaches are used, namely:

1)The Bree diagram shown here is sufficient to model at least the initial incremental straining.
2)For most piping components pressure will be the major constant driving force.
3)Membrane + bending from any other varying load can produce the stress range used in the Bree diagram in A5-Fig. 2.

For stress states where stress concentration factors (SIFs) are greater than 1.3 it will be conservative to use the Code calculated SIF x M/Z stress range in the calculation. If incremental straining is not predicted, the user can feel confident that ratcheting likely will not occur.

To use this approach, the analyst finds the highest varying stress in a range case, and computes the membrane stress using either PD/(2T) or by using a local finite element model to find the pressure SIF. For a branch connection, the user might conservatively use a pressure SIF of 2.3 to be used with the run pipe dimensions (even if ratcheting is being evaluated for the branch).

Equation (1d) from B31.3 is shown below.

$$N = N_E + \sum \left(r_i^3 N_i\right) \text{ for } i = 1, 2, \ldots, n \qquad (1d)$$

where

N_E = number of cycles of maximum computed displacement stress range, S_E

N_i = number of cycles associated with displacement stress range, S_i

r_i = S_i/S_E

S_i = any computed displacement stress range smaller than S_E

To include the effect of low cycle seismic or water hammer dynamic (or static) loading appropriate r_i factors need to be computed and paired with the associated cycles N_i. For seismic loads, depending on the source of the excitation and design purpose, 10-to-20 cycles are used for strong motion earthquakes [TIM?]. Calibration with ASCE 7 ASD and LRFD spectral results are ongoing.

Two terms are added for any single dynamic load when pressure, or any other high nonvarying stress is acting on the system. One term (the standard expected term) is included for fatigue represented by single or two-sided reverse plasticity, and the other term is included for incremental ratcheting strain. For all tests this author has seen to date, the ratcheting term is only associated with constant applied pressure. Plastic cycling can be evaluated using Eq. 17 to compute ($S_{E\text{-}occ}$) and Eq. 1c. (See low cycle test results (without pressure) in [10],[11],[12]. The nonvarying term (pressure usually) S_{Lp} should be determined using the maximum pressure that might exist during the event and is found from S_{Lp} = MAX(S_L (eq. 23a), PD/2T).

If ε_g is not identified in any of these regions then $\varepsilon_g = 0$. If ε_g is less than 0.002 then r_i associated with this strain term can be ignored.

For inertial seismic and water hammer reverse-dynamic occasional dynamic loads that exceed $2S_h$ the user may follow the guidelines below to include effects of ratcheting.

1)The user should be sure that displaced geometries cannot become unstable due to plastic or other nonlinear action. Redundant supports and configurations should be incorporated in the design when possible.

2)Extra care should be exercised when installations are within 10 miles of active faults.

3)The value of S_E should not be changed by the evaluated low cycle seismic or water hammer dynamic loading. Seismic and water hammer load effects on fatigue and ratcheting are included in Eq. 1d. Local or systemic instability is provided by proper limiting S_L stresses and occasional load allowables.

4)When an elastic analysis of high dynamic loads is performed using ASD and system linear elastic behavior the stress $S_{E\text{-}occ}$ should be multiplied by an appropriate displacement amplification factor (C_d?). Use of this factor identifies a lack of certainty in the analysis which can be removed using equivalent lateral load methods, LRFD approaches and plastic behavior identified in B31J Appendices C and D.

Commentary:
Seismic and water hammer load effects on instability, collapse or excessive straining due to dynamic induced displacements are considered by proper application of 320.1 and incorporation of the allowable stress design (ASD) guidelines in ASCE 7. For elastic equivalent static loadings, factors are applied so that excessive conservatism is eliminated although displacements and support loads may be underestimated. The use of equivalent static loadings and plastic analysis may be included to properly distribute inelastic loadings and demonstrate system stability. These loads and guidance are provided in ASCE 7 under the load and resistance factor design (LRFD). Plastic deformation of piping components can be incorporated in any analysis using nonlinear load-rotation capability in most commercial pipe stress programs. Models shown in B31J-2017 Appendices C and D demonstrate this approach.

Appendix 4 – Ratcheting Determination

Expressions for r_i that can be included in B31.3 to evaluate ratcheting are given below:

Fatigue For elastic stresses:
r_i - for seismic or other short term dynamic loadings for fatigue is taken equal to ($S_{E\text{-}occ}$)/S_E where $S_{E\text{-}occ}$ is the range of the dynamic loading during the event. ASCE 7 equivalent lateral force methods compute the amplitude of the loading, and most modal spectrum results are given in terms of amplitude. When there is inelastic behavior at the point being evaluated ratcheting shall be evaluated.

SLp = PDm/(2t)

Dm = mean pipe diameter

T – pipe corroded thickness

P = 1.2 times the design pressure in the absence of a detailed assessment. 1.2 times the design Pressure is the estimated full flow back pressure when the relief valves are opening, assuming this is the condition that could easily occur in case of a seismic event.

Unbalanced relief loads might have steady state and range characteristics, and for conservatism the stresses computed from those loads should be added to both the varying and non-varying stresses used to determine r_i per Eq. XX.

Fatigue for inelastic stresses (strains):

Ratcheting for elastic stresses:
r_i – for seismic ratcheting damage is equal to C_o (0.12 ε_g / (2m_2) $)^{1/3.}$; C_o = 50 S_h/S_E. ; $m_2 = C_1(1\text{-}R)$; $R=S_y/S_u$.
C_1 = 0.6(ferritic steel), 0.75(stainless steel and nickel alloys). For other materials use VIII-2(2023) Table 5.7 for the equation for m_2.

ε_g – incremental strain found from 302.3.5(g) below.

302.3.5 (g) Incremental strain due to ratcheting

ε_g is the incremental strain due to ratcheting used to find r_i for seismic ratcheting.

If S_{Lp} is less than 0.5 S_{yh} and greater than $S_y^2/ S_{E\text{-}occ}$ then ε_g is calculated from Eq. 17k:

$$\varepsilon_g = (2\ S_{E\text{-}occ}/E) \times (S_{Lp}/S_{yh} - S_{yh}/S_{E\text{-}occ}) \qquad \text{Eq. 17k}$$

If S_{Lp} is greater than or equal to 0.5 S_{yh} and S_{Lp} is greater than S_{yh} – 0.25 $S_{E\text{-}occ}$ and S_{Lp} is greater than ($S_{yh} - S_{yh}^2/S_{E\text{-}occ}$ then ε_g is calculated from Eq. 17m:

$$\varepsilon_g = (2\ S_{E\text{-}occ}/E) \times (1 - 2 (\mathrm{MAX}(0,(S_{yh} - S_{Lp})\ )/S_{E\text{-}occ})^{0.5}) \qquad \text{Eq. 17m}$$

If S_{Lp} is greater than or equal to 0.5 S_{yh} and S_{Lp} is greater than S_{yh} – 0.25 $S_{E\text{-}occ}$ and S_{Lp} is less than or equal to $S_{yh} - S_{yh}^2/S_{E\text{-}occ}$ then ε_g is calculated from Eq. 17n:

$$\varepsilon_g = (2\ S_{E\text{-}occ}/E) \times (S_{Lp}/S_{yh} - S_{yh}/S_{E\text{-}occ}) \qquad \text{Eq. 17n}$$

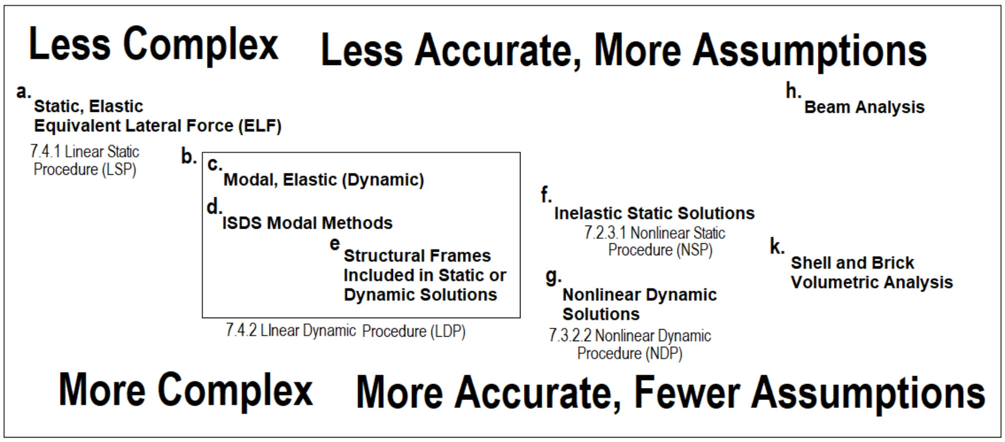
If ε_g is not identified in any of these regions then ε_g = 0. If ε_g is less than 0.002 then r_i associated with this strain term can be ignored.

Appendix 5 Inelastic Method for Instability, Redundancy, Support Loads and Elastic Followup

[INCOMPLETE]

Inelastic behavior is described for beam-column structures in AISC-360-__, and in references [1], and when used for piping systems can eliminate

Various techniques are available to users competent in applying those solutions. Solutions become more accurate and less conservative as more comprehensive solutions are employed. Figure A below shows different types of solutions and methods and their reference identification in ASCE 43.



References from ASCE 41-13

Various more complex techniques eliminate unknowns from more simplified methods. Large seismic events are characteristically difficult to predict, and so being sure that any one solution is not sensitive to a particular solution method increases confidence in the design predictions.

Rodabaugh addressed the theoretical and assumption eliminations in ref [].

Linear and nonlinear methods may all be used as long as the analyst is familiar with the method employed. It is also possible (and recommended), that static solutions are compared to dynamic solutions and that inelastic solutions are compared to elastic solutions so that users have an understanding of the potential sensitivity of the analysis to the mechanical behavior

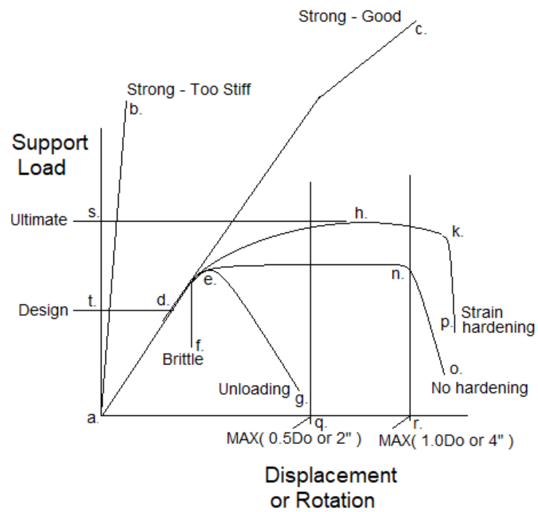
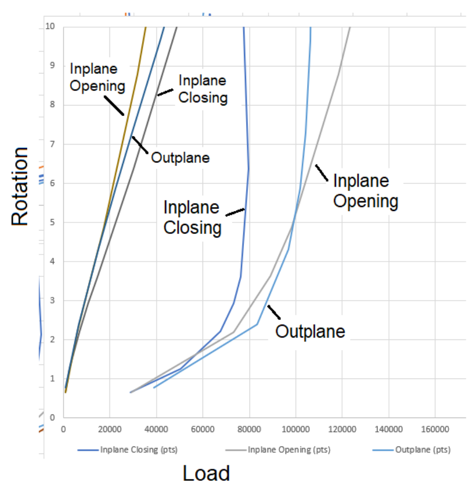
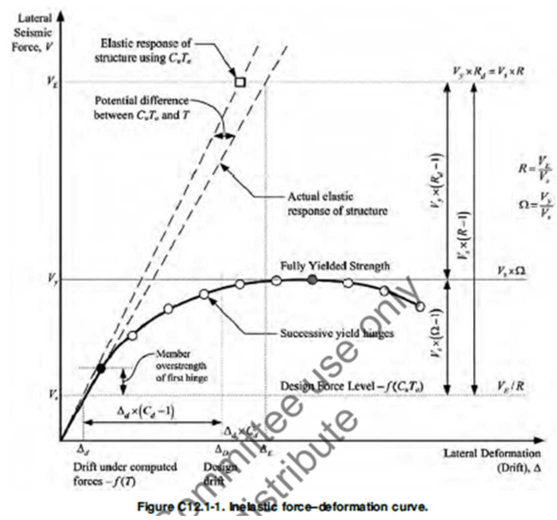
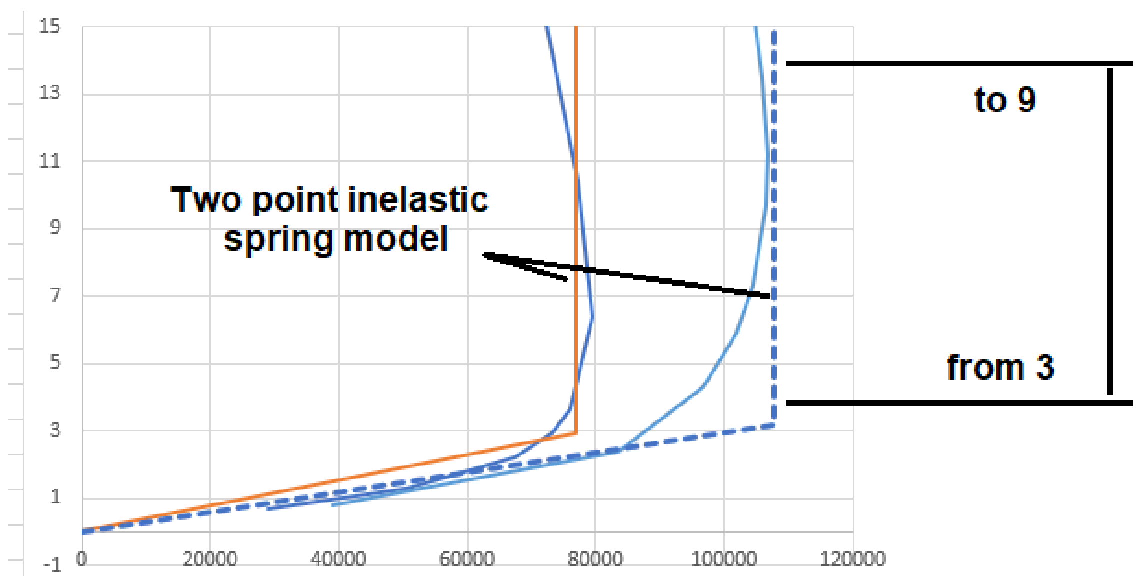


Fig. 5.5 Ductile and Brittle Support Behavior







Allowed rotations of bend and branch connections for inelastic strain and rotations are given by the following equations. Users may provide more appropriate values if available.

Table 2a Inelastic strain and rotation limits for any combination of Weight, Pressure, Other Sustained loads, plus seismic primary or reversing dynamic loads. These limits are for a static inelastic analysis.

Category	Allowed Rotation (deg)	Allowed Strain
1	$1.5\ k^{0.5}$	3%
2	$2.4\ k^{0.5}$	6%
3	$3.2\ k^{0.5}$	8%

Notes:
1)These limits are for non-cyclic seismic or reversing dynamic loads.
2)The factor "k" is the flexibility factor found in B31J Table 1-1 for the direction of load-deflection.

References:
[1] W.F.Chen, S.E, Kim, "LRFD Steel Design using Advanced Analysis", 1997
[2] AISC 360-??
[3] ASCE 43-?? Chap (look these up) this is criteria
[4] ASCE 41- Chapter 7 Analysis Procedures.

Appendix 6 – Recommended Inelastic Modeling

Elastic models can be converted to simplified inelastic models at any time by providing the nonlinear rotational springs described herein. It is believed that most commercial pipe stress programs today can implement these supports in 3D and planar models can be readily defined in Excel.

These are considered a highly simplified, easy to use approach for the relatively small degrees of gross plasticity anticipated.

Engineering assumptions and approaches are discussed in Appendix 5. The following topics are covered in Appendix 6:

6.1 general 3 dimensional nonlinear springs
6.2 straight pipe
6.3 straight pipe at supports
6.4 commercial bend modeling
6.5 simplified bend modeling (using straight elements only)
6.6 branch connection modeling

6.7 solution procedure

6.8 allowable relative rotations and strain estimates.

6.1 *general 3 dimensional nonlinear springs*

Nonlinear behavior as highlighted here is intended to replicate component inelastic load-deflection. Small areas of plasticity may develop prior to nonlinear deviation shown here but they are believed to be small zones surrounded by larger areas of elastic material. Once the twice elastic slope is passed, these plastic zones are enlarged and the surrounding elastic zones are not large enough to force the component back to its original position. The definitions for twice elastic slope (TES) can be found in Ref. (34) Appendix II and in Ref (17) Appendix D. A background discussion can be found in Ref. (7). The first deviation occurs at approximately 0.75 x TES load. At the TES load, the component inelastic displacement (rotation) is twice what the elastic analysis would define. This is shown Fig. A6.1 below.

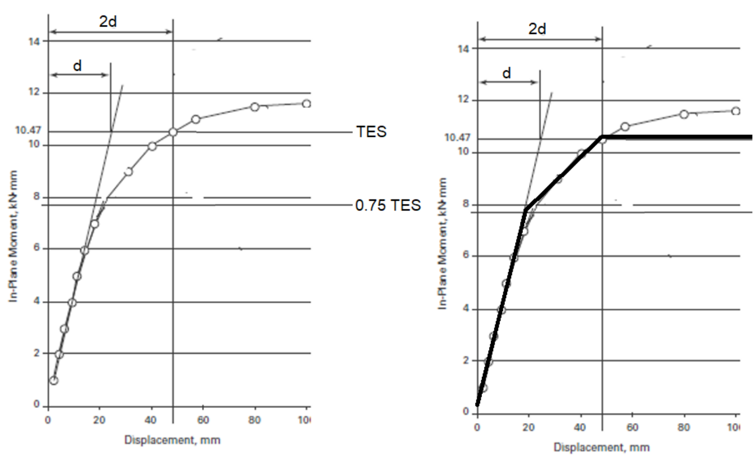


Fig. A6.1 - Twice Elastic Slope Curve and Straight Line Modeling

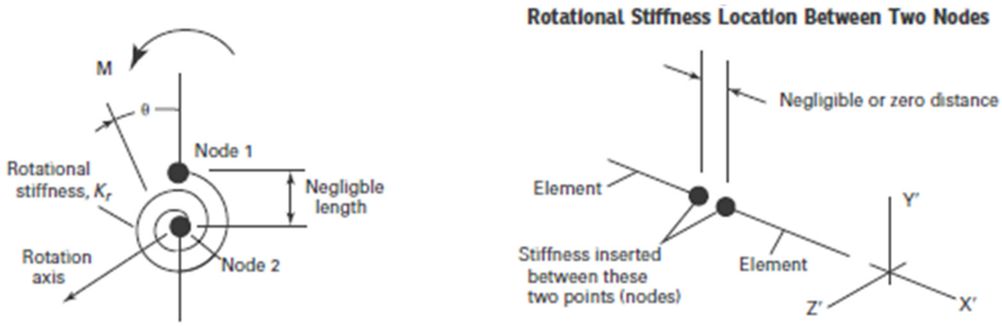


Fig. A6.2 General rotational spring between two nodes.

These nonlinear elements are designed to be essentially zero length six degree of freedom elements. The translational relative stiffnesses in between the two nodes are rigid and linear for all loading conditions.

The rotational springs can use two or three stiffness definitions as shown below:

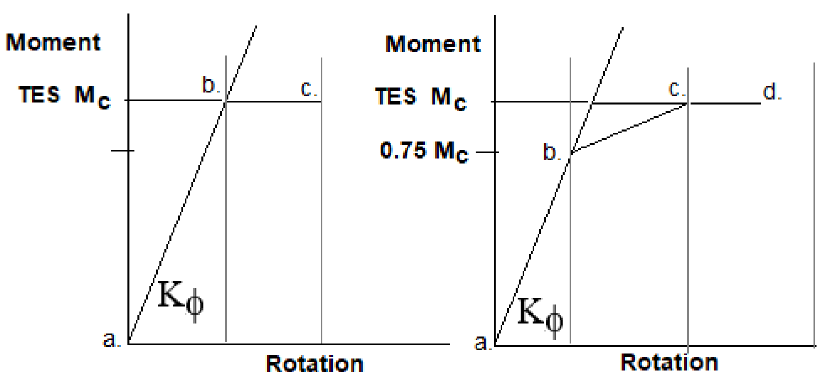


Fig. A6.2.1

For branch connections and simplified bend models $K\phi$ is a defined stiffness. For straight elements and standard bends Kf should be a rigid stiffness. It is often easy enough when modifying models from commercial pipe stress programs as entering three orthogonal rotational stiffnesses with a rigid initial stiffness and a “yield” stiffness at a value of $Mc = D^2$ T Sy. In most cases rotations far beyond the yield point and the possible associated unloading or “collapse” will not occur. This will be illustrated in the next sections.

6.2 straight pipe nonlinear bending

There will always be three nonlinear rotational springs between each node and three linear, rigid translational springs between the two nodes. The springs can be simulated as shown in Fig. A6.3-1 or A6.3-2 below. The rigid-plastic stiffness for straight pipe is recommended and is given in A6.3-1. The torsional capacity is approximately 10% too large but the similification is acceptable. The user is welcome to consider more sophisticated approaches to local nonlinearities. Be sure to use moments and rotation units consistent with the spring model you are using in your program.

Using Fig. A6.3-1, K_ϕ = <program rotational rigid> , and the plastic point is identified as M_c.

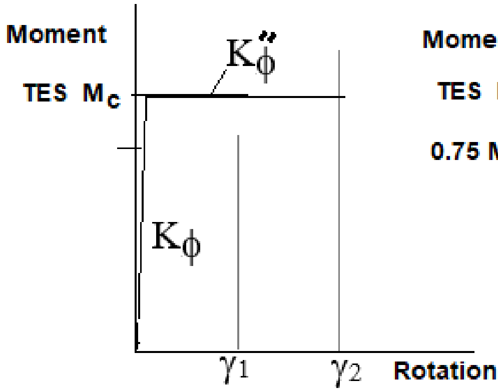


Fig. A6.3-1

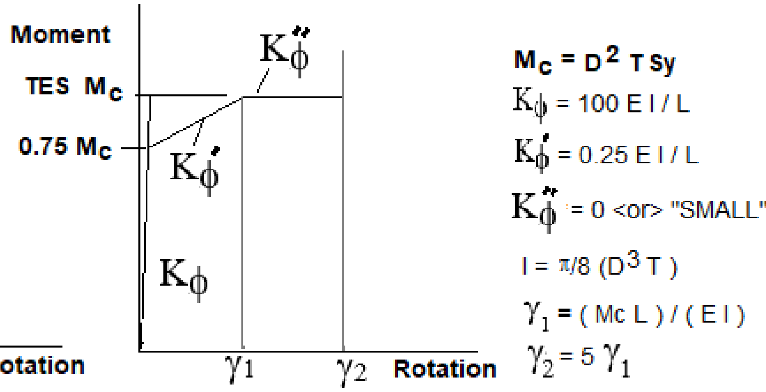


Fig. A6.3-2

Rigid stiffness rotational springs:

6.3 straight pipe at supports: there are several ways to construct these models. The model shown below is likely the most straight forward but involves including a short rigid element to simulate the support at the surface (or just beyond) the surface of the pipe:

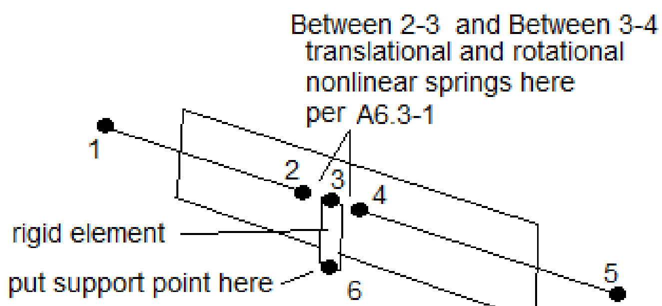


Fig. A6.3-3

6.4 Commercial bend modeling: the bend that should support inelastic behavior should be modeled as usual and at the midpoint of the bend two nodes (2-3) should be included as shown

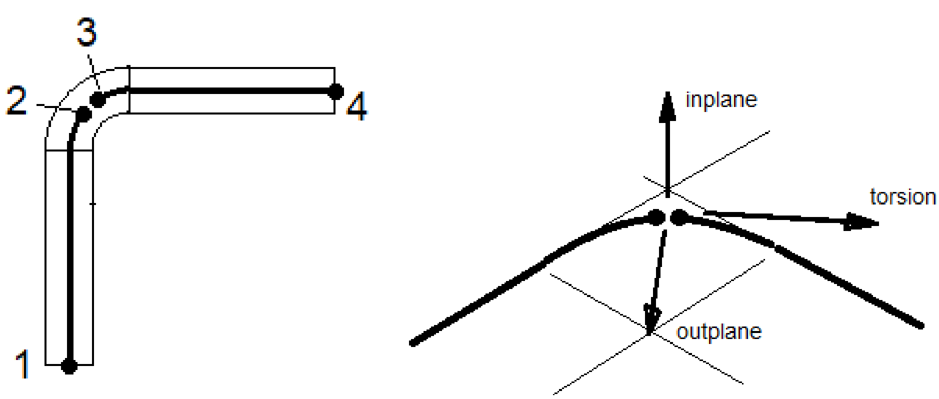


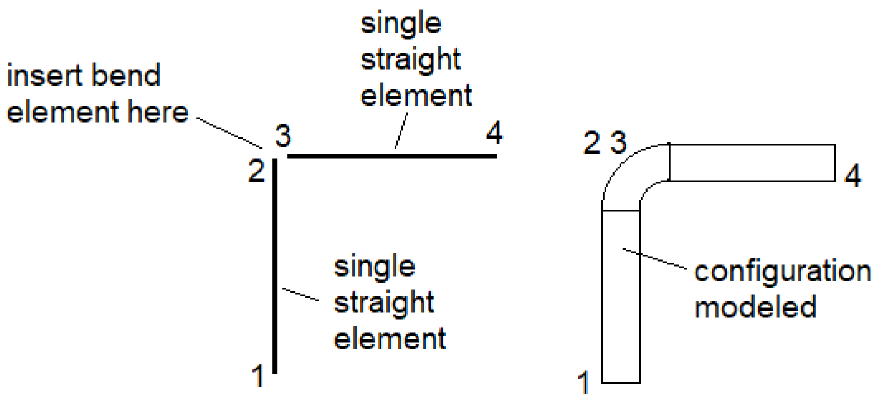
Fig. A6.3-4 Commercial Bend Modeling

The inelastic spring shown in Fig. A6.3-1 can be used in between nodes 2 and 3. Note that there are three unique twice elastic slope moments for the bend to be used with each of the three relative displacements:

In-plane: $M_{c\ in} = D^2\ T\ Sy\ /\ I_{in}$
Out-plane: $M_{c\ out} = D^2\ T\ Sy\ /\ I_{out}$

Torsion: $M_{c\ tor} = D^2\ T\ Sy / I_{tor}$

6.5 simplified bend modeling (using straight sections only):



A 6.3-4 – simplified bend modeling

The simplified bend modeling allows the user to run straight elements to the bend tangent intersection points. The local rotational spring stiffnesses are derived to remove the radius length of straight pipe and then to include the flexibility of the bends. Stiffness factors for each directional component are given below. Closing and opening stiffnesses for the bend are different and so plus and minus direction stiffnesses must be entered.

In-plane opening, out-of-plane and torsional moment-rotation diagrams are sufficiently similar to be used interchangeably. Moment rotation stiffnesses can be defined by two positive or negative directional points on the moment rotation diagram:

1) M_{fpy}, ϕ_{fpy}
2) M_{TES}, ϕ_{TES}

M_{fpy} = moment at point of first yielding,
ϕ_{fpy} = rotation at point of first yielding (radians)

Simplified Bend Coefficients for use with Straight Pipe Beam Elements:

in-plane closing:

$M_{fpy} = 0.75\ M_{TES}$
$\phi_{fpy} = (M_{fpy})(G_{in})$
$M_{TES} = (4/3)\ Sy\ (\pi\ r^2\ t) / I_{in\ bend}$
$\phi_{TES} = (M_{TES})(G_{in\ TES})$
$G_{in} = (R/EI)[\ k_i\ \beta - 2\tan(\ \beta/2\ )\ ]$; in.lb./rad.
$G_{in\ TES} = (R/EI)\ [\ 2\ k_i\ \beta - 2\tan(\ \beta/2\ )\ ]$; in.lb./rad.
$I_{in\ bend} = 0.9/(h^{2/3})$; $h = TR/r^2$

out-of-plane; in-plane opening, torsion:

$M_{fpy} = 0.75\ M_{o\ TES}$
$\phi_{fpy} = (M_{fpy})(G_o)$
$M_{o\ TES} = (4/3)\ Sy\ (\pi\ r^2\ t) / I_{o\ bend}$
$\phi_{TES} = (M_{TES})(G_{o\ TES})$
$B_3 = ¼\ (2\ \beta - \sin(\ 2\beta\ )\ )$
$G_o = (R/EI)\ [\ k_o\ (\beta - B3\ ) + (\ 1+u\ )B_3 - (\ \tan\beta/2\ )(\ 2+u\ )$

$G_{o\ TES} = (R/EI)\ [\ k_o\ (\beta - B3\ ) + (\ 1{+}u\ )B_3 - (\ \tan \beta/2\ )(\ 2{+}u\ )$
k_i, k_o – B31J Table 1-1.

For bends two types of inelastic models are provided for beam solutions. For branch connections, support locations and midspans only a single inelastic model is provided. The simplest bend model behavior is shown in Fig. X below. This model is used with the straight beam model. (The user inputs two straight sections of pipe to the tangent intersection of the bends and then places the point spring in between.)

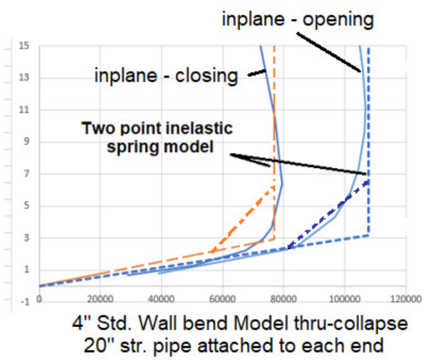


Fig. A6 – 3 – Stick Model of 4” bend and Comparison with EP, large rotation, MITC8 shell element solution.

The point spring bend model in between two straight pipe lengths. There will be two unique moment-rotation diagrams/equations: in-plane closing and in-plane opening. In-plane opening, out-of-plane and torsional moment diagrams are sufficiently similar to be used together. Moment rotation stiffnesses can be defined by two points on the moment rotation diagram:

3) M_{fpy}, ϕ_{fpy}
4) M_{TES}, ϕ_{TES}

M_{fpy} = moment at point of first yielding,
ϕ_{fpy} = rotation at point of first yielding (radians)

Type 1 inelastic models allow designers to perform hand or spreadsheet calculations to:
1) quickly estimate the effect of inelastic behavior on support loads,
2) calculate total strains and actual displacements
3) estimate the mode shape influence and displacements to compare with target displacements for the purpose of evaluating nonlinear response spectrum behavior.
4) evaluate actual redundancy and overstrength of the piping system. Significant redundancy suggests that some local plastic deformation will occur but any high seismic loads would be redistributed. If systems are not redundant, then inelastic target displacement estimates (for seismic and water hammer loads), ref [](ASCE 41), can demonstrate that even cantilevered structures will survive earthquake overloads.
5) Produce accurate loads for restraint designs
6) Probably most importantly is to design for seismic restraints to reduce coefficient of variance

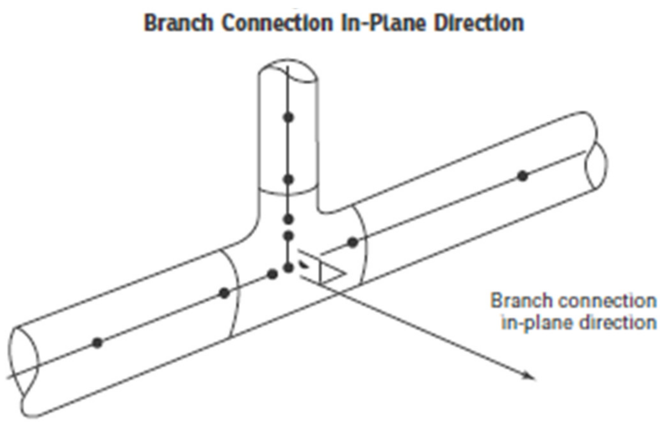
Static inelastic response spectra and nonlinear response spectra solutions provide the accurate displacements (and stresses) from enveloped response spectrum seismic data. Improved solutions can be obtained by performing actual transient nonlinear simulations using time history records designed to represent the spectrum responses and energy distribution but at much greater time and machine costs.

Inelastic behavior has been used for more than three decades extensively in building, structure, and ship designs

Note:

1)There is some nonlinear behavior non-symmetry in the models when they are non-planar. The error introduced by this irregularity is considered small.

2)The general behavior for plastic collapse (although not thought implemented in most commercial pipe stress programs can be found in Ref. 35.



Appendix 7 –Seismic and Other Dynamic Load Characteristics

[INCOMPLETE -–NOTES ONLY]

6)Gapped, plastic deforming supports should replace snubbers and should be placed in particular locations – when this is done appropriate ratcheting checks should be made. Only based on pressure.

When fatigue due to seismic inertial cyclic loads is the primary failure mode, as is the case for piping with D/t of 50 or less and design by

We found in bend testing that the incremental ratcheting strains can diminish quickly in bend geometries subject to in-plane varying moments, (and I presume branch connection geometries.). When we try to include Bauschinger effects on the compression side, Chaboche hardening models (where do you get the material parameters), varying stress/strain principle directions and the fact that Von Mises in certain stress states and for certain materials doesn't describe an accurate yield surface, (burst pressures for example), the time we need to perform the analysis gets beyond the time we can spend trying to perform it. Using Gupta to calibrate the ratcheting beam models has given us the best results we have obtained so far, (although it is a very crude approach). We combine the fatigue and ratcheting effects independently: The Hinnant (and welded fatigue curve approach), doesn't predict thru-wall cracking in the Gupta geometry when there is ratcheting strains associated with the failure, e.g. the Hinnant approach predicts that the geometry should not fail. The Hinnant approach is given by (Sf,range) = 1895N^(-1/3), ksi. (PVP 2007-61871). We use the Bree diagram incremental strain to predict the remainder of the damage, i.e. Total Damage = Nfat/Nallow +N x eg / eg_allow, where eg_allow = m2 and eg is the incremental strain per cycle. The multiple Gupta tests seemed to correlate reasonably well given the time I had to play with the models. I use stresses from beam models (and SIFs).

When looking at Mr. Osage's ratcheting paper including phase relationships our conclusion was that a reasonable conservative assumption was to assume that the primary stress did not cycle, and that the range stress always did. Any combination producing differences seemed like they were smaller than what we considered the accuracy of the actual problem.

I have some other test results to compare, but if there is any other test data on ratcheting in piping geometries, (pipe, bends, tees), I'd be glad to get a look. If the model compares with Gupta, but nothing else, we definitely shouldn't be recommending it and we can dial back the expectations. Anindya, perhaps we could work on this together. It sounds like you have some ratcheting simulations or tests we can try to compare to.

Appendix 8 – Target Displacements

[INCOMPLETE]

Users not familiar with ASCE 4 calculations for seismic systems may not recognize the term "Target Displacements" Recognizing that seismic inertial loads are displacement limited, ASCE 4 has developed a method that permits users to compute those "limited displacements" and perform a pipe stress analysis using them. This is likely the most accurate static analysis available.

Target displacements explain why high allowable primary/occasional load stresses are permitted for seismic events. Short term dynamic seismic (or water hammer) events can be considered low cycle high amplitude strain limited loads because of the short duration of the load period.

Seismic inertial and displacement loading can be described by the equation:

$$Ma + Kd = F(t)seismic.$$

When peak load durations are short: $Ma >> Kd$ and d is small. When peak load durations are long, $Ma << Kd$, $Kd = F(t)seismic$ and k is large.

Appendix 9 – Leak Tightness

FOR CODE DEVELOPMENT USE ONLY. FACTORS MAY BE ADJUSTED AS ADDITIONAL DATA IS COMPILED AND REVIEWED. SOME COEFFICIENTS ARE IN THE PROCESS OF BEING DETERMINED AND REFINED. This is a second version of this Appendix after first initial review. Flange stresses at low leak tightness levels were included in the evaluation. QC of the new version is underway. Please contact Anindya B., or Tony P. if questions.

Scope:
These guidelines are provided to augment the use of B16.5 flanges or flanges designed by the method of ASME Section VIII-Div. 1 Appendix 2 that are used in piping systems with a focus on operating plus occasional loads, seismic loads and other reverse dynamic loads. These rules are intended to be used to establish loading conditions that may cause leakage of B16.5 flanges or those flanges that have been designed to ASME Section VIII-Div. 1 Appendix 2 or an equivalent standard. These rules are not intended to design or size flanges.

Two criteria are provided to identify leak tightness for critical piping.

1)High tightness – gas leak rates, usually detectable by audio enhanced sensing, and
2)Low tightness – liquid leak rates, visible detection.

When high tightness is needed for liquid leak rates, then the criteria for high tightness – gas leak rates should be used.

Depending on the hazardous nature of the media and the tolerable leak rates the user should select the leak tightness required for the noncritical or critical piping.

High tightness leak rates are on the order of 10 -to- 0.001 mg./sec/m of N_2 at standard pressure and temperature. Additional criteria may be specified. Gasket loads, test results and analytical approaches exist in these ranges to determine permissible bolt, pipe and gasket loads. (Refs. 5, 6).

Low tightness leak rates are on the order of 10 mg./sec/m of water or as specified in the Low Tightness Leak Test (Appendix 14). These leak rates are “visible” and/or audibly detectible by acoustic methods and do not generally impede the ability of the pipe to deliver its intended flowrate. The recommended leak test procedure is described in *Appendix 14 – Low Tightness Leak Detection.*

Design level bolt loads and moments prescribed by many flange evaluation methods intend to provide high tightness – gas leak rate levels. Methods provided in this standard prescribe external loads and bolt preloads to satisfy either criteria so that critical piping needs can be addressed.

External bending and torsional moments, overpressure, and pipe collapse loads are considered. Uniform piping systems are not often subject to large torsional loads, but where large and small systems interact and reducers or branch connections permit large pipe to load small pipe in three dimensions bending moments from larger pipe can induce torsional moments in the smaller pipe Limits provided for torsional loads are based on theory and analytical experience available from ASME Sect. III existing guidance, (ORNL 2913-3).

Visible water-equivalent leaks are established as limit conditions for large external loads so that the user wishing to do so can predict the probability that loads will result in visible leakage.


Typical HydroTest Leak


Drops from Test Vessel


Spray from Test Rig

Leakage:

Most piping system emissions or “leakage” occurs at:

1) valve flanges,
2) valve flanged bonnets,
3) equipment flanged connections, or
4) other equipment seals.

Critical gas system joints are “bagged” at representative joints, (valve bonnets, equipment flanges), and the results taken to be representative for operating conditions. For this purpose, accurate prediction of gas emissions is used to qualify or address issues, although these evaluations are performed in operating cases only when they are performed.

When overload, relief, or safe shutdown events occur these same flanged joints must undergo significant external loading often associated with some local plastic deformation of the surrounding piping system components. For seismic or other reverse dynamic loads, joints may alternately leak and seal. When bolts are stressed beyond yield, degrees of leakage can result in a few equivalent drops of water, or depending on the extent of the yielding considerable flow.

Some Section III piping systems are designed to accommodate this considerable flow in Loss of Coolant (LOCA) situations and pumping systems are designed to maintain necessary liquid levels while these large flows continue. (Ref:).

Section III (Refs) also contains simple rules to address load levels that can produce “visible leakage” at flange locations subject to bending moments. For refineries or chemical facilities, the owner must decide the level of “leakage” that can be accommodated when the facility is subject to particular events.

When the owner has alternate rules or guidelines that can be used to evaluate and limit leakage, those rules may be used. When no guidelines are available, the rules here provide load evaluations based on test data, experience and existing Sect. III piping (NC/D – 3658) recommendations that include:

1) Tightness (Tp) level leak rates
2) Visible leak rates of water
3) Gross equivalent leak pressures
4) Yield controlled leak pressures

This Appendix intends to secure low (Tightness Class 1 or better) leak rates for design load cases, and then providing upper load limits for occasional and safe-shutdown seismic and reverse dynamic loads. PCC-1 should be consulted for additional information.

Yield controlled leak pressure fall into two categories:

1) Bolt yield level
2) Attached pipe yield level

At load levels that yield the bolts, the joint is experiencing loading that can produce significant water (or equivalent fluid) flowrates.

Increasing bolt preloads, reduces tightness level (Tp) leak rates but also lowers bolt overstrength, i.e. smaller external loads are required to yield the bolts when pretensioning is high.

Of the variety of gaskets, "locked" and not "locked" are included so that users do not need to differentiate when performing allowable load calculations although gaskets designed and installed under engineering supervision with locked-up provisions can eliminate a number of operating considerations when maintenance becomes a consideration. "Locked" RTF or Spiral Wound Gaskets (SWG) compress the gasket to the intended tightness and then experience a "bottomed-out" metal-to-metal contact as shown in Fig. A below:

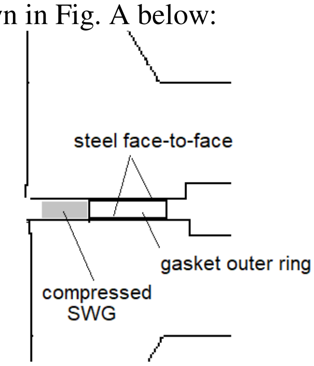


Fig. A – Outer steel ring, metal-to-metal contact after tightening.

External Loads:
External loads for the analysis of flanged joints are usually taken from elastic pipe stress evaluations of the surrounding piping. Load cases are typically comprised of weight, pressure, thermal and occasional static loads and possibly some type of dynamic or non-uniform thermal load.

Non-uniform thermal loads can be due to uninsulated flanges, transients, or layered flow and can be damaging to the flange and bolts and have an impact on leak rates. Users are urged to follow established guidelines for slow heating (10 degF per min.?) and to control strong thermal gradients.

Most thermal (expansion load case) pipe stress allowables are a function of the number of cycles and the yield and tensile strength of the pipe material, i.e. Thermal Allowable = $20N^{-1/3}$ x 1.25 (Sc + Sh). If the cold and hot allowables are equal to 2/3Sy, and $20N^{-1/3}$ is limited to 1.2, then the thermal allowable will be equal to 1.2 x 1.25 (4/3 Sy) = 2Sy. The twice elastic slope or lower bound limit load can be taken for round sections as $4/\pi$ Sy = 1.27 Sy. While thermal loads may cause local overstrain in piping components, at flange joints allowable thermal load can exceed the maximum capacity of the attached straight pipe.

When there is at least two diameters of straight pipe attached to at least one end of a flange pair the maximum load applied to the flange joint for analysis need not exceed M_c, where $M_c = D^2$ T Sy. Early Markl (Ref) fatigue tests of flanged joints showed that under a low pressure (less than 5 psi), welded flanges could be reverse cycled without leakage to collapse level moments. Some of Markl's 4" standard wall carbon steel flanges were pressurized to 600 psi. and reverse cycled without leakage to values approaching but removed from collapse level moments. (The B16.5 rated ceiling pressure for these flanges is 290 psi, i.e. p_c = 290 psi.) See Fig. B below.

Bolt-up of flanges may be sensitive to the gap required to be closed by bolt pull-up. The gap allowed is a function of the stiffness of the attached pipe or equipment. Flanges should never be positioned so that the flanges are used to pull open gaps together when there rigid elements on both opposite ends of the flange joints. Fortunately this situation is not often present, but designers and installers of critical piping should evaluate flange locations and be sure that shear, offset and rotational mismatch is not corrected by pulling flange faces together. This is particularly important where gases or soft (rubber) gaskets or o-rings are part of the gasket fabrication. Installers are encouraged to heat the attached pipe as appropriate to close gaps prior to tightening the bolts instead of using the bolt tightening to close the gaps. Care of the flange and gasket faces should be exercised. Damage is observed most often in larger diameter (12" or greater) joints.

Equations 4a and 4b are provided so that the user can improve on the bolt load estimate. f_M used with equation 4b is computed from a discrete bolt model. The factor 16 M / (πG^3) is derived from a uniformly distributed cylinder model. Eq. 4a uses the same model as UG-44 and NCD-3658, i.e. the uniformly distributed cylinder model. Rodabaugh discusses these differences briefly in ORNL 2913-3, Appendix A.

Evaluating Allowable Bending Moments

Several methods can be used to evaluate external moments applied to already qualified flanged joints in piping systems:
1)ASME Sect. VIII-Div. 1 UG-44(b)
2)NCD 3658.
3)Collected Methods from NUREG-5928 ISLOCA Research Program

A variation of the NUREG-5928 method is described below. Four criteria are provided to identify low leak tightness, moments associated with low tightness, torsion, flange overload and a probability of leakage.

The following criteria are evaluated for each load case:

1) Leaking (Eqs. 1, 2, or 3).
2) Bolt Loading. (Eqs.4a or 4b).
3) Flange Ring Overload (Eq. 5)
4) Torsional Loading (Eq. 6).

Steps 1 through 7 should be satisfied for each case.

STEP 1: Separate external torsional and external bending applied moments into M_t and M_{pipe}. Evaluate axial loads if necessary. (If unsure if the axial loads unrelated to pressure should be evaluated, then include them in the calculation per Step 5 below.)

STEP 2: If $M_{pipe} > Mc$, then replace M_{pipe} by Mc.

STEP 3: If $M_t > Mc$, then replace M_t by Mc.

STEP 4: If S_{pre} is unknown then replace S_{pre} with MIN(40,000, $0.7S_{yb}$)

STEP 5: If there is a large tensile axial load unrelated to the line pressure then use $M_{pipe} = M_{pipe} + (G/4)\ F_{axial.}$

STEP 6: Any loading satisfying the inequality in Eq. 1 can be considered to maintain a "standard" tightness during the defined loading event providing the bolts and flange are sufficiently strong. These limits include loads due to reverse dynamic loadings. Where some visible water-equivalent leakage is permitted, (Appendix 14) the value of "m" in Eq. 1 can be taken to be 1. The Eq. 1 inequality simulates a design condition for the flange of any material and at any temperature not including creep.

STEP 7: Compute $P_{leak\ P}$, and $M_{leak\ P}$ using Eqs. 2 and 3.

STEP 8: If Eq. 1, 4a, 4b, 5 and 6 are satisfied the external loads are acceptable.

STEP 9: For load cases where Eqs. 1, 4a, 4b, 5 and 6 are not satisfied the designer must decide if some level of leakage is acceptable. Leak rates can be estimated using the methods identified in Appendix 14. The coefficient of variance for the lognormal random variables $P_{leak\ P}$ and $M_{leak\ P}$ can be taken to be 0.5.

$(m)(P_c)(A_g) \le S_{pre}\ N_b\ A_b - (\pi/4)G^2\ P - 4\ M_{pipe} / G$ Eq. 1

$P_{leak\ P} = S_{pre}\ N_b\ A_b / (\ A_g + \pi/4\ G^2\ )$ Eq. 2

$M_{leak\ P} = (\ G/4\ )\ (S_{pre}\ N_b\ A_b - \pi\ P\ G^2\ )$ Eq. 3

$(P - 0.5\ P_{leak\ P})\ A_g / (N_b\ A_b) + 4\ (M_{pipe} - 0.5\ M_{leak\ P}) / (N_b\ A_b\ G\ ) + S_{pre} \le S_{yb}$ Eq. 4a (Note 1)

$(P - 0.5\ P_{leak\ P})\ A_g / (N_b\ A_b) + (M_{pipe} - 0.5\ M_{leak\ P}) / (f_{bM\ x}\ N_b\ BC/2\ ) + S_{pre} \le S_{yb}$ Eq. 4b (Note 1)

$$0.8(S_{pre}\, N_b\, A_b + (\pi/4)G^2\, P + 4\, M_{pipe} / G\,)(BC - G)/\,(2\,\pi\, G\,)\, Y / t^2 \le 2\, S_{yh} \qquad \text{Eq. 5}$$

$$M_t \;\le \mu\, (G/2)(\, S_{pre}\, N_b\, A_b - (\pi/4)G^2\, P - \; M_{pipe} / G\,) \qquad \text{Eq. 6}$$

Nomenclature:

M_{pipe} – moment caused by the pipe acting on the flange, calculated from stress analysis of the piping system in the vicninity of the flange. If greater than Mc then use Mc.
P – pressure during upset event that must be evaluated for leakage. If emergency pressure is not known, use 1.2 x P_{design}. The simultaneously applied moment and pressure is M_{pipe} and P.
M_c – collapse moment of attached pipe. Use: $M_c = \; D^2\, T\, S_y$.
S_{pre} – bolt pretension stress. Bolt relaxation should be included. If unknown use 20%, i.e S_{pre} = 0.8 times the initial planned initial pretension in the bolts. If the flange locks up when bolted, then bolt relaxation is not required.
A_g – effective gasket area. Use π G b. See flange and gasket properties in Tables 1, 2 and 3 below for properties to use with B16.5 flanges. The value b is one-half the gasket width.
$N_b\, A_b$ – the product of the number of bolts and the bolt tensile area. See Table 1 below for collected values.
G – effective gasket reaction diameter. Both the gasket reaction diameter and the flange section moment arm change as the flange is loaded and the ring-hub assembly rotate. The equations here are similar in form to the equations used in the equivalent leak pressure method but are calibrated to best match available leakage tests and maintain simplicity. If the gasket dimensions or surface contours are not known, the average of the pipe OD and the OD of the flange hub can be used for G.
P_c – Displacement-based rated pressure from Table 3. (Taken from B16.9 Table A-2.)
$P_{leak\,P}$ – theoretical water-equivalent visible leak pressure, the pressure that will cause some small amount of visible leakage at the flange joint, i.e. 1 -to- 10 drops per min. Usually underestimated by 1 to 1.4 times.
$M_{leak\,P}$ – theoretical water-equivalent visible leak moment. The combination of $M_{leak\,P}$ and P in Eq. 3 will cause a water-equivalent visible leak, i.e. 1-to-10 drops per min. Usually underestimated by 1 to 1.4 times.
BC – Bolt circle diameter (see Table 5).
f_{bM} – discrete bolt factor for external moments applied to flanges. (See Table X below.)
S_{yh} – hot yield stress for the flange material in psi. at the loading temperature.
μ – damage coefficient (similar to friction coefficient) for torsional loads on flange faces. See Table 6.
t – flange ring thickness (include raised face)

Note 1 – where the terms (P - $P_{leak\,P}$) or (M – $M_{leak\,P}$) are less than zero then use zero. P_{leak} and M_{leak} are theoretical limits where change in load transfer is believed to occur. When at the leakage pressure loading, increased load, either moment or pressure will go directly to the bolt loading, adding to the original preload. At this point the joint is believed to be at the onset of theoretical gross leakage. Equations 4a and 4b are considered underestimates and describe an early on worst case load transfer possibility.

The calculated values $M_{leak\,P}$ and $P_{leak\,P}$ are considered "limit" values for the moment and the pressure and the relationship between the moment and the pressure that results in water-equivalent leaks. Reasonable allowables can be taken as ½ of these loads. Actual leak causing loads can be found by multiplying $M_{leak\,P}$ and $P_{leak\,P}$ by 1.4. Guidelines are provided in Appendix 14.

When bolt stresses may exceed yield due to load or temperature gradients the designer should consider the use of Belville washers or bolt sleeves.

Loads evaluated here are for typical piping systems. F_{axial} / A_{pipe} should not approach the yield stress of the pipe material.

Leakage will most often occur when the bolt increment occurs, i.e. at 3 and 8" 150# flanges. These flanged joints have the lowest load per length on the gasket and are geometrically at the point where the flanges go from 4 to 8, and from 8 to 12, i.e.

#	Nom. Dia.	Class	# bolts	Load/Length
1	1	150	4	0.1368

2	2	150	4	0.1789
3	3	150	4	0.0822
4	4	150	8	0.1278
5	6	150	8	0.1285
6	8	150	8	0.0987
7	10	150	12	0.1641
8	12	150	12	0.1383
9	14	150	12	0.1653
10	16	150	16	0.1928
11	18	150	16	0.2236
12	20	150	20	0.2516
13	24	150	20	0.2652

Rodabaugh in ORNL/2913-3 identified leakage problems at 3 and 8" class 150 lb. flanges. These particular 150# flanges show the lowest load per length for a given bolt pre-stress and are the point in the flange designs where the number of bolt is incremented. (See rows 3 and 6 in the above table.)

Table 1 – Approximated B16.5 Gasket Properties for Allowable External Load Estimates

All Units in inches or square inches.

Nom Diam (in.)	150# est b	150# est G	150# Nb Ab	300# est b	300# est G	300# Nb Ab	600# est b	600# est G	600# Nb Ab	1500# est b	1500# est G	1500# Nb Ab
1	0.238	1.630	0.568	0.238	1.720	0.904	0.260	1.720	0.904	0.160	1.690	1.847
2	0.388	2.720	1.338	0.388	2.845	1.808	0.420	2.845	1.808	0.295	3.250	3.694
3	0.483	3.875	0.904	0.483	4.060	2.676	0.525	4.060	2.676	0.350	4.375	6.324
4	0.540	4.905	1.808	0.540	5.125	2.676	0.590	5.250	3.694	0.398	5.440	7.998
5	0.565	6.000	2.676	0.565	6.280	2.676	0.625	6.500	4.846	0.403	6.655	11.935
6	0.608	7.095	2.676	0.608	7.375	4.014	0.685	7.690	7.269	0.438	7.815	14.802
8	0.660	9.160	2.676	0.660	9.440	5.541	0.748	9.690	9.485	0.468	10.065	21.297
10	0.683	11.375	5.541	0.683	11.685	9.692	0.750	12.125	15.995	0.750	12.625	28.969
12	0.750	13.565	5.541	0.750	13.750	12.647	0.813	14.250	19.994	0.813	15.250	44.330
14	0.750	14.875	7.269	0.750	15.375	15.809	0.813	15.500	24.670	0.813	16.750	56.917
16	0.813	17.000	9.692	0.813	17.500	19.994	0.875	17.750	29.837	0.875	18.875	71.074
18	0.938	18.940	12.647	0.938	19.500	23.993	1.000	19.750	35.494	1.000	20.750	86.802
20	0.938	21.000	15.809	0.938	21.560	23.993	1.000	22.000	42.593	1.000	22.625	104.101
24	1.000	25.060	19.994	1.000	25.810	35.804	1.063	26.125	57.939	1.063	27.000	143.411

Table 2 – "m" Gasket Factors for Allowable External Load Estimates

Gasket Type	m
Non-metallic, elastomer, self-sealing, composition, fiber, graphite	2.0
Spiral wound, kammprofile, corrugated metal	3.0
Flat metal	4.0
Ring Joint (soft steel)	5.0
Ring Joint (hardened steel or alloy)	6.0

Note: Where non-metallic, elastomer, composition, fiber or graphite gaskets are used without a metal restraining provision to prevent radial gasket failure and blow-out, and where external loads, pressures or human error may occur that can influence flanged joint performance in an area where human occupancy, control panels or other sensitive equipment, the designer should consider relocating the flange or providing protective shielding to direct ejected pieces in a safe direction, (i.e. parallel to the pipe).

Table 3 – Maximum Rated Pressure (psi) for B16.5 Flanges for Allowable External Load Estimates

T °F	150	300	400	600	900	1500	2500
to 100	290	750	1000	1500	2250	3750	6250
200	260	750	1000	1500	2250	3750	6250
300	230	730	970	1455	2185	3640	6070
400	200	705	940	1410	2115	3530	5880
500	170	665	885	1330	1995	3325	5540
600	140	605	805	1210	1815	3025	5040
700	110	570	755	1135	1705	2840	4730

Table 4 – fM factor as a function of the number of bolts in the flange.

Nb	f_M
4	0.5
8	0.375
12	0.333
16	0.312
20	0.300
24	0.292
28	0.286
32	0.281
36	0.278

Table 5 – Bolt Circle, ID, OD, Y (for use in Eqs 5 through 8).

Nom	150#		150#	150#	300#		300#	300#	600#		600#	600#	1500#		1500#	1500#
Diam (in.)	BC	Y	ID (est)	Flg OD	BC	Y	ID (est)	Flg OD	BC	Y	ID (est)	Flg OD	BC	Y	ID (est)	Flg OD
1	3.120	1.437	1.054	4.250	3.500	1.284	1.054	4.880	3.500	1.284	1.054	4.880	4.000	1.099	1.042	5.880
2	4.750	1.934	2.072	6.000	5.000	1.791	2.072	6.500	5.000	1.791	2.072	6.500	6.500	1.307	1.877	8.500
3	6.000	2.308	3.068	7.500	6.620	2.083	3.068	8.250	6.620	2.083	3.068	8.250	8.000	1.504	2.748	10.500
4	7.500	2.562	4.026	9.000	8.500	2.267	4.026	10.000	8.500	2.098	4.026	10.750	9.500	1.641	3.547	12.250
5	8.500	3.000	5.044	10.000	10.500	2.642	5.044	11.000	10.500	2.178	5.044	13.000	11.500	1.680	4.382	14.750
6	9.500	3.436	6.070	11.000	11.500	2.847	6.070	12.500	11.500	2.467	6.070	14.000	12.500	1.890	5.227	15.500
8	11.750	3.872	7.986	13.500	13.750	3.248	7.986	15.000	13.750	2.794	7.901	16.500	15.500	2.005	6.804	19.000
10	14.250	4.323	10.020	16.000	17.000	3.655	10.020	17.500	17.000	2.898	9.841	20.000	19.000	2.063	8.474	23.000
12	18.000	4.400	12.000	19.000	19.250	3.799	12.000	20.500	19.250	3.231	11.672	22.000	22.500	2.126	10.051	26.500
14	18.750	4.391	13.250	21.000	20.750	3.694	13.250	23.000	20.750	3.316	12.816	23.750	25.000	2.096	11.036	29.500
16	21.250	4.664	15.250	23.500	23.750	3.951	15.250	25.500	23.750	3.344	14.647	27.000	27.750	2.179	12.613	32.500
18	22.750	5.402	17.250	25.000	25.750	4.178	17.239	28.000	25.750	3.555	16.478	29.250	30.500	2.215	14.189	36.000
20	25.000	5.611	19.250	27.500	28.500	4.348	19.154	30.500	28.500	3.650	18.309	32.000	32.750	2.294	15.766	38.750
24	29.500	6.240	23.250	32.000	33.000	4.502	22.985	36.000	33.000	3.899	21.970	37.000	39.000	2.322	18.919	46.000
Note 1 - All units in inches.																

Table 6 – Torsional Damage Coefficient

Gasket Type	μ	Notes
Non-metallic	0.5	
Non-metallic lock-up design	0.7	
Metallic	0.7	

Commentary:

Leak Rates:

From NUREG/CR-5928, ISLOCA Research Program, 1993: If a drop of water is a 1/8" diameter sphere, a leak rate of 1 mg/s. would correspond to 3.5 drops per minute. Leak rates on the order of 200 to 500 mg./s results in a spray and can inhibit operator action in the vicinity of the leak. Many leak rates are given in rate per inch of diameter and so have units of mg/s./mm or mg/s/m.

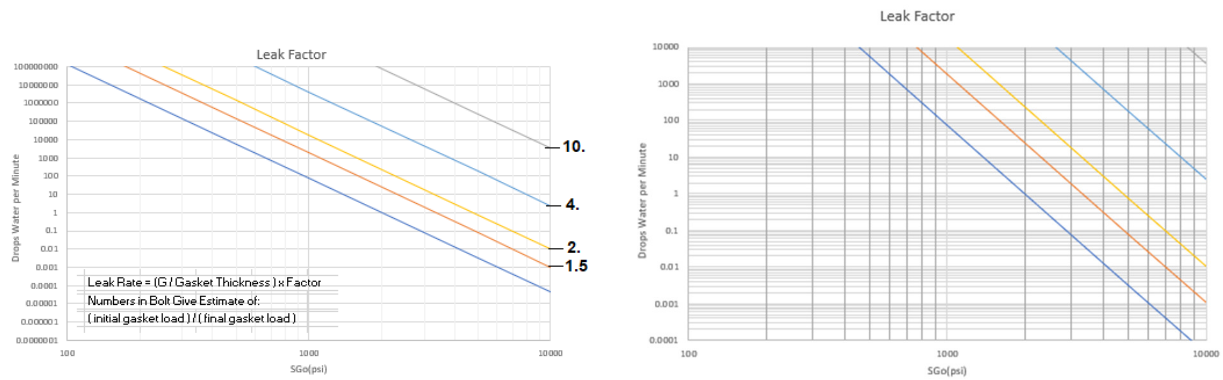
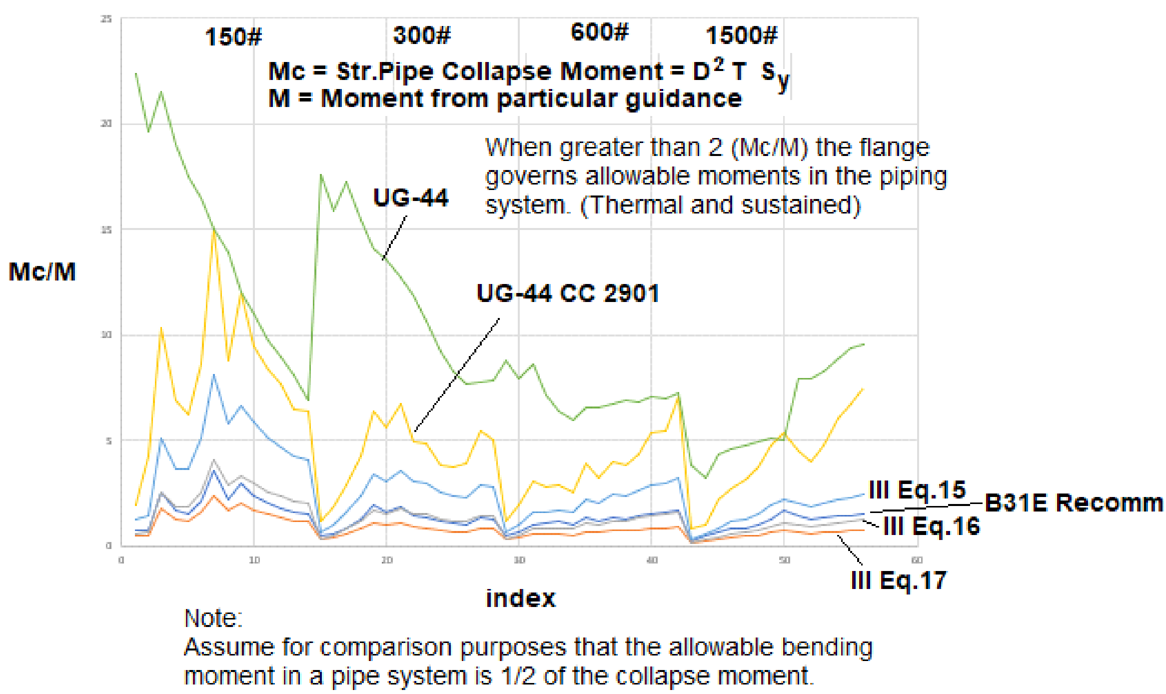
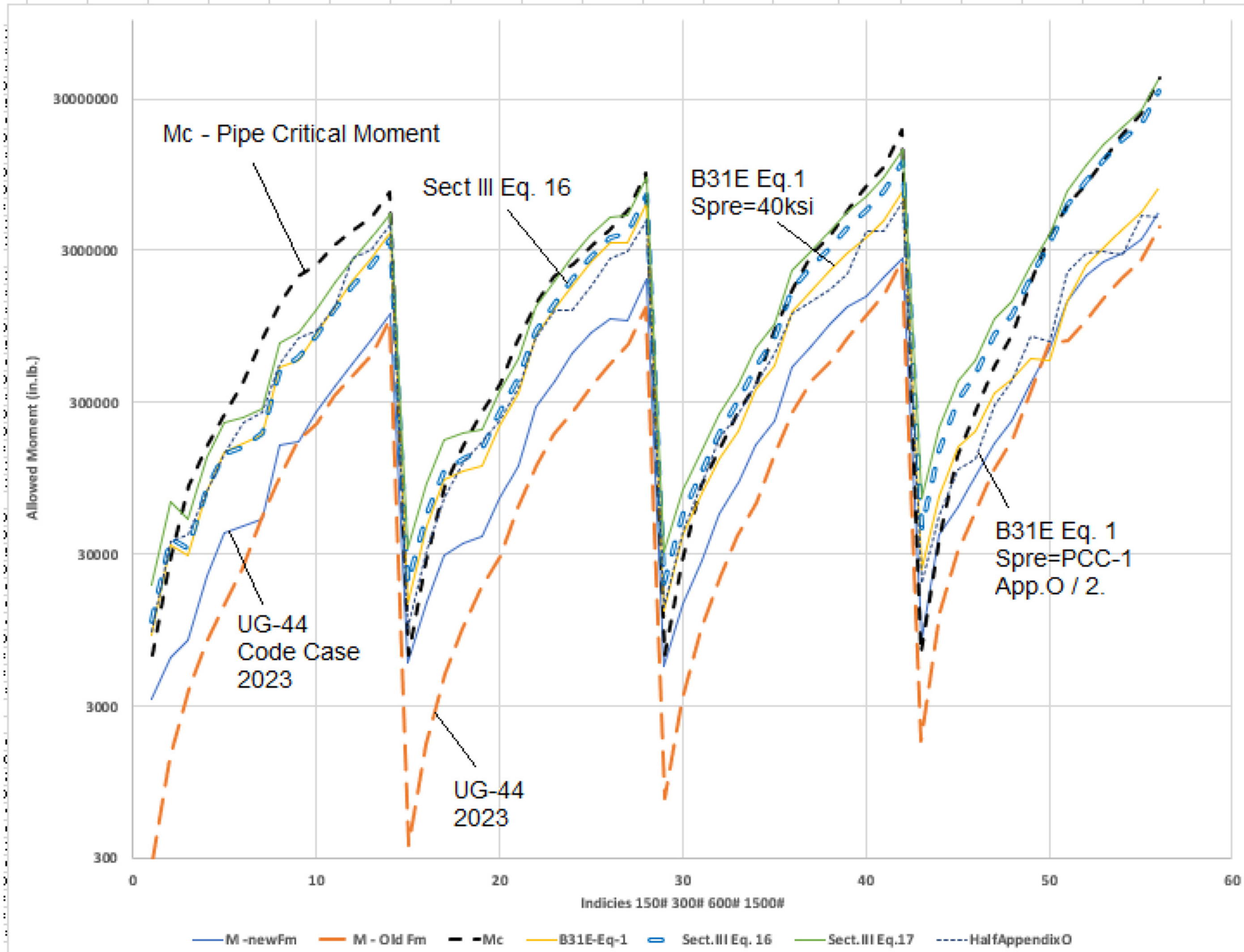


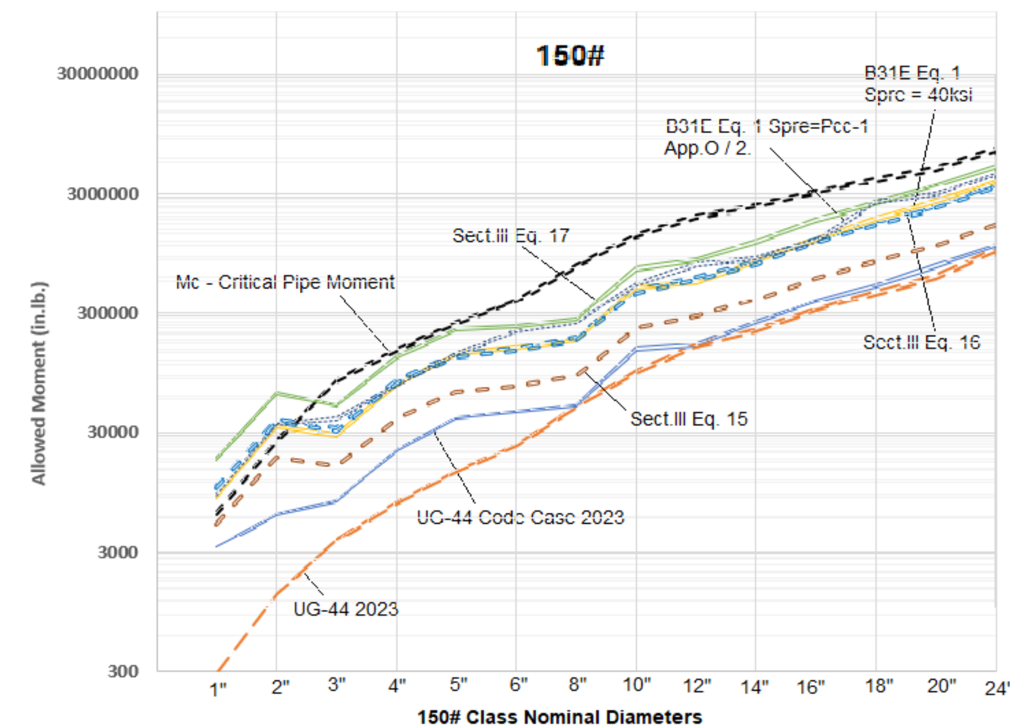
Fig. C – GLP Water Leak Rate Estimator (Note that final factor in NUREG/CR-5928 Eq. 3 is increased from 0.79 to 7.9 believed to better match high unload leak results. <u>Do not use until B31E TG verification.</u>) (3.5 mg./sec is assumed to be equal to 1 drop per minute.) Note: The prediction of the onset of leakage at high external loads (low gasket loads) is considered an order-of-magnitude estimate. Before using multiply the “Leak Factor” from Fig. C by the ratio of G/(gasket thickness).

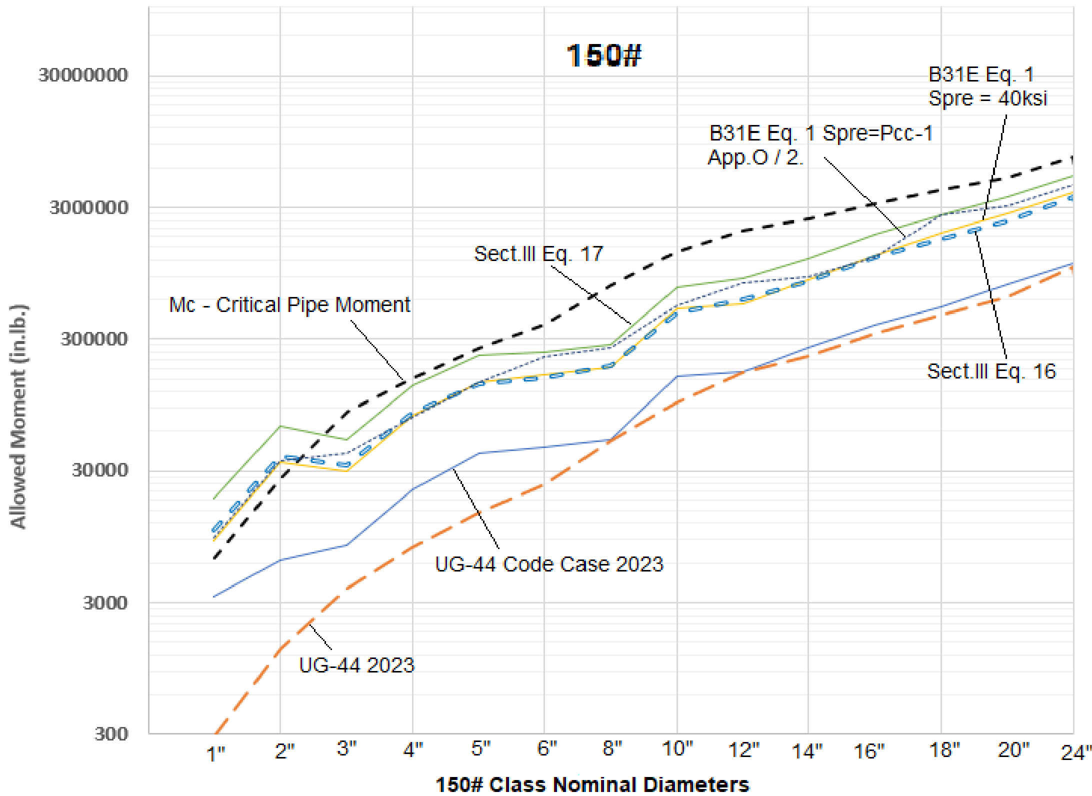
B16.5 Ceiling Pressure:
The ceiling pressure for 150# flanges can be found from: (2.5) x 115. The ceiling pressure cannot exceed 300 – 0.3 T, where T = deg.F.

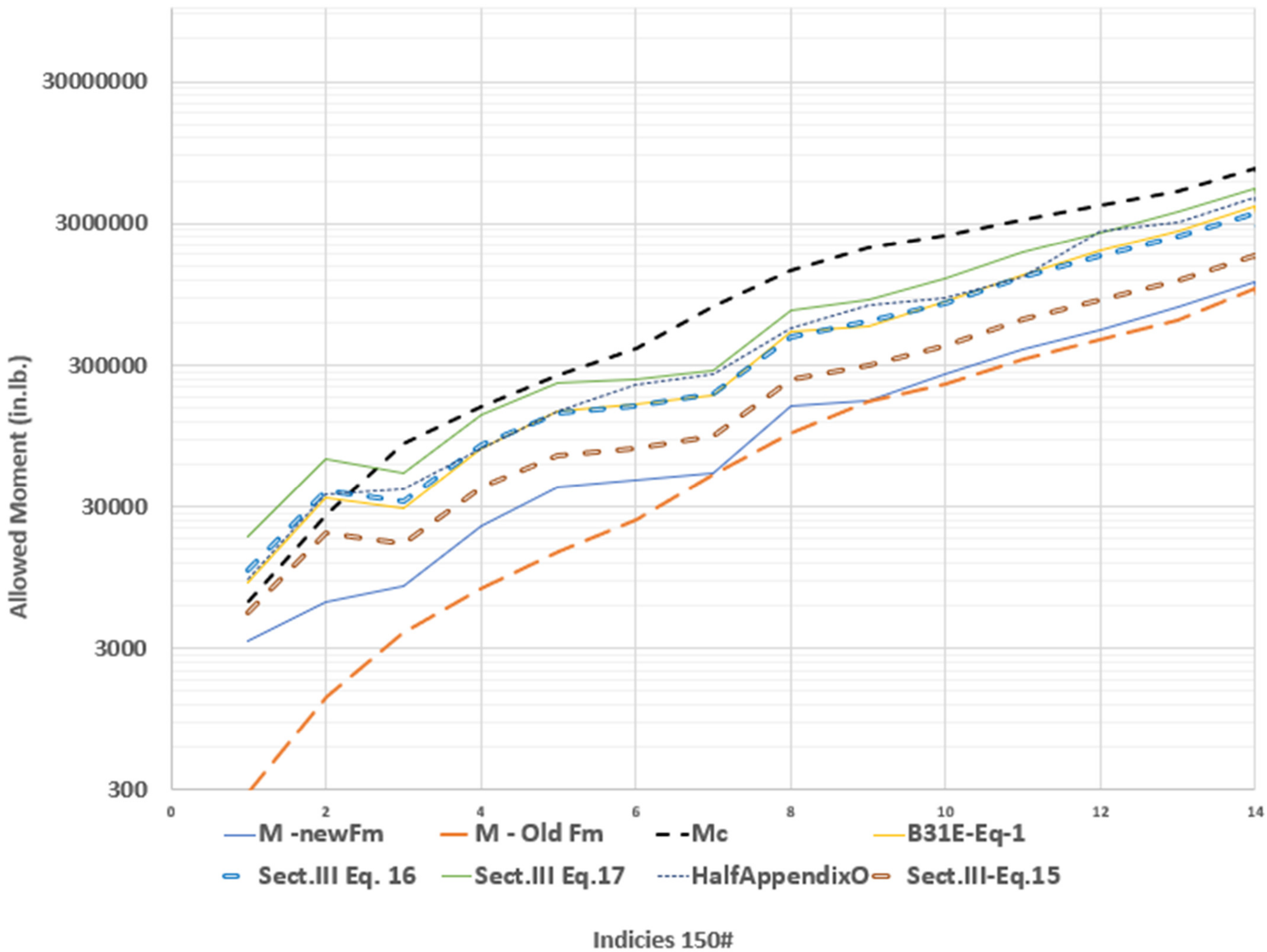
Lockup loads




Mc - Pipe Critical Moment
Sect III Eq. 16
B31E Eq.1
Spre=40ksi
B31E Eq. 1
Spre=PCC-1
App.O / 2.
UG-44
Code Case
2023
UG-44
2023
Allowed Moment (in.lb.)
Indicies 150# 300# 600# 1500#
M -newFm
M - Old Fm
Mc
B31E-Eq-1
Sect.III Eq. 16
Sect.III Eq.17
HalfAppendixO


150#
B31E Eq. 1
Spre = 40ksi
B31E Eq. 1 Spre=Pcc-1
App.O / 2.
Sect.iii Eq. 17
Mc - Critical Pipe Moment
Sect.III Eq. 16
Sect.III Eq. 15
UG-44 Code Case 2023
UG-44 2023
Allowed Moment (in.lb.)
150# Class Nominal Diameters


150#
30000000
3000000
300000
30000
3000
300
Allowed Moment (in.lb.)
B31E Eq. 1
Spre = 40ksi
B31E Eq. 1 Spre=Pcc-1
App.O / 2.
Sect.III Eq. 17
Mc - Critical Pipe Moment
Sect.III Eq. 16
UG-44 Code Case 2023
UG-44 2023
1"
2"
3"
4"
5"
6"
8"
10"
12"
14"
16"
18"
20"
24"
150# Class Nominal Diameters



30000000
3000000
300000
30000
3000
300
Allowed Moment (in.lb.)
0
2
4
6
8
10
12
14
M -newFm
M - Old Fm
-Mc
B31E-Eq-1
Sect.III Eq. 16
Sect.III Eq.17
HalfAppendixO
Sect.III-Eq.15
Indicies 150#

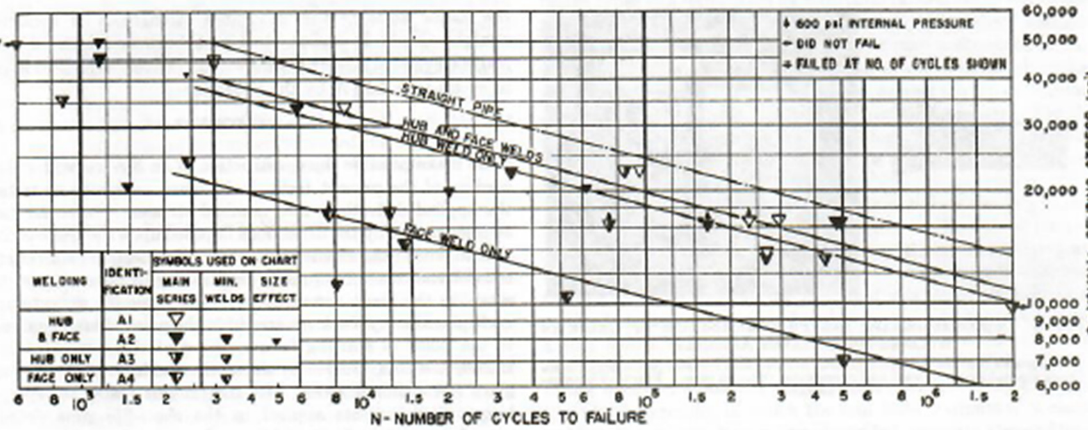


Fig. 7 *S-N* Curves for Slip-On Flanges

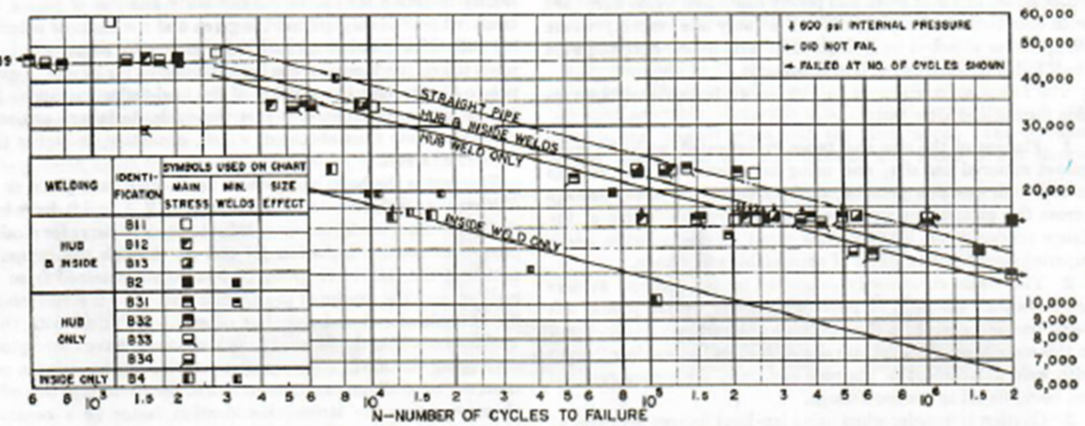


Fig. 8 *S-N* Curves for Socket Welding Flanges

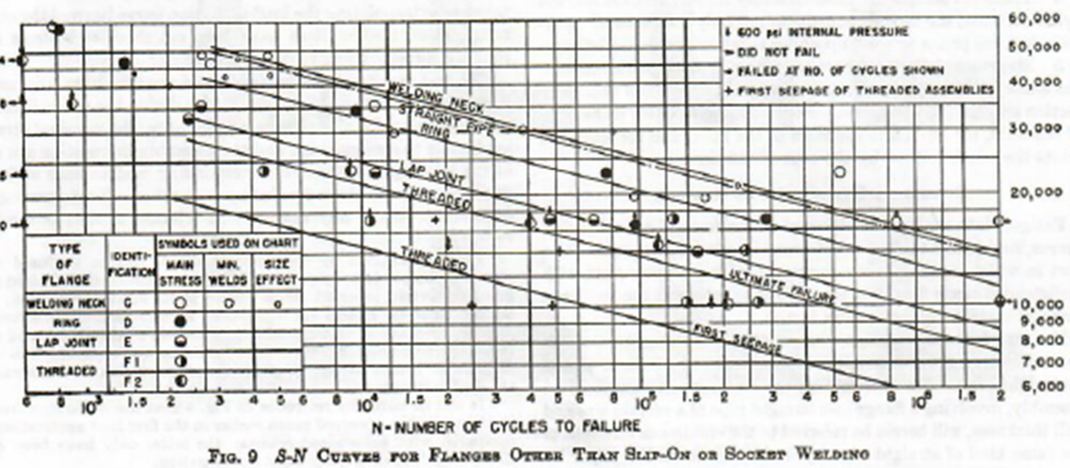


Fig. 9 *S-N* Curves for Flanges Other Than Slip-On or Socket Welding

Fig. B – Markl (ref)

Table O-4.1-2M
Bolt Stress Limit for SA-105 Steel Flanges Using Elastic–Plastic FEA (MPa)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	579	398	579	434	471	471
2½	688	326	434	398	471	543
3	724	434	615	579	471	579
4	543	615	688	434	507	507
5	543	724	652	507	543	543
6	724	579	579	579	615	579
8	724	579	615	507	579	579
10	579	543	543	507	615	579
12	724	543	507	543	579	615
14	579	434	471	543	543	...
16	543	434	471	579	507	...
18	724	471	579	543	543	...
20	615	507	507	579	507	...
24	615	471	507	543	507	...
26	253	253	362	434	...	...
28	217	253	326	398	...	...
30	253	290	434	434	...	...
32	217	253	398	434	...	...
34	190	290	434	398	...	...
36	217	253	398	434	...	...
38	253	579	579	543	...	...
40	217	543	615	543	...	...
42	253	543	615	579	...	...
44	226	579	615	543	...	...
46	253	615	652	543	...	...
48	253	507	579	579	...	...

Table O-4.1-2
Bolt Stress Limit for SA-105 Steel Flanges Using Elastic–Plastic FEA (ksi)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	84	58	84	63	68	68
2½	100	47	63	58	68	79
3	105	63	89	84	68	84
4	79	89	100	63	74	74
5	79	105	95	74	79	79
6	105	84	84	84	89	84
8	105	84	89	74	84	84
10	84	79	79	74	89	84
12	105	79	74	79	84	89
14	84	63	68	79	79	...
16	79	63	68	84	74	...
18	105	68	84	79	79	...
20	89	74	74	84	74	...
24	89	68	74	79	74	...
26	37	37	53	63	...	...
28	32	37	47	58	...	...
30	37	42	63	63	...	...
32	32	37	58	63	...	...
34	28	42	63	58	...	...
36	32	37	58	63	...	...
38	37	84	84	79	...	...
40	32	79	89	79	...	...
42	37	79	89	84	...	...
44	33	84	89	79	...	...
46	37	89	95	79	...	...
48	37	74	84	84	...	...

Table O-4.1-3 Flange Rotation for SA-105 Steel Flanges Loaded to Table O-4.1-2M/Table O-4.1-2 Bolt Stress Using Elastic–Plastic FEA (deg)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	0.37	0.34	0.23	0.21	0.20	0.16
$2\frac{1}{2}$	0.36	0.31	0.24	0.20	0.21	0.17
3	0.23	0.32	0.26	0.26	0.22	0.16
4	0.50	0.37	0.29	0.26	0.21	0.17
5	0.56	0.33	0.29	0.28	0.20	0.17
6	0.61	0.41	0.30	0.27	0.21	0.16
8	0.46	0.45	0.31	0.28	0.21	0.17
10	0.70	0.43	0.34	0.30	0.21	0.17
12	0.74	0.48	0.35	0.34	0.22	0.16
14	0.68	0.48	0.39	0.33	0.24	...
16	0.83	0.48	0.39	0.34	0.23	...
18	0.88	0.51	0.41	0.33	0.24	...
20	0.87	0.58	0.40	0.32	0.24	...
24	0.95	0.59	0.41	0.31	0.26	...
26	0.87	0.59	0.43	0.35	...	...
28	0.84	0.50	0.40	0.37	...	...
30	0.97	0.60	0.43	0.35	...	...
32	0.98	0.49	0.48	0.37	...	...
34	0.87	0.52	0.41	0.35	...	...
36	0.85	0.51	0.44	0.38	...	...
38	1.09	0.51	0.39	0.34	...	...
40	0.93	0.52	0.43	0.37	...	...
42	1.04	0.60	0.43	0.35	...	...
44	0.91	0.54	0.43	0.35	...	...
46	1.00	0.52	0.43	0.37	...	...
48	1.04	0.63	0.42	0.35	...	...

Table O-4.1-4M
Bolt Stress Limit for SA-105 Steel Flanges Using Elastic Closed Form Analysis (MPa)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	450	310	515	332	413	447
2½	576	284	388	377	441	496
3	724	394	545	517	432	531
4	445	561	633	417	492	454
5	402	724	663	468	528	501
6	541	593	630	543	605	535
8	724	614	657	463	576	557
10	503	639	566	444	627	543
12	712	607	563	494	554	594
14	583	454	513	526	485	...
16	563	398	508	532	487	...
18	614	472	594	534	521	...
20	568	451	482	545	501	...
24	479	365	450	546	481	...
26	218	242	359	448	...	...
28	193	264	354	399	...	...
30	228	290	447	465	...	...
32	173	272	396	460	...	...
34	160	296	463	418	...	...
36	207	261	404	436	...	...
38	211	557	623	551	...	...
40	199	536	634	532	...	...
42	218	581	626	585	...	...
44	221	676	638	570	...	...
46	238	724	687	563	...	...
48	222	524	605	625	...	...

ASME B16.5 — Slip-On					
	Class				
NPS	150	300	600	900	1500
2	724	360	572	423	413
2½	534	321	410	377	441
3	714	446	563	518	...
4	394	594	601	467	...
5	446	678	507	492	...
6	603	458	495	536	...
8	724	538	515	456	...
10	477	472	430	429	...
12	674	476	421	468	...
14	445	283	344	504	...
16	453	320	370	509	...
18	561	376	546	514	...
20	487	428	499	524	...
24	535	395	500	528	...

Table O-4.1-4
Bolt Stress Limit for SA-105 Steel Flanges Using Elastic Closed Form Analysis (ksi)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	65	45	75	48	60	65
2½	83	41	56	55	64	72
3	105	57	79	75	63	77
4	65	81	92	61	71	66
5	58	105	96	68	77	73
6	78	86	91	79	88	78
8	105	89	95	67	83	81
10	73	93	82	64	91	79
12	103	88	82	72	80	86
14	84	66	74	76	70	...
16	82	58	74	77	71	...
18	89	69	86	77	76	...
20	82	65	70	79	73	...
24	69	53	65	79	70	...
26	32	35	52	65	...	...
28	28	38	51	58	...	...
30	33	42	65	67	...	...
32	25	40	58	67	...	...
34	23	43	67	61	...	...
36	30	38	59	63	...	...
38	31	81	90	80	...	...
40	29	78	92	77	...	...
42	32	84	91	85	...	...
44	32	98	93	83	...	...
46	35	105	100	82	...	...
48	32	76	88	91	...	...

ASME B16.5 — Slip-On					
	Class				
NPS	150	300	600	900	1500
2	105	52	83	61	60
2½	77	47	60	55	64
3	103	65	82	75	...
4	57	86	87	68	...
5	65	98	74	71	...
6	87	66	72	78	...
8	105	78	75	66	...
10	69	68	62	62	...
12	98	69	61	68	...
14	65	41	50	73	...
16	66	46	54	74	...
18	81	55	79	75	...
20	71	62	72	76	...
24	78	57	73	77	...

Table O-4.1-5
Flange Rotation for SA-105 Steel Flanges Loaded to Table O-4.1-4M/Table O-4.1-4 Bolt Stress Using Elastic Closed Form Analysis (deg)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	0.20	0.20	0.15	0.13	0.09	0.08
2½	0.22	0.19	0.17	0.11	0.09	0.07
3	0.20	0.22	0.19	0.15	0.12	0.08
4	0.28	0.27	0.19	0.17	0.14	0.10
5	0.29	0.26	0.20	0.18	0.14	0.10
6	0.33	0.32	0.24	0.16	0.15	0.10
8	0.35	0.36	0.28	0.18	0.15	0.11
10	0.44	0.40	0.27	0.17	0.16	0.10
12	0.46	0.42	0.32	0.21	0.15	0.11
14	0.46	0.38	0.35	0.24	0.15	...
16	0.54	0.36	0.36	0.23	0.17	...
18	0.54	0.41	0.34	0.26	0.18	...
20	0.60	0.39	0.33	0.24	0.19	...
24	0.59	0.37	0.34	0.26	0.20	...
26	0.77	0.55	0.42	0.33	...	...
28	0.79	0.56	0.43	0.33	...	...
30	0.88	0.58	0.42	0.34	...	...
32	0.84	0.58	0.43	0.34	...	...
34	0.85	0.57	0.43	0.34	...	...
36	0.90	0.56	0.43	0.34	...	...
38	0.93	0.71	0.48	0.35	...	...
40	0.93	0.71	0.48	0.35	...	...
42	0.94	0.71	0.48	0.36	...	...
44	0.96	0.71	0.48	0.36	...	...
46	0.98	0.71	0.48	0.36	...	...
48	0.95	0.71	0.48	0.36	...	...

Table O-4.1-5
Flange Rotation for SA-105 Steel Flanges Loaded to Table O-4.1-4M/Table O-4.1-4 Bolt Stress Using Elastic Closed Form Analysis (deg) (Cont'd)

ASME B16.5 — Slip-On					
	Class				
NPS	150	300	600	900	1500
2	0.34	0.28	0.21	0.14	0.10
2½	0.35	0.29	0.24	0.12	0.10
3	0.40	0.32	0.27	0.21	...
4	0.52	0.38	0.27	0.21	...
5	0.64	0.43	0.30	0.20	...
6	0.73	0.49	0.33	0.20	...
8	0.84	0.57	0.38	0.22	...
10	1.02	0.59	0.40	0.27	...
12	1.09	0.66	0.47	0.33	...
14	1.14	0.70	0.50	0.33	...
16	1.26	0.76	0.52	0.33	...
18	1.34	0.80	0.52	0.34	...
20	1.38	0.86	0.55	0.33	...
24	1.52	0.91	0.58	0.33	...

Table O-4.1-6M Bolt Stress Limit for SA-182 F304 Steel Flanges Using Elastic–Plastic FEA (MPa)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	434	326	471	362	362	398
2½	543	253	362	326	398	434
3	724	362	507	471	362	471
4	362	471	543	362	434	434
5	398	615	543	398	434	434
6	543	471	471	471	471	471
8	579	471	507	434	471	471
10	434	434	434	434	507	471
12	471	434	434	434	471	507
14	434	326	362	434	434	...
16	362	362	362	471	434	...
18	398	398	471	471	434	...
20	362	398	398	471	434	...
24	362	362	398	434	398	...
26	217	181	290	362	...	...
28	181	217	290	326	...	...
30	217	217	362	362	...	...
32	181	217	326	362	...	...
34	172	253	362	326	...	...
36	181	217	326	362	...	...
38	181	471	471	434	...	...
40	145	434	507	434	...	...
42	217	434	507	471	...	...
44	154	471	471	434	...	...
46	217	507	507	434	...	...
48	217	398	471	471	...	...

Table O-4.1-6 Bolt Stress Limit for SA-182 F304 Steel Flanges Using Elastic–Plastic FEA (ksi)

ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	63	47	68	53	53	58
2½	79	37	53	47	58	63
3	105	53	74	68	53	68
4	53	68	79	53	63	63
5	58	89	79	58	63	63
6	79	68	68	68	68	68
8	84	68	74	63	68	68
10	63	63	63	63	74	68
12	68	63	63	63	68	74
14	63	47	53	63	63	...
16	53	53	53	68	63	...
18	58	58	68	68	63	...
20	53	58	58	68	63	...
24	53	53	58	63	58	...
26	32	26	42	53	...	...
28	26	32	42	47	...	...
30	32	32	53	53	...	...
32	26	32	47	53	...	...
34	25	37	53	47	...	...
36	26	32	47	53	...	...
38	26	68	68	63	...	...
40	21	63	74	63	...	...
42	32	63	74	68	...	...
44	22	68	68	63	...	...
46	32	74	74	63	...	...
48	32	58	68	68	...	...

Table O-4.1-7
Flange Rotation for SA-182 F304 Steel Flanges Loaded to Table O-4.1-6M/Table O-4.1-6 Bolt Stress Using Elastic–Plastic FEA (deg)

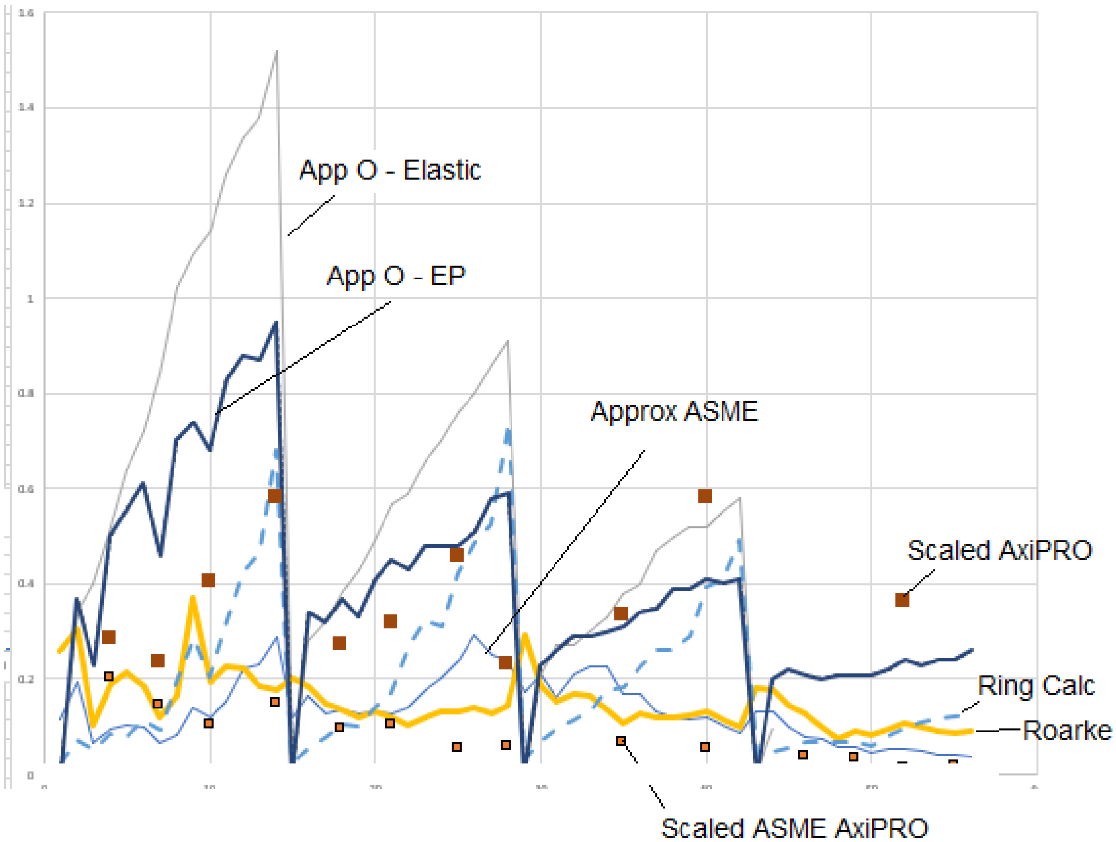
ASME B16.5 and ASME B16.47 Series A — Weld Neck						
	Class					
NPS	150	300	600	900	1500	2500
2	0.47	0.34	0.21	0.17	0.15	0.16
$2\frac{1}{2}$	0.40	0.29	0.20	0.20	0.24	0.13
3	0.21	0.27	0.29	0.23	0.16	0.12
4	0.55	0.41	0.25	0.21	0.19	0.15
5	0.61	0.32	0.27	0.25	0.20	0.18
6	0.64	0.38	0.27	0.24	0.17	0.15
8	0.46	0.42	0.34	0.25	0.19	0.15
10	0.91	0.47	0.26	0.26	0.17	0.15
12	0.79	0.37	0.31	0.26	0.20	0.17
14	0.89	0.41	0.28	0.25	0.19	...
16	1.02	0.41	0.29	0.31	0.20	...
18	0.93	0.54	0.28	0.25	0.18	...
20	1.02	0.53	0.35	0.29	0.20	...
24	1.12	0.44	0.37	0.24	0.23	...
26	0.81	0.53	0.33	0.29	...	...
28	0.52	0.45	0.37	0.25	...	...
30	0.91	0.41	0.35	0.29	...	...
32	0.59	0.43	0.31	0.31	...	...
34	0.68	0.37	0.34	0.24	...	...
36	0.54	0.44	0.30	0.31	...	...
38	1.00	0.46	0.35	0.26	...	...
40	0.91	0.55	0.35	0.28	...	...
42	0.52	0.64	0.34	0.32	...	...
44	0.54	0.48	0.34	0.27	...	...
46	1.00	0.55	0.41	0.28	...	...
48	0.51	0.55	0.38	0.32	...	...

Horizontal (Value) Axis Major Gridlines

	y	Do	theta	DEG theta NE'	PreLoad per inch	Mc	stress	stress with mc Bending	DEG rotation with mc	Flg ID est	Flg OD	
8	2.19	1.315	0.00295	0.00191	0.37252	8049.54	344.836	-671.2	0.00357	1.054	4.25	4.03226
9	2.5	2.375	0.00532	0.00496	0.55666	30403	719.63	74.7687	0.0091	2.072	6	2.89575
10	2.75	3.55	0.00233	0.0047	0.27083	95274.9	599.616	318.644	0.01747	3.068	7.5	2.44459
11	3	4.5	0.00648	0.01258	0.86706	167974	1268.51	1624.1	0.0364	4.026	9	2.23547
12	3.5	5.563	0.01098	0.00944	1.05801	279451	778.274	1066.53	0.02587	5.044	10	1.98255
13	3.5	6.625	0.01014	0.00956	0.90127	430128	708.91	1036.08	0.03121	6.07	11	1.81219
14	4	8.625	0.00878	0.00863	0.70315	838382	555.535	1329.35	0.03816	7.986	13.5	1.69046
15	4	10.75	0.0189	0.02042	1.76369	1476311	1124.49	2923.31	0.06826	10.02	16	1.59681
16	4.5	12.75	0.02686	0.03648	1.47179	2133633	1769.46	6160.26	0.14005	12	19	1.58333
17	5	14	0.02147	0.02605	1.76288	2572500	1271.78	4297.7	0.08801	13.25	21	1.58491
18	5	16	0.02931	0.04614	2.74225	3360000	2056.89	6251.7	0.14023	15.25	23.5	1.54098
19	5.5	18	0.03123	0.03557	3.24004	4252500	1541.81	4964.84	0.09871	17.25	25	1.44928
20	5.69	20	0.03336	0.04946	4.57471	5250000	2095.01	6180.75	0.12768	19.25	27.5	1.42857
21	6	24	0.03866	0.07001	4.87314	7560000	2764.46	8723.31	0.17565	23.25	32	1.37634
22	2.44	1.315	0.00268	0.00235	0.54293	8049.54	496.583	-312.85	0.00357	1.054	4.88	4.62998
23	2.75	2.375	0.00427	0.00822	1.39096	30403	1338.81	364.839	0.01308	2.072	6.5	3.13707
24	3.12	3.55	0.00432	0.01084	1.4748	95274.9	1574.1	1560.99	0.02035	3.068	8.25	2.68905
25	3.38	4.5	0.00358	0.01157	1.18497	167974	1484.62	1987.23	0.02573	4.026	10	2.48385
26	3.88	5.563	0.00343	0.00991	0.97337	279451	1146.12	2014.11	0.02639	5.044	11	2.18081
27	3.88	6.625	0.0054	0.01957	1.888	430128	2011.4	3520.54	0.04801	6.07	12.5	2.05931
28	4.38	8.625	0.00667	0.02215	2.06481	838382	2000.81	4488.65	0.05766	7.986	15	1.87829
29	4.62	10.75	0.00824	0.03186	3.91129	1476311	2698.26	6215.85	0.0734	10.02	17.5	1.74651
30	5.12	12.75	0.01048	0.03789	4.36691	2133633	2900.67	7382.6	0.08438	12	20.5	1.70833
31	5.62	14	0.0127	0.0528	6.00857	2572500	3831.68	8638.38	0.10868	13.25	23	1.73585
32	5.75	16	0.0145	0.06546	6.69929	3360000	4429.33	10419.6	0.12831	15.25	25.5	1.67213
33	6.25	18	0.01658	0.07366	8.72821	4315680	4732.01	10751.2	0.14161	17.2389	28	1.62424
34	6.38	20	0.01546	0.07635	7.92788	5920000	4659.67	11692	0.16373	19.1543	30.5	1.59233
35	6.62	24	0.02038	0.11339	9.90311	1E+07	6358.89	17598.7	0.23892	22.9851	36	1.56623
36	2.44	1.315	0.00268	0.00235	0.54293	8049.54	496.583	-312.85	0.00357	1.054	4.88	4.62998
37	2.88	2.375	0.00291	0.00727	1.39096	30403	1345.72	366.723	0.01157	2.072	6.5	3.13707
38	3.25	3.55	0.00311	0.00972	1.4748	95274.9	1575.25	1562.13	0.01825	3.068	8.25	2.68905
39	4	4.5	0.00311	0.01101	1.56773	167974	1655.32	2574.32	0.02054	4.026	10.75	2.67014
40	4.5	5.563	0.00329	0.01456	1.65862	279451	2063.24	3893.83	0.02748	5.044	13	2.57732
41	4.62	6.625	0.00423	0.01997	3.17318	430348	2569.24	4547.37	0.03534	6.06971	14	2.30653
42	5.25	8.625	0.00431	0.01935	3.37039	949596	2301.98	5326.83	0.03935	7.90057	16.5	2.08846
43	6	10.75	0.00606	0.02865	6.03432	1838599	3108.69	7330.88	0.0558	9.84086	20	2.03234
44	6.12	12.75	0.00756	0.03708	8.08168	3067554	3588.59	8942.96	0.07701	11.6717	22	1.8849
45	6.5	14	0.00881	0.03899	9.23849	4061120	3641.22	9761.16	0.08041	12.816	23.75	1.85315
46	7	16	0.00944	0.04533	9.74088	6062080	4032.01	11530	0.09721	14.6469	27	1.8434
47	7.25	18	0.00942	0.04648	10.51	8631360	4025.29	13064.4	0.1037	16.4777	29.25	1.77512
48	7.50	20	0.00998	0.06008	13.5579	1.2E+07	5030.3	15766.1	0.13598	18.3086	32	1.74782
49	8.00	24	0.01029	0.06806	15.668	2E+07	5484.78	20122	0.16006	21.9703	37	1.68409
50	2.88	1.315	0.00138	0.0031	1.14155	8424.91	1082.63	761.097	0.00394	1.0416	5.88	5.64518
51	4	2.375	0.00206	0.00628	2.2831	49634	1525.58	1796.98	0.00888	1.87718	8.5	4.52807
52	4.62	3.55	0.00226	0.00682	3.06723	165758	1542.31	2914.88	0.01091	2.74841	10.5	3.82038
53	4.88	4.5	0.00244	0.00875	3.19214	337618	1794.2	4207.95	0.01554	3.54729	12.25	3.45334
54	6.12	5.563	0.00178	0.008	3.92149	637845	1822.42	5067.1	0.01443	4.38223	14.75	3.36586
55	6.75	6.625	0.00168	0.0081	6.28217	1077323	1773.61	4753.22	0.01565	5.22739	15.5	2.96515
56	8.38	8.625	0.00216	0.00681	7.07369	2377199	1289.4	4275.19	0.01437	6.80396	19	2.79249
57	10	10.75	0.00216	0.00652	7.6314	4602710	1156.07	4351.69	0.01474	8.47407	23	2.71416
58	11.12	12.75	0.00249	0.00905	12.7195	7679249	1524.82	5261.28	0.01934	10.0506	26.5	2.63665
59	11.75	14	0.00291	0.01141	14.8654	1E+07	1881.83	6481.19	0.02357	11.036	29.5	2.67307
60	12.25	16	0.00312	0.01339	16.6426	1.5E+07	2146.09	8115.05	0.02853	12.6126	32.5	2.57679
61	12.88	18	0.00321	0.01591	18.8119	2.2E+07	2574.25	10326	0.03499	14.1891	36	2.53715
62	14	20	0.00318	0.01471	20.9974	3E+07	2395.09	10654.7	0.03322	15.7657	38.75	2.45787
63	16	24	0.00356	0.01655	24.3463	5.1E+07	2580.16	11986.4	0.03843	18.9189	46	2.43144

	Len/blt	Load	theta based stress	Inew	Iold	FEA Str at bolt	FEA Str	ASME hub	ASME Flg	DEG ASME Rot	DEG FEA Rot
8	1.28016	22703.8	1641.68	0.71884	0.02[illegible]						
9	2.13622	53513.6	7552.61	1.17612	0.0[illegible]						
10	3.04333	36160.3	11153.8	1.97358	0.15338						
11	1.92613	72320.5	26481.8	2.868	0.17214	17000	12000	21000	21290	0.103	0.13
12	2.35613	107027	16188.7	5.1434	0.17152						
13	2.78612	107027	16600.9	5.43641	0.20542						
14	3.59702	107027	18251.9	9.35809	0.32278	14000	9100	25354	33027	0.055	0.099
15	2.97788	221632	45231.7	10.4988	0.41989						
16	3.5512	221632	91929.2	16.7265	0.56966						
17	3.89415	290757	89159	23.5374	0.84865	20000	11000	19318	20527	0.05	0.16
18	3.33784	387676	167142	24.2976	1.02643						
19	3.71875	505890	138126	31.7713	1.22593						
20	3.29858	632362	234481	35.5193	1.65922						
21	3.9363	799764	406095	41.9828	2.42254	20000	9200	24600	22391	0.066	0.23
22	1.35085	36160.3	4296.64	1.05956	0.05237						
23	1.1172	72320.5	21806.5	1.71173	0.12573						
24	1.59431	107027	48602.6	3.21178	0.30335						
25	2.01252	107027	65825.5	4.4998	0.48617	19000	12000	22655	22655	0.042	0.08
26	2.46608	107027	61750.2	7.53736	0.6522						
27	1.93071	160541	127388	7.98004	0.79999						
28	2.47131	221632	174942	12.9235	1.24251	16700	9500	23491	23491	0.049	0.123
29	2.29428	387676	338840	16.8197	2.07092						
30	2.69973	505890	468458	24.2877	2.83333						
31	2.41503	632362	797553	36.5428	3.8708						
32	2.74881	799764	1091744	40.4116	4.86475	21500	12384	47916	33970	0.034	0.265
33	2.55247	959716	1370098	52.8162	6.04475						
34	2.82211	959716	1569496	60.2332	7.38653						
35	3.37842	1432166	2972896	78.6133	11.2778	21000	20000	68592	37512	0.033	0.376
36	1.35085	36160.3	4296.64	1.05956	0.05237						
37	1.1172	72320.5	28304.6	1.93515	0.1845						
38	1.59431	107027	30292.2	3.58196	0.42171						
39	2.06161	147755	59477.8	7.99103	0.94556						
40	2.55247	193838	119395	13.0833	1.77663						
41	2.01318	290757	171030	15.3223	2.19559						
42	2.53676	379417	225487	25.9956	3.76349	18700	12719	29165	29165	0.03	0.103
43	2.38067	639811	468790	48.6226	6.61403						
44	2.23832	799764	604252	58.0818	7.73964						
45	2.43466	986800	715080	74.1337	9.47471						
46	2.78808	1193472	1064646	105.997	13.8973						
47	3.10223	1419779	1289724	125.429	18.2687	26000	15554	51646	40820	0.026	0.237
48	2.87971	1703734	2003746	153.292	24.4592						
49	3.41965	2317556	3132519	210.156	40.0792						
50	1.32728	73877.3	15605.6	1.70294	0.28323						
51	1.27623	147755	53991.2	8.67063	0.93133						
52	1.71801	252945	100355	16.8685	2.14611						
53	2.13622	319905	166671	23.4623	3.45502	29000	11811	38613	38613	0.023	0.05
54	2.61334	477389	372204	55.3827	10.3193						
55	2.0459	592080	457057	83.5307	14.6933						
56	2.63493	851867	489425	207.924	24.1064	30000	21000	35786	35786	0.014	
57	3.30512	1158778	720391	444.934	46.4622						
58	2.99424	1773206	1418631	733.847	79.6521						
59	3.28876	2276669	2274513	947.699	111.325	30000	17940	42342	42342	0.005	0.154
60	3.70599	2842963	3351396	1174.42	157.533						
61	4.07413	3472089	5427858	1455.16	236.006						
62	4.44228	4164046	6406368	1997.45	328.484	37000	29000	54091	54091	0.008	0.19
63	5.30128	5736458	1.1E+07	3538.48	577.731						

	asme STRESS	Rot Ratio	ROT/ CALC ROT	Rot Calcfrm FEA		Roarke	theta roarke		ASME Approx theta			150	Nom Diam (in.)	G" H
8						2746.64	0.12429	0	0.05522	0.44433	1		1	
9						17355.9	0.14597	0	0.09246	0.63342	2		2	
10						6512.01	0.0392	0	0.0255	0.65054	3		3	
11	9.45995	1.50065	10.3368	0.1429	0.68771	17449.2	0.09523	1.50065	0.04709	0.49446	4		4	
12	0	0	0		0	23697.1	0.10848	0	0.05173	0.4768	5		5	
13	0	0	0		0	18919.3	0.07113	0	0.03789	0.53269	6		6	
14	16.3806	1.96186	11.4681	0.0894	0.68934	13201	0.04557	1.96186	0.02582	0.5666	7			
15	0	0	0		0	24388.2	0.07895	0	0.04009	0.50776	8		10	1
16	0	0	0		0	35700.1	0.14171	0	0.0534	0.37685	9		12	1
17	8.6493	2.06808	6.14294	0.1912	0.44368	24792.5	0.09245	2.06808	0.05713	0.61798	10		14	
18	0	0	0		0	30875.6	0.11491	0	0.07812	0.67984	11		16	
19	0	0	0		0	28527.4	0.08491	0	0.08492	1.00007	12		18	
20	0	0	0		0	28655	0.08283	0	0.10385	1.25372	13		20	
21	3.32795	3.30669	3.28504	0.2612	0.31818	28914.4	0.07899	3.30669	0.13031	1.6497	14		24	
22	0	0	0		0	-1724.5	0.13901	0	0.08248	0.59337	15	300	1	
23	0	0	0		0	12021.9	0.12848	0	0.11438	0.89027	16		2	
24	0	0	0		0	15670.7	0.09493	0	0.07984	0.8411	17		3	
25	8.08287	1.97365	6.91731	0.1224	1.3094	9164.52	0.06202	1.97365	0.06157	0.99282	18		4	
26	0	0	0		0	11532.3	0.04589	0	0.0494	1.07633	19		5	
27	0	0	0		0	15866.6	0.06203	0	0.06339	1.02185	20		6	
28	4.74808	2.63393	5.55251	0.1508	0.56509	16811.5	0.05725	2.63393	0.0617	1.0777	21		8	
29	0	0	0		0	18398.8	0.05194	0	0.07106	1.36809	22		10	1
30	0	0	0		0	19552.8	0.05994	0	0.08958	1.49433	23		12	1
31	0	0	0		0	25804.7	0.08455	0	0.12746	1.50747	24		14	
32	2.79591	3.51491	4.04854	0.2904	0.46717	26508.3	0.08262	3.51491	0.15241	1.84474	25		16	
33	0	0	0		0	27073.4	0.08287	0	0.17297	2.08717	26		18	
34	0	0	0		0	23194.1	0.0694	0	0.13578	1.95639	27		20	
35	3.1452	1.61281	3.31587	0.1359	0.72042	27761.6	0.08426	1.61281	0.1406	1.66854	28		24	
36	0	0	0		0	-1724.5	0.13901	0	0.08248	0.59337	29	600	1	
37	0	0	0		0	9309.79	0.08755	0	0.09976	1.13941	30		2	
38	0	0	0		0	12580.7	0.06828	0	0.07255	1.0625	31		3	
39	0	0	0		0	10291.5	0.06726	0	0.0846	1.25784	32		4	
40	0	0	0		0	12078.9	0.06911	0	0.09581	1.38621	33		5	
41	0	0	0		0	14965.3	0.06516	0	0.107	1.64217	34		6	
42	5.52525	3.06742	5.32235	0.1503	0.92814	13703.8	0.049	3.06742	0.07541	1.53898	35		8	
43	0	0	0		0	19382.8	0.06486	0	0.0847	1.30595	36		10	1
44	0	0	0		0	22789.9	0.06416	0	0.07096	1.10601	37		12	1
45	0	0	0		0	24508.1	0.06928	0	0.07134	1.02964	38		14	
46	0	0	0		0	25714.4	0.07393	0	0.06777	0.9167	39		16	
47	3.86407	4.46012	5.09933	0.2769	0.65748	23656.9	0.06208	4.46012	0.05778	0.93071	40		18	
48	0	0	0		0	25194.7	0.06325	0	0.05562	0.87928	41		20	
49	0	0	0		0	23634.2	0.05421	0	0.04738	0.874	42		24	
50	0	0	0		0	-12815	0.10582	0	0.0775	0.7324	43	1500	1	
51	0	0	0		0	8770.49	0.10336	0	0.07801	0.75468	44		2	
52	0	0	0		0	8297.65	0.08376	0	0.0585	0.69842	45		3	
53	6.58287	0	5.71587		1.15963	10185.2	0.076	0	0.04589	0.60384	46		4	
54	0	0	0		0	8675.99	0.05294	0	0.03997	0.75505	47		5	
55	0	0	0		0	10337.1	0.03759	0	0.03023	0.80422	48		6	
56	16.2867	0	0		1.73758	12085.7	0.04132	0	0.02582	0.62474	49		8	
57	0	0	0		0	12370.6	0.03848	0	0.02215	0.57548	50		10	1
58	0	0	0		0	16278.2	0.04248	0	0.02358	0.5552	51		12	1
59	9.53327	3.33543	13.4999	0.172	0.97426	18414	0.05157	3.33543	0.02632	0.51041	52		14	
60	0	0	0		0	19233.8	0.05061	0	0.02429	0.47994	53		16	
61	0	0	0		0	18223	0.0494	0	0.02307	0.46695	54		18	
62	12.1081	0	12.9178		1.69266	17132.8	0.04429	0	0.0211	0.47647	55		20	
63											56		24	


App O - Elastic
App O - EP
Approx ASME
Scaled AxiPRO
Ring Calc
Roarke
Scaled ASME AxiPRO

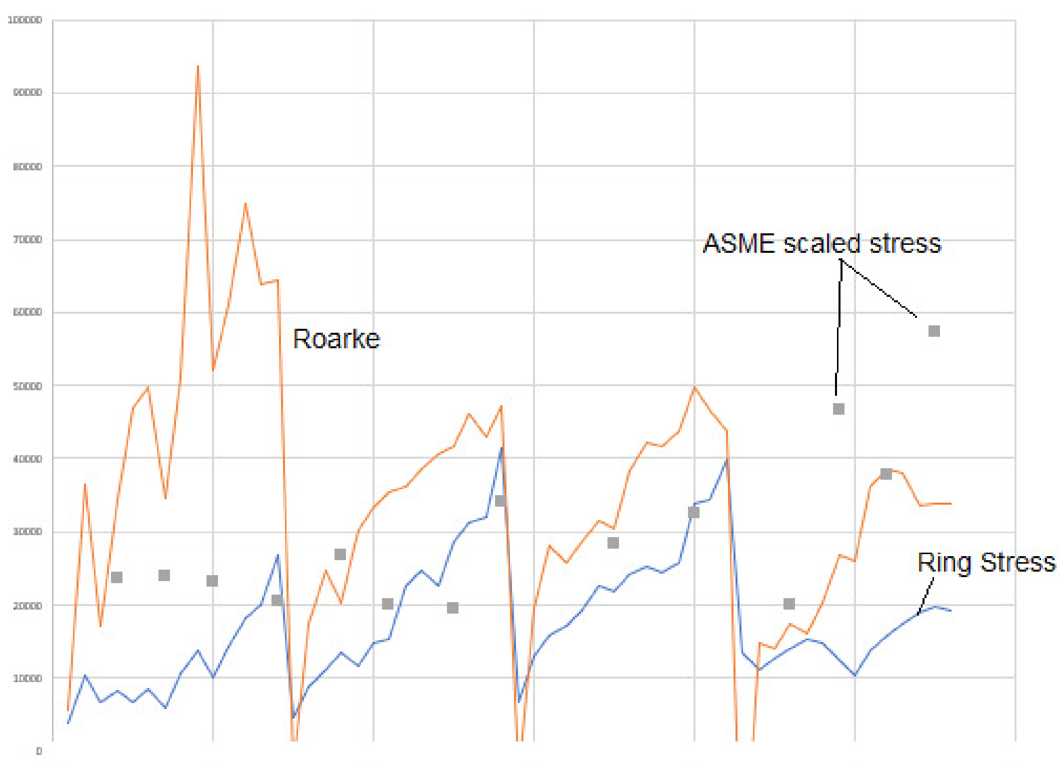

ASME scaled stress
Roarke
Ring Stress

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Table A-2 Rating Ceiling Pressure — p_c, psi

Temperature °F	Class 150	300	400	600	900	1500	2500
−20 to 100	290	750	1,000	1,500	2,250	3,750	6,250
200	260	750	1,000	1,500	2,250	3,750	6,250
300	230	730	970	1,455	2,185	3,640	6,070
400	200	705	940	1,410	2,115	3,530	5,880
500	170	665	885	1,330	1,995	3,325	5,540
600	140	605	805	1,210	1,815	3,025	5,040
650	125	590	785	1,175	1,765	2,940	4,905
700	110	570	755	1,135	1,705	2,840	4,730
750	95	530	710	1,065	1,595	2,660	4,430
800	80	510	675	1,015	1,525	2,540	4,230
850	65	485	650	975	1,460	2,435	4,060
900	50	450	600	900	1,350	2,245	3,745
950	35	385	515	775	1,160	1,930	3,220
1,000	20	365	485	725	1,090	1,820	3,030
1,050	[Note (1)]	360	480	720	1,080	1,800	3,000
1,100	[Note (1)]	325	430	645	965	1,610	2,685
1,150	[Note (1)]	275	365	550	825	1,370	2,285
1,200	[Note (1)]	205	275	410	620	1,030	1,715
1,250	[Note (1)]	180	245	365	545	910	1,515
1,300	[Note (1)]	140	185	275	410	685	1,145
1,350	[Note (1)]	105	140	205	310	515	860
1,400	[Note (1)]	75	100	150	225	380	630
1,450	[Note (1)]	60	80	115	175	290	485
1,500	[Note (1)]	40	55	85	125	205	345

NOTE:
(1) Ratings of flanges and flanged fittings terminate at 1,000°F (538°C).

For Reference Ceiling Pressures from B16.5.

III. BACKGROUND FLANGE RIGIDITY CRITERION

The background of the flange rigidity criterion stems from the analysis developed by Waters et al.[5] which included a calculation of the hub ring junction rotation of a hubbed integral flange. The equation developed for the angular rotation of an integral flange is:

$$\boxed{\theta = \frac{52.4\, V\, M_0}{L\, E\, g_0^2\, h_0} \text{ (degrees)}}$$

This equation has been successfully applied by many designers to limit flange rotation to 0.3° for integral flanges. This equation, in modified form has been added to the ASME BPVC Section VIII, Division 1 and 2 [1] [2], where the flange rotation was changed to a rigidity index (J). The ultimate goal of the ASME J-index is to control the angular rotation of flanges within acceptable limits in order to avoid flange leakage.

IV. FLANGE RIGIDITY ASPECTS AND ANALYSIS

Table 1: Overview of flange rigidity index factor "J" and stress reduction factor "k"

Provision	Equation
Integral type shell girth flange (all diameters) (Symbols conforming ASME Code)	$J = \frac{52.4\, V\, M_0}{L\, E\, g_0^2\, K_I\, h_0} \leq 1.0$
Inside diameter of flange ≤ 1000 mm Inside diameter of flange (mm): 1000 > B or D < 2000 Inside diameter of flange ≥ 2000 mm (Symbols conforming PD 5500 and / or EN 13445-3)	$k = 1.0$ $k = \frac{2}{3}\left(1 + \frac{B \text{ or } D}{2000}\right)$ $k = 1.333$

Table 2: Data of selected shell girth flanges

Flange Identification	**Flange # 1000**	**Flange # 1600**	**Flange # 2000**	**Flange # NPS 60**
Design pressure (bar)	20	27.5	10	21.5
Hydrostatic test pressure (bar)	As per code	As per code	As per code	As per code
Design temperature (°C)	250	250	250	250
Corrosion allowance (mm)	0	0	0	0
Thickness tolerance (mm) (%)	0	0	0	0
Geometric flange data				
Outside diameter of flange [A] (mm)	1160	1825	2175	1675
Inside diameter of flange [B] (mm)	980	1560	1980	1494
Bolt-circle diameter [C] (mm)	1100	1725	2110	1615
Thickness of hub at large end [g_1] (mm)	20	30	20	22
Thickness of hub at small end [g_0] (mm)	10	20	10	15
Hub length [h] (mm)	30	30	30	22.5
Flange thickness [t] (mm)	As per code	As per code	As per code	As per code
Flange material	**A 105**	**A 105**	**A 105**	**A 105**
Gasket data: (Semi-Confined)	**Solid flat metal**	**Solid flat metal**	**Solid flat metal**	**Spiral Wound**
Material:	Monel	Monel	Monel	Graphite filled
Outside diameter gasket (mm)	1050	1660	2050	1570 - 3 (bead) = 1567
Inside diameter gasket (mm)	1018	1628	2018	1519.2
Gasket thickness (mm)	1.6	1.6	1.6	4.5
Bolting data				
Size of stud bolts (inch)	1 1/8" - 8UN	1 1/2" - 8UN	1 1/4" - 8UN	1 1/8" - 8UN
Number of stud bolts (-)	48	60	68	64
Material of stud bolts	A 193 B7	A 193 B7	A 193 B7	A 193 B7

Appendix 10 Stress and Strength Basis (0.7E or 1.0E)

1.0 ASCE Seismic Load Factors (0.7E or 1.0E):

LRFD and strength based analysis introduced in the latter quarter of the 20th century aims to simplify and improve design optimization and understanding by incorporating probability based concepts into standard Code solution procedures calibrated against already accepted design solutions. Improved quality and inspection, strength-based solutions and better understanding of loads can reduce the separation between the estimated mean values for strength and capacity (resistance) while improving the probability that the structure will undergo a successful life. Strength based solutions involve determination of capacity beyond the onset of first member outer fiber yielding, including (usually behind the scenes) concepts involving the plastic section modulus, overstrength factors, push-over system analysis, awareness of ductility design criteria, the potential for an underestimation of displacements and support loads, and failure mechanisms (or limit states).

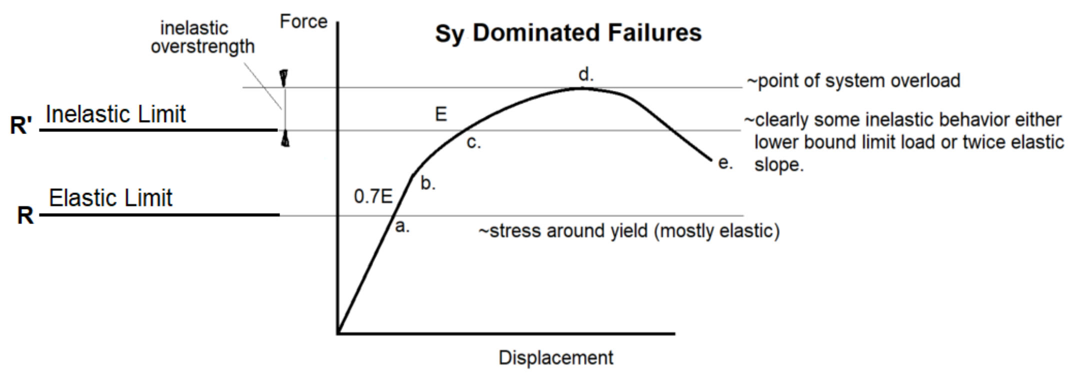
Limit states can define any failure criteria. For piping and pressure vessels, limit states generally include rupture, twice elastic slope, service criteria, ultimate strength criteria, ratcheting, creep, and creep-fatigue. Limit states can be established for each loading/failure condition, and a successful design involves a sufficient probability that each limit state load will be less than the limit state capacity.

Once an applicable limit state is established, a calibration is made to align the limit state solution with existing successful design procedures. This calibration has been performed for most loading types and structures, ie. bridges, ships, commercial structures, etc. The calibration is performed such that a probability of failure is established so that the member sizes are similar.

For a properly calibrated approach, the member sizes for design by strength and design by stress should be the same if the design by stress methods are considered acceptable, generally by long historic satisfactory application. When this is the case, the design by strength methods provide probabilities of failure that have been used historically with design by stress approaches.

Z = Elastic section modulus required for Design by stress (ASD)
Z' = Plastic section modulus required for Design by strength (ASD or LRFD)
β = Number of standard deviations between mean of load and mean of resistance.

F = Load required for design by stress (ASD)
F' = Load required for design by strength (LRFD)



From AISC 360 B2. 16.1-311:

This Specification is based on strength limit states that apply to structural steel design in general. The Specification permits design for strength using either load and resistance factor design (LRFD) or allowable strength design (ASD). It should be noted that the terms "strength" and "stress" reflect whether the appropriate section property has been applied in the calculation of the available strength. In most instances, the

When adopting strength evaluations the objective is to provide a more thorough evaluation of the loading and capacity relations so that an accurate probability of failure can be determined. The safety factor approach used for decades in piping and vessel evaluations is a single number that defines the separation of the estimated mean (or average) strength and the estimated mean (or average) load. Seismic loads can have considerable variation. Weight loads can be estimated more accurately than seismic loads, and likely a little more accurately than thermal loads. An accurate estimate of the safety of the load is represented by the difference between the means and the standard deviation of load.

2.0 Terminology Usage:

Structural ship or building evaluations are often associated with load and resistance factor design, and so that terminology will be used with piping in the discussions below.

The load and resistance factor design can be used with ASD (strength) and LRFD(strength). It could also be used with ASD (stress) methods, but the typical (and more advanced and practical use is with ASD or LRFD strength approaches. ASD strength has only one SAFETY factor to apply to all aspects of the design while LRFD strength approaches have multiple "SAFETY" or "load and resistance) factors (ϕ, γ_1, γ_2, …) that can be applied both to the variations of the material and geometry properties, but also to the loads. Weight loads are far more accurately known that seismic loads for example, and this is reflected in their separate load factors. The factors on loads to separate stress and strength methods of 0.7 or 1.0 are not related to the load and resistance factors ϕ, γ_1, γ_2, … although they can appear comingled in the same expressions and can be confused with the point-in-time factor of 0.75.

Potentially, ASD stress (0.7E) and ASD strength (1.0E) were confused because the plastic section modulus was not used in the B31 sustained and occasional stress equations. The factors that separate the elastic and plastic section modulus of pipe is implicitly included with the safety factors to derive the B31 allowable stresses where Z_p can be taken as 4/3 Z. (1.33 Z).

The general criteria equation requires the ability to predict resistances and loads in a given limit state, i.e. collapse, excessive displacements, cycle exhaustion, ratcheting to failure level strains, etc.

The resistance is normally termed R, and the load is normally termed L.

The criteria equation that describes the limit state is R = L.

For ASD design there are safety factors (SF), often between 1.67 and 3, but the safety factor can have any value the designer and owner deems appropriate. The safety factor is used in the load and resistance factor equation as follows:

$$R > SF \times L, \quad \text{<or>} \quad R/SF > L.$$

It is not uncommon that nominal stresses limited to the yield stress are used to define the limit state. This is termed the "working stress" approach. To apply the working stress limit state to a simple cantilever in bending:

$$M/Z < Sy.$$

The load in this case is the moment, and the resistance is Z Sy, so that L = M, and R = Z Sy.

For a strength approach. M / Zp < Sy; where Zp is the plastic moment of inertia, which for straight pipe is D^2 T. Using the plastic section modulus provides a more accurate evaluation of the limit state of the cantilever beam.

The load in this case is still M, but the resistance is Zp Sy, so L = M and R = Zp Sy.

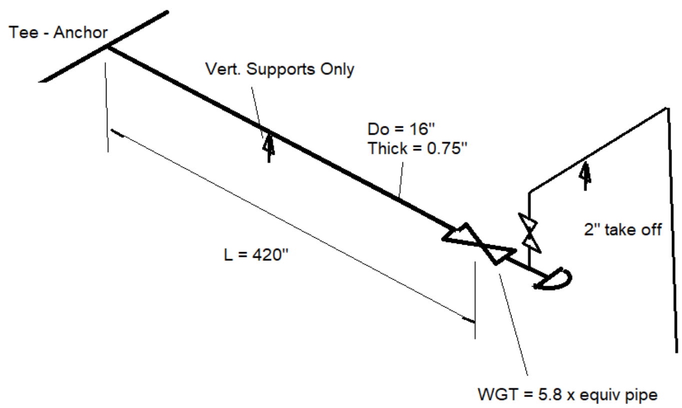
Both approaches are intended to predict the limit state of the cantilever. One uses a "working stress" approach, i.e. the nominal bending stress equals yield, and the other uses a strength approach, i.e. the moment equals the estimated plastic state of the geometry.

Since around 1989 the LRFD/ASD(strength) approaches have been used for designs and to specify loads in structures and in minimum load standards, i.e. NEHER, UBC, IBC2000 and ASCE 7.

Whether LRFD or ASD(strength), or ASD(stress) is used the intention is that the approach should be calibrated so that they each predict failure (or the reaching of the limit state) when R = L.

In the simple example below, we can use ASCE 7 to find the component lateral acceleration based on the geographic location and the site code. The acceleration times the weight, importance factors and adjustments for attachments to structures and ductility factors gives the load, and the load times the length to the point of support gives us the actual moment that the attachment point should see. We are interested in the moment applied at the Tee (anchor) on the left side of the figure. The lateral seismic load acts on the valve at the right side of the system in the horizontal direction. The seismic load on the valve is the g-load (g) times the weight of the valve multiplied by necessary factors. If the adjustment factors are equal to 1.0, the moment is:

$$M = L \times (g) \times \text{weight} = 420'' \times (g) \times WGT.$$



For the strength calculation (M”), the failure limit state will occur when $M'' = Zp\ Sy = D^2\ T\ Sy$.

For the “stress” calculation (M’), the failure limit state will occur when $M' = Z\ Sy = (\pi/4)\ D^2\ T\ Sy$.

Each moment (M and M’) should predict the same failure limit state to be used equally.

If $D^2\ T = 1$, the strength limit state would occur when $M'' = Sy$.
For the same $D^2\ T = 1$ the stress limit state would occur when $M' = \pi/4\ Sy$.

To predict the same limit state using ASD (stress) and ASD (strength) $M' = \pi/4\ M$. If the specified load M” is to be used with the strength calculation, then the load to be used with the “stress” calculation must be multiplied by a factor less than 1, i.e. 0.7 or $\pi/4=0.78$.

Use the example in the sketch above to demonstrate the Code calculation.

Valve weight = 5000#, Effective seismic g load = 0.6 g.
The static equivalent force on the valve is 0.6 * 5000 = 3000#; E = 3000#
Additional factors = 1.0.

The moment to be applied is 420” x 3000# = 1,260,000 in.lb.

The section modulus of the pipe (elastic as used in the Code) = $\pi/4\ d^2\ T = \pi/4\ (16-0.75)^2\ 0.75 = 136.9$ cu.in.

The sustained stress index can be estimated as 0.75 x SIF = 0.75 x $0.9(R/T)^{2/3}$. = 0.75 x 0.9 $(7.625/0.75)^{2/3}$ = 3.167

The sustained stress indices are established so that a stress of 2Sh produces a point whose actual displacements are twice the elastic displacements, i.e. at the twice elastic slope point, when Sh = 2/3Sy. Restating, the twice elastic slope (collapse) point occurs when SSI x M/Z = 2Sh, when Sh=2/3 Sy. The strength is 2 Sh = 2 x 2/3 Sy = 4/3 Sy. If Sy for the pipe in the example is 35,000 psi, then the TES "stress" can be found from 4/3 x 35,000 = 46667 psi. SSI x M/Z = 3.167 x (1,260,000 / 136.9) = 29,148 psi. The limit state ratio is 46667 / 29148 = 1.6.

The same stress would equal "yield" when SSI x M/Z = Sy. In this case the stress would be 29,148 psi, and the "stress" limit state would be 35,000 psi. The limit state ratio would be 35,000 / 29,148 = 1.20, so the limit state ratios are different!

If 0.7E is used for the "yield" stress limit state, then SSI x M/Z = 29,148 x 0.7 = 20,403. In this case, 35,000 / 20,403 = 1.7, and in this case 1.7 is close to 1.6.

One could argue that the B31 codes, at least for collapse loading definitions have always used strength based definitions. Prior to Rodabaugh's, "Background" paper (Ref 7) in 1980, it was not clear that the stress allowables were based on strength methods when primary/sustained loads were evaluated.

Mr. Rodabaugh's additional comments in the Functional Capability paper (Ref 12, Paper No. 11) are considered to support the concept that the difference between 0.7E and 1.0E for unpredictable seismic loads is not a large difference given the inertial overcapacity of most piping systems and unknowns associated with ductility factors, in-structure factors, etc. Whereas it is recommended that all B31 seismic users apply 1.0E for seismic loads and not 0.7E, when 0.7E is used, no further action is required as the existing overconservative safety factor is reduced but still believed to be within acceptable limits.

Since 2017 B31J established SSIs, the intent is to provide a uniform primary load safety factor of two against a twice elastic slope loading so that when design loads are removed, the system will move back to its original position (even though some small plastic straining may have occurred at concentrations, weld toes, etc.)

The intended SF is 2.0. The actual load is 5. i.e. L=5. It is recognized that for this load C = 10, C/L = 2. When a factor of the load is used, i.e. 0.7L, the safety factor doesn't change, and so the designer would establish the required C as 2 x 0.7L = 2 x (0.7)(5) = 7. The actual load hasn't changed, the designer is only using 70% of it. So the actual safety factor will be 7 / 5 = 1.4.

At worst the sustained safety factor would be 0.7 x 2 = 1.4 instead of 2 for the seismic loadings.

The B31J SSIs are based on one-half of the twice elastic slope load, where Sh = 2/3Sy, which is similar to the approach used in the Background paper.

The collapse calculation in VIII-2 prior to 2007 was identical to the current Section III Appendices II and is given as the twice elastic slope. This is the same definition used in B31J Appendix D. It is referenced in the 2006 version of VIII-2 in Fig. 6-153. In 4-136.5 it is stated: "The limits of general membrane stress intensity (4-131), local membrane stress intensity (4-132), and primary membrane plus primary bending stress intensity (4-133) need not be satisfied at a specific location if it can be shown that the specified loadings do not exceed 2/3 of the plastic analysis collapse load determined by 6-153. VIII-2 2006 defines 6-153 as the twice elastic slope load determined by experiment. Section VIII-Div 2 vessels prior to 2007 could have primary load analysis satisfied if it could be shown that they were 2/3 of the TES load. B31 Code rules use ½ of the TES load, (as is used in the "Background" paper, for all but straight pipe.) For straight pipe in Sect. III, it can be shown that the limit against a TES collapse load is about 2/3. This is because the lower bound of B_2 is 1.0, and the allowable is 1.5Sh instead of Sh as used in the B31 Codes.

Appendix 11 – Examples

Appendix 12 – ASME Section III NC/ND Seismic Load Recommendations

When applying NCD-3650 “Analysis of Piping Designs”, the criteria of this Standard can be applied to minimize snubber or other lateral seismic support requirements and reduce variance in results by use of gapped bumpers with ductile behavior. See C4.7 Fig. C4-1 Type 1 support behavior, and Appendix 5 Fig. 5.5.

When using this standard all requirements not including seismic or reverse dynamic loads in NCD-3650 must be satisfied.

NCD-3653 Equation 9a, can be satisfied or any appropriate para. 3.4.1 Category allowable stress can be satisfied using direction B_2 values identified in Table ??

When para. 3.4.1 Table 2 allowable values are used to evaluate the effects of pressure, weight, other sustained loads and occasional loads including reversing an nonreversing dynamic loads all requirements specified in para. 3.4.1 including ductility considerations, fatigue, ratcheting and result verification should be satisfied as determined by the designer.

NCD-3655 Level D Service Limits can also be qualified by any of the allowables in para. 3.4.1 Table 2. When Table 2 allowables are used all other considerations in para 3.4.1 including ductility, fatigue, ratcheting and other verification shall be considered and applied as determined by the designer or as specified by the owner.

NCD-3655 (b)(4) Seismic anchor moments can be evaluated per para. 3.4.4 Seismic Anchor Movements.

For any inertial loading, in-structure loading or seismic anchor movements, fatigue and ratcheting evaluations can be performed per guidelines in para. 3.4.2.

Directional B_2 values can be used per para. XXX. As described B_2 specification in Section III Appendices II are defined using the collapse criteria of B31J Appendix D and Ref(7). Use of B_2 values for branch connections are believed to produce a more uniformly safe system.

Analysis of Flanged Joints per NCD-3658 can be analyzed per this standard’s Appendix 9 for leak tightness. The user is also recommended to consult PCC-1.

Ductility factors as described in para. 3.4.1 Table 2 shall be used with Allowable stresses from that table.

Appendix 13 – Coupling Leakage

Appendix 14 – Leak Criteria

Mechanically attached fitting design in larger diameter pipe (>12”) should be reviewed carefully and the design verification validated to be sure that externally applied axial and bending loads can be carried successfully without leakage or component failure.

Issue: The problem occurs when the fitting is at the rated pressure and does not perform in a manner similar to straight pipe when subject to external loadings.

Straight pipe limit loads can be estimated in equations 13-1 and 13-2 below:

$(3/4)(p)^2 + m_b^2 + f^2 + m_t^2 = 1$

$p = PD/(2t\ Sy)$; $mb = M_b / (D^2\ t\ Sy)$; $f = Fax / (\pi\ D\ t\ Sy)$; $m_t = (2)(3^{0.5})\ M_t / (\pi\ D^2\ t\ Sy)$

Coupling design often involves separation of hoop and longitudinal capacity. In straight pipe, using Tresca, theoretically the longitudinal load at the pressure capacity can be doubled before failure or leakage occurs.

For straight pipe, the additional longitudinal capacity can be used to accommodate external loading due to any mechanism other than pressure, i.e. weight, seismic, dynamic loading or thermal expansion.

For couplings, Sifs (i-factors) and SSIs (I-factors) are 1.0 if the fitting can behave like pipe. In this case the system designer can use couplings and assume that they will support the same loading as straight pipe without leakage.

Issue: - Evidence of Leakage F1367-19 identifies leakage in the pneumatic test as the appearance of bubbles during a 4 min. test period at temperature. This leak rate is considered the initiation of the leak rate used in Appendix XX for flanges, and is considered the “visibly identified water based leak rate”. These are not tightness based leakage tests.

A13.1 Coupling External Load Capacity

Coupling manufacturers can provide any level of testing or analysis or can select from coupling and fitting standards. Assurance testing for piping and tubing mechanically attached fittings (MAFs) is provided in ASTM F1387-19. ASTM F1387 covers a)radially swaged, b)flared, c)flareless (bite type), d)grip type, e)shape memory alloy, and f)axially swaged. Tests in ASTM F1387 can be described below:

1)Sizes are only limited by what the manufacturer is willing to fabricate and test.
2)Mechanical tests include: 1)burst tests, 2)impulse tests, 3)fatigue tests, 4)tensile tests and 5)rotary flexure test.

When evaluating the test results, the major questions to be answered are the following:

1)Is the pressure capacity adequately defined. (From the rated pressure to the mean of the failure pressure is there at least a 2.4 times difference?

2)When just prior to the instability pressure is there still some additional axial load and bending capacity in the coupling as there is with straight pipe? (The problem occurs not a the instability pressure but at the rated pressure when the designer expects the coupling to be as strong as pipe and it is not.) It is possible to verify rated pressures and external load capacity separately, but not at the same time. This is when couplings may fail in firewater or other critical services during emergency events, i.e. fire, seismic, etc.)

3)Is there any torsional sensitivity? Is the torsional moment capacity under pressure the same as the externally applied bending moment capacity?

4)Are rated and minimum properties being used? The separation between minimum and rated properties can be quite large and distort the test performance.

Most bends and tees (unless the D/T ratio is very low) are not as strong as matching nominal straight pipe when external loads are applied, but the designer is cautioned by the Code defined SSI (I) value used for sustained and occasional loadings. Even still, when these "I" factors are used there is generally some displacement or load overstrength so that failure is not eminent. This may not be the case with couplings and so further reductions in bending or torsional load capacity is warranted. Where low confidence, high magnitude loads can act on a critical piping system, the I factors should be increased by 2.0. Where the overstrength has not been evaluated and there is an extensive service and engineering design levels are maintained, then the I factor increase can be 1.5.

Issue:
We have used these couplings 000's of times and never had a problem.

Have you used the couplings in the current diameter (more concern with larger diameters and diameters not previously used much)

Were the current couplings used in a retrofit to replace welded pipe systems that have corroded? If yes, was the new pipe analyzed for emergency loads (waterhammer, RV, seismic)? Coupling systems used in emergency service as the diameters increase generally do not have the rugged, ductile capacity of pipe and can suffer guillotine failures early on in an emergency event life.

Have the current sizes gone through the test procedures or have then been qualified by scaling?

Were the current sizes qualified only by calculation?

Couplings in B31.9 service (especially larger diameter service) can be subject to acts of vandalism, unlike welded steel pipe (in similar diameters). (This is not so much a diameter issue, but vandalism of larger diameter firewater lines for example can result in significant property loss.)

F1367-19 7.3.1 requires testing of the smallest and largest sizes within the size range being tested. Interpolation and scaling of sizes is permitted inside within the largest and smallest size tests.

The F1367-19 A6 fatigue tests seemingly requires an addition to the rated pressure stresses of 22 ksi amplitude nominal stress in the pipe or tube for 80,000 cycles for carbon steel without leakage or other failure. The positive and negative strains during the testing shall be equal to within positive or negative 2%, which is an equivalent elastic stress of $E\varepsilon$ = 30e6 psi x 0.02 = 600,000 psi., which suggests that we have some misunderstanding of the test, since this would be a large excursion for 80,000 cycles. It might be that the fatigue test provides the best indication of external load capacity under pressure.

Appendix 14 – Low Tightness Leak Detection

Low tightness leak detection is commonly used to establish a mean value for leakage that may be used in a system or test evaluation and may be used to establish a tightness limit state i.e. in B31H, or F1387. The basis for the test involves pressurization of the test article followed by increased loads until leakage as described herein occurs.

14.1 Contained Media

Leakage as described herein is based on either gas or liquid as the contained media.

When gas is used, it should be either nitrogen, air or any other similarly sized molecule. Unless otherwise specified by the user, helium should not be used for general purpose establishment of leak testing. Where circumstances warrant, the additional tightness required by helium leak testing may be used, and the requirements set forth herein may also be used.

Water is the preferred liquid for testing medium although oil, alcohol or antifreeze can be used if necessary.

Flange or coupling leak testing at rated pressures or greater and with applied external loads can be very dangerous and should conducted with caution. Gas testing can release considerable energy in a kinetic way and should be conducted from a remote, protected location as soon as the nominal diameter tested is larger than 0.5”. Energy calculations below give users an idea of the safety zones that should be applied when pressurized leak testing is conducted.

14.1.1 Alternate to Pressure

Where the concern for external load and pressure is significant, the test designer may substitute axial load for pressure such that the axial force used to simulate pressure is $\pi G^3 P/4$

14.2 Leak Criteria

The leak criteria threshold is three drops or bubbles per minute or an acoustic calibrated gas leak for pressurized gas leak testing. Bubble testing can be performed as identified below, or can be augmented with the acoustic leak detection defined in 14.3 below.

The target leak definition can be established by:

1)Observing drops of water at or above the target rate
2)Observing bubble appearance at or above the target rate.
3)Detecting an acoustic sound level in dB at or above the target level.

Target rates and the acoustic level are established in para. 14.3.

14.2.1 Diameter Affect

The energy in a leak test can be very roughly estimated from $P D^3$. A very crude safety distance for depressurization is given by equation 14.2.1:

$X = 15 C (C_o P D^3)^{0.333}$. Eq. 14.2.1

C=1.0 for X in ft. and C=0.305 for X in meters.
C_o = 2.7e-8 in U.S. Customary units, and 0.239 for SI units.

This distance is established as the length in ft. or m. away from the test article so that overpressure expansion or liquid release does not cause damage to observers or lab personnel.

Inspection for leakage must be conducted very carefully, inspection for leakage should always be conducted remotely using cameras or liquid sensors. In no case should anyone ever look directly into the flange gap, especially when external loads are applied to the joint and where gaskets are not restrained from blowout.

Washers, gasket parts, separated nuts, clamps and other tested mounted components can travel at high velocities away from components for distances equal to X_q given in equation 14.2.2 below:

$X_q = 200\ C\ (C_o\ P\ D^3)^{0.333}$ Eq. 14.2.2

In all cases the upper and lower portions of the assembly should constrained in case of separation.

For gas tests the test designer can add (2)(H)(P)(V)(C_o) to the energy calculation, where P is the test pressure (psi), and V is the volume in cubic. In. H is the constant 15 or 200 used in equations 14.2.1 or 14.2.2.

Gas leak testing should only be considered for small diameter relative low pressure components, or should be conducted in large bunker-type structures designed for the purpose.

At low tightness leak rates the diameter of the joint has a secondary effect on the threshold leakage:

1)Larger diameter joints are more prone to leakage due to improper tightening, fit up, gasket, or flange manufacturing tolerances. Consistency and tolerances are more difficult to maintain over larger size ranges.

2)Low level leakage flow paths may involve one or more limited flow zones. Uniform saturation will exist from the gasket ID to an irregular circumferential surface closer to the OD. Migration from the circumferential surface will often occur over angular zones that are randomly placed around the circumference approximately equal to the minimum of 30 deg. or the distance between three bolt holes as shown in the figure below. Multiple leak sites can occur at various zones around the flange.

3)Adjustment of the flowrate using the circumferential mean gasket diameter is performed for low tightness tests in a manner similar to the adjustment for high tightness tests even though the flow mechanism may be different.

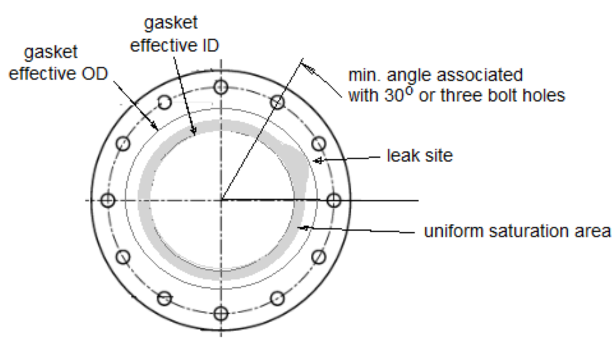


Fig. 14.2 Low Tightness Leakage Pattern

14.2.2 Inspection Procedure

This guideline provides no restriction to the pressure or external loads applied to the tested joint and as such the user and test designer must establish all safety limits involved in conducting the test. B31J Appendix D provides a set of test procedures and calculations that may be used to determine the energy in the test and the necessary precautions needed to avoid damage due to leakage or rupture.

Depending on the strength of the flange, attached pipe may bend around the flange. Composition or PTFE gaskets can be blown out from between the flange faces at dangerous velocities. Applied external loads can introduce considerable elastic energy into the tested specimen, which can be accidentally released when leakage, gasket failure or rupture occurs. Additionally, trapped air can be compressed when a system is pressurized that may also be released accidentally on accidental leakage, rupture or gasket failure. 22

Either of the following approaches can be used to inspect for flange or coupling leakage. Prior to starting the test make the more detailed set of calculations included in B31J Appendix D-8, or perform the calculations in accordance with 14.1.2 above and design the safety protocols that should be executed prior to and during the test.

It is possible that couplings will undergo uncontrolled failure under pressure and external load in close proximity to the onset of leakage. These failures may represent guillotine like failures and so the facility conducting the test must be prepared to withstand the kinetic energy associated with pipe whip and thrust loading due to at least some compressed air that may accidentally be included in the test article.

1)Water (liquid): The following steps can be used to detect low tightness leakage using liquid as the test medium.

a)install the gasket according to the manufacturer's instructions. If the gasket is subject to blowout, i.e. does not have a surrounding metal jacket that will not be subject to ejection at the pressure and loading specified, then a light metal circumferential shield should be installed around the outer edge of the flange.

b)before loading, use compressed air to make sure the test surface is dry.

c)install video or leak sensors.

d)install personnel protection.

e)apply target pressure (usually rated or design pressure).

f)apply bending moment until leakage or maximum pipe moment found from D^2 T Sy is reached.

g)remove pressure.

h)remove moment

i)disassemble shields, etc., and inspect joint for indications of moisture.

j)repeat steps c through h as requested by the designer or owner, preferably at least 10 times.

2)Gas: (nitrogen or air): The following steps can be used to detect low tightness leakage using gas as the test medium. We are assuming that the nominal diameter is less than 1 inch and that the pressure is less than 100 psi.

a)install the gasket according to the manufacturer's instructions. If the gasket is subject to blowout, i.e. does not have a surrounding metal jacket that will not be subject to ejection at the pressure and loading specified, then a light metal circumferential shield should be installed around the outer edge of the flange.

c)install video or leak sensors and liquid spray nozzles.

d)install personnel protection.

e)apply target pressure (usually rated or design pressure).

f)apply bending moment until leakage or maximum tube moment found from D^2 T Sy is reached.

g)leakage is detected when bubbling at the rate specified begins to appear from the joint.

h)calibrated audio probes can also be used to detect the onset of gas leakage when the critical low-tightness leakage moment is applied.

g)remove pressure.

h)remove moment

i)repeat steps c through h as many times as the specification requires (at least 5 times).

3)Acoustic: the acoustic leak detection must be calibrated per 14.3 but can be used to augment but not replace the procedure in 14.2.2(1), but can be used to replace the procedure is 14.2.2(2). The calibrated leak sound level must be a clear function of the moment. Tests with identical sizes and applied loads should be conducted to establish a consistent mean and standard deviation.

14.3 Calibration of Acoustic Leak Detection for Low Tightness

14.4 Coupling Tests per F1836-19

<Tony Please Complete>

Table D-8.1-1 Distance and Precaution for Pressurized Twice Elastic Slope Test

Distance Between Personnel and Pressurized Test Specimen and Conditions of the Test	Precautions Required
Distance more than $2X_1$ and solid walls or other shielding separate personnel from test specimen	No added precaution required
Not separated from test specimen by distance of more than $2X_1$	Hard hat, eye and ear protection required
Within a distance X_2 but outside of X_3 and changes to the test state as described in para. D-8.1 are occurring	Hard hat, eye and ear protection required; personnel must be behind metal shielding
Head and torso are within X_3 of test specimen and no changes to the stress state as described in para. D-8.1 are occurring	Hard hat, eye and ear protection required; personnel must be behind metal shielding; pressure and load must be decreased by at least 10%
$X_3 > 24$ in. (0.6 m); head and torso are within X_3 of the test specimen and changes described in para. D-8.1 are occurring	No provision is given; test should be discontinued and personnel removed from this exclusion zone until pressure is reduced

To apply Table D-8.1-1, the exposure distances X_1, X_2, and X_3 must be computed using Steps 1 through 5 below.

Step 1: Estimate the air trapped in the test specimen using Table D-8.1-2 unless some other method is available.

Step 2: Compute the kg-TNT equivalent of the compressed gas and elastic energy from eq. (D-14):

$$E = (C)[(P_T)(V)/(0.4) + \cancel{0.5}F_{\text{onset}}D_{\text{onset}} \times G + 0.75\sigma_h^2(1+\nu)(V_s)/E_s] \tag{D-14}$$

where

E_s = the modulus of elasticity, psi (MPa)
V_s = the volume of metal in the vessel or piping specimen, in.^{3} (m^3)
σ_h = the hoop stress in the vessel or test piping specimen due to pressure
ν = Poisson's ratio, psi (MPa)

~~When using metric units, F_{onset} should be in units of MN, and σ_h in MPa.~~

Step 3: Compute the distance from the specimen X_1, where protection must be provided for personnel or critical equipment due to flying debris upon specimen rupture, ft (m).

$$X_1 = (C_1)(200)(E^{0.333}) \tag{D-15}$$

Step 4: Compute the distance from the specimen X_2, where protection against eardrum rupture must be provided for personnel, ft (m).

$$X_2 = (C_1)(15)(E^{0.333}) \tag{D-16}$$

Table D-8.1-2 Inadvertent Air Volumes in Test Specimens

Test Specimen Nominal Diameter, in.	Entrapped Air, in.^{3}	Entrapped Air, L
≤10	122	2
10–24	244	4
24–48	976	16
48–120	3,904	64
>120	7,564	124

Step 5: Compute the distance from the specimen X_3, where protection against lung damage must be provided for personnel, ft (m).

$$X_3 = (C_1)(7)(E^{0.333}) \tag{D-17}$$

where

~~C = 2.7e-8 for X distance, ft; 0.239 for X distance, m~~
C_1 = 1.0 for X distance, ft; 0.305 for X distance, m
E = compressed gas energy using Brode equation (see Refs. [21] and [22])
P_T = gage test pressure (usually the design pressure), psig (MPa)
V = pressurized volume of test specimen, in.^{3} (m^3)
X_1, X_2, X_3 = exclusion distances, ft (m)

G = 0.5 in U.S. Customary Units; 1.e9 for SI Units.

C = 2.7e-8 in U.S. Customary Units; 0.239 for SI Units.

D-8.2 Air Loss Due to Solubility in Water

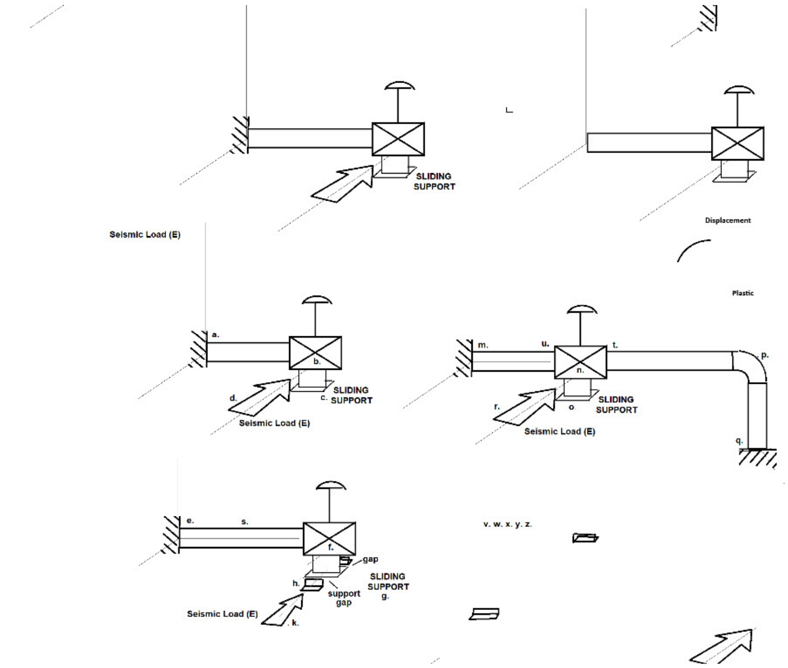
D-8.2.1 Introduction. If a pressurized test specimen is held at the test pressure for a period of time, usually measured in hours, some of the inadvertent air trapped in the system will be absorbed into the water and the compressed air energy will be reduced.

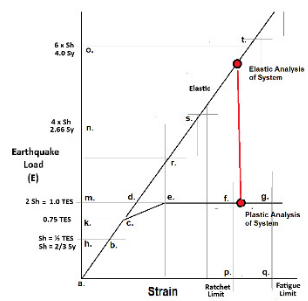
The time, in minutes, it takes for compressed air to be absorbed into the test water volume can be estimated using eq. (D-18). Times in excess of two days should not be used.

$$T = -Ln(h)/b \tag{D-18}$$

where

A = area of test volume exposed to the compressed air, in.^{2} (m^2)
(A/Vol) = $(25D)^{-1}$ if unknown, in.$^{-1}$ (m^{-1})
b = $(C_2)(A/Vol)(f)$
C_2 = 0.3937 for X_1, X_2, X_3 distances, ft; 0.01 for X_1, X_2, X_3 distances, m
D = vessel or pipe diameter, in. (m)
f = factor equal to 0.01 in./min (0.0003 m/min)
h = reduction factor = (100 − %air absorbed by mass)/100
$Ln()$ = natural log
T = time, min (not to exceed 2 days)





seismic loading components should be included in eq. (17). Pressure should not

$$= \sqrt{(|S_a| + S_b)^2 + (2S_t)^2} \quad (17)$$

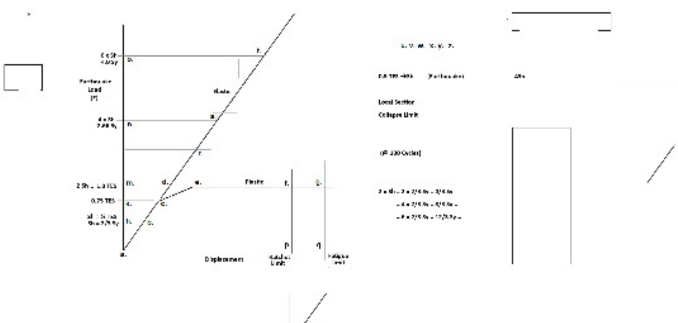
The ELF seismic case contribution should be included in Eq. 1d as follows:

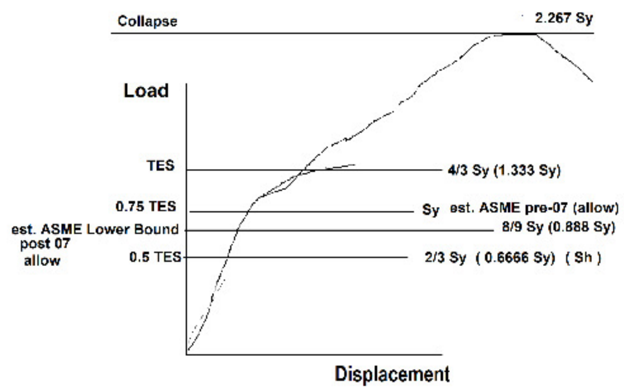
$N_{strong\ motion} = 10$ to 20

$$N = N_E + \left(N_{strong\ motion}\right)$$

$$\left(2 \times C_d \frac{S_{E}}{S_E} + S_{ratchet}\right)^3 + \sum \left(r_i^3 N_i\right) \text{ for } i = 1, 2, \ldots, n \quad (1d)$$

$C_d = a_p = 2.5$





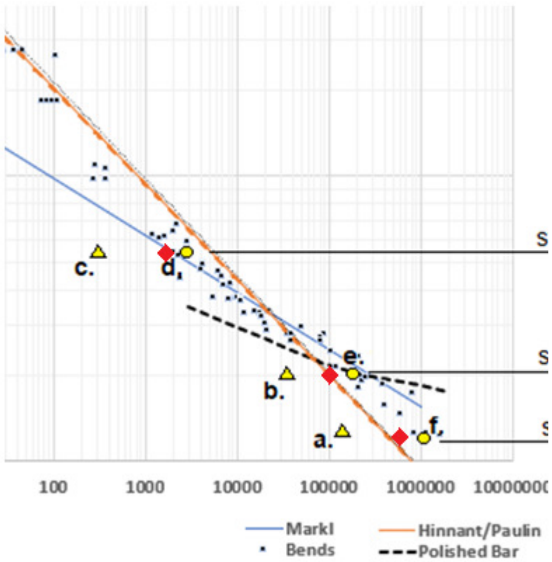
For Cantilever: M
<or> S
<or> B

For Bend: S
B

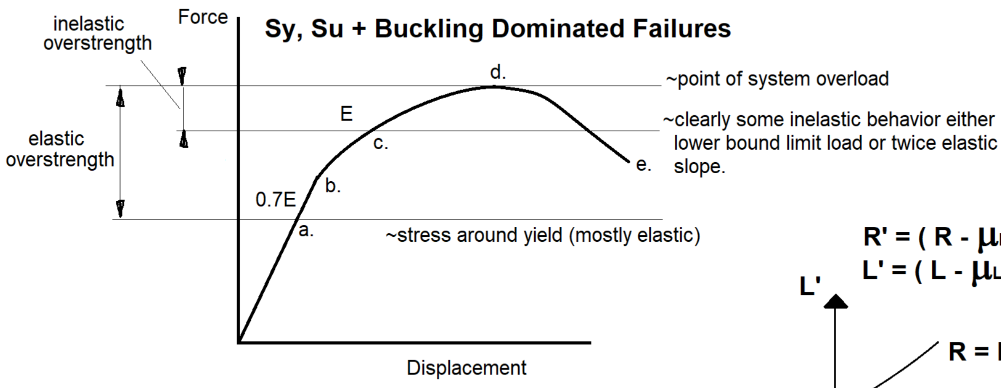
B_2 = 1.5 x SSI (f

B_2 M/Z = III Allow

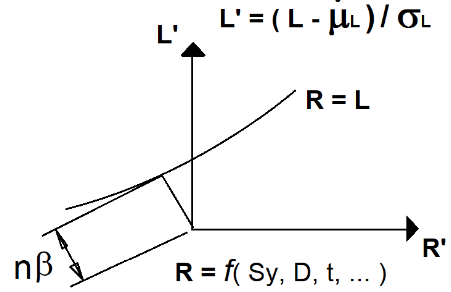
SSI = B_2 = 1 for



S
S
S
c.
d,
e.
b.
a.
f,
100
1000
10000
100000
1000000
MarkI
Hinnant/Paulin
Bends
Polished Bar

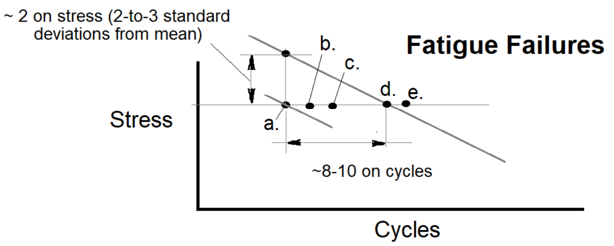


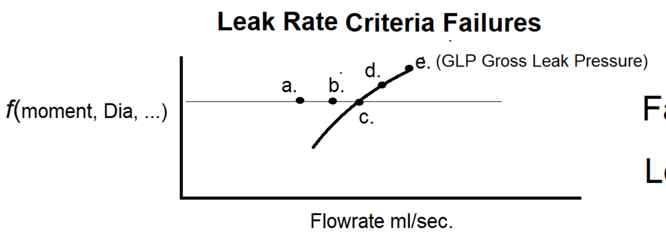
$R' = (R - \mu_R) / \sigma_R$
$L' = (L - \mu_L) / \sigma_L$



R = f(Sy, D, t, ...)
L = f'(P, W, E, Wind, ...)

μ_R mean resistance
σ_R resistance standard deviation
μ_L mean load
σ_L load standard deviation

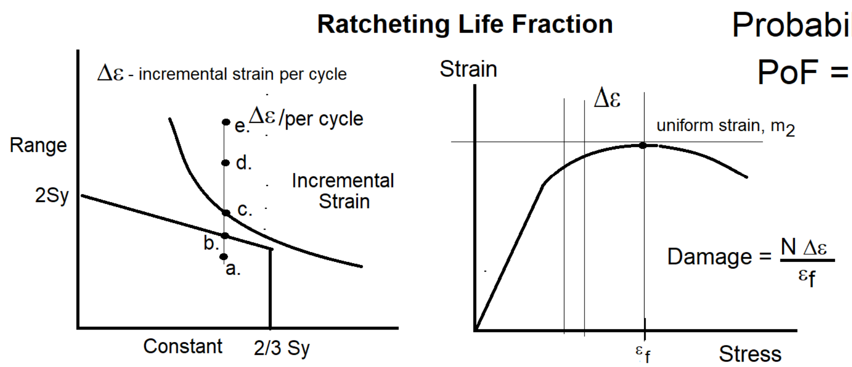




Fatigue: Damage: R=1; L=N/Nallow

Leak Rate: R = Pe leak limit
L = Peq;

Peq = f(P,M,Bolt Torque, ...)



Probability of Failure

PoF = 1 - ϕ($n\beta$)

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