STP-PT-034

ALIGNMENT OF SUSTAINED LOAD STRESS INDICES IN THE ASME B31 CODE

ASME STANDARDS TECHNOLOGY, LLC

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

Loads on piping systems and pipelines are categorized in ASME B31 as sustained, occasional or thermal loads. None of the ASME B31 codes explicitly define "sustained loads." But because they are often called out as "sustained loads such as pressure and weight," sustained loads are understood to mean pressure and weight. In the case of buried pipe, the soil weight on the pipe would also be a sustained load. Occasional loads are loads "such as wind or earthquake" to which we may add pressure transients (waterhammer). Finally, thermal expansion and contraction loads and loads due to thermal gradients constitute the third category of loads on piping systems. Unlike ASME VIII or ASME III, ASME B31 does not refer to "primary" or "secondary" loads or stresses.

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ABSTRACT

Loads on piping systems and pipelines are categorized in ASME B31 as sustained, occasional or thermal loads. None of the ASME B31 codes explicitly define "sustained loads." But because they are often called out as "sustained loads such as pressure and weight," sustained loads are understood to mean pressure and weight. In the case of buried pipe, the soil weight on the pipe would also be a sustained load. Occasional loads are loads "such as wind or earthquake" to which we may add pressure transients (waterhammer). Finally, thermal expansion and contraction loads and loads due to thermal gradients constitute the third category of loads on piping systems. Unlike ASME VIII or ASME III, ASME B31 does not refer to "primary" or "secondary" loads or stresses.

Each of these load categories (sustained, occasional, thermal) have their own design equations. In the current codes, there are three areas among the piping and pipeline codes design equations for stresses due to sustained loads which deserve attention, clarification and possibly improvement:

- Consistency of design equations
- Consistency in the use of stress indices and stress intensification factors
- Use of fatigue-based factors to calculate stresses due to sustained loads

The objective of this report is to address these areas and to propose design equations for sustained loads which would be technically sound, practical, and could be applied consistently by all ASME B31 Code books and the ASME Section III Code.

1 BACKGROUND

Loads on piping systems and pipelines are categorized in ASME B31 as sustained, occasional or thermal loads (the latter also referred to as displacement strains in ASME B31).

Interestingly, none of the ASME B31 codes explicitly define "sustained loads." But because they are often called out as "sustained loads such as pressure and weight," sustained loads are understood to mean pressure (internal or external) and weight. In the case of buried pipe, the soil weight on the pipe would also be a sustained load.

In contrast, occasional loads are loads "such as wind or earthquake" to which we may add pressure transients (waterhammer, explosions, etc.). Finally, thermal expansion and contraction loads and loads due to thermal gradients constitute the third category of loads on piping systems. Unlike ASME VIII or ASME III, ASME B31 does not refer to "primary" or "secondary" loads or stresses.

There are in the current codes three areas among the piping and pipeline codes design equations for stresses due to sustained loads which deserve attention, clarification and possibly improvement. These are:

a. Consistency of design equations.

   Since the stresses caused by pressure and weight in pipes and pipelines are the same irrespective of application (power, process, pipelines), the ASME III and ASME B31 codes should have the same design equations for sustained loads. This is not the case today.

b. Consistency in the use of stress indices and stress intensification factors.

   While ASME III uses stress indices (Sis such as B, C and K indices), ASME B31.1 and B31.3 use stress intensification factors (i_i and i_o or i). As stated in the request for proposal for this project "since they are defined by principles of engineering mechanics, there should be no differences in stress indices from book to book." In fact, the SIFs and Sis relate to two different failure modes, and are different.

c. Use of fatigue-based factors for sustained loads.

   It is questionable whether stress intensification factors "i" developed based on cyclic fatigue tests are appropriate for the analysis of sustained loads. As stated in Rodabaugh and Moore (1984) "*There does not appear to be a good reason, however, to use the stress intensification i-factors to evaluate primary loadings*." 0.75i is only an approximation of a sustained stress index.

2 OBJECTIVES

The first objective of this report is to address the discrepancies listed in Section 1:

- Consistency of design equations
- Consistent use of stress indices and stress intensification factors
- Use of fatigue-based factors to calculate stresses due to sustained loads.

The second objective of this report is to propose design equations for sustained loads which would be technically sound, practical (simple) and could be applied consistently by all ASME B31 Code books and the ASME Section III Code.

3 APPROACH

The report takes the following approach.

1. Conduct a literature search on the topic including compiling the existing sustained load stress indices of B31.1, B31.3, B31.4 and B31.8, and Section III, Subsection NC/ND.
2. Gather relevant historical data and references.
3. Obtain and reduce recently published test data for sustained stress multipliers.
4. Recommend applicable equations for sustained stress indices and notes for use in B31 books and Section III, Subsection NC/ND.

4 EXISTING SUSTAINED STRESS EQUATIONS AND INDICES

4.1 Existing Sustained Stress Equations

Existing equations for stresses due to sustained loads are reproduced in Appendices:

- Appendix A ASME B31.1 Power Piping
- Appendix B ASME B31.3 Process Piping
- Appendix C ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids
- Appendix D ASME B31.8 Gas Transmission and Distribution Piping Systems
- Appendix E ASME III Division 1 Rules for Construction of Nuclear Facility Components, Subsection NC Class 2 Components.

4.2 Summary of Stress Equations for Sustained Loads

4.2.1 ASME B31.1

4.2.1.1 Pressure Design B31.1

The 1955 edition of ASME B31.1 design for sustained loads included the pressure design equation in the same form as today's:

$$t = \frac{P \times D}{2 \times (S + P \times y)}$$

The 2005 addendum of ASME B31.1 reduced the design margin against ultimate strength (increased the allowable stress S) from 4 to 3.5.

4.2.1.2 Longitudinal Stresses B31.1

The 1955 edition did not include sustained load design equations, but, instead, required piping and equipment to "be supported in a thoroughly substantial and workmanlike manner…."

This is consistent with the practice of the 1950s, as described in the M.W. Kellog Co. manual "Design of Piping Systems," which stated:

> *Other loading which may act on piping systems includes: the weight loads of the piping, including structural members, the weight of the insulation and contents; snow and ice loading; wind loading if exposed; loading due to acceleration imparted by earth tremors; special shock loading, such as gun fire or moving vehicles; an unbalanced static pressure or flow effects.*
>
> *It is possible to include any or all of these loads in a complete solution, following the methods of Chapter 5 [Flexibility Analysis by the General Analytical Method]. Ordinarily, these effects are not sufficiently critical to warrant the extra engineering cost of this more precise approach. Instead they are indirectly controlled in a standardized way (e.g. support standards) or individually estimated and controlled so that the sum of all effects will approximately meet the same combined stress criterion.*

The 1967 edition of B31.1 included the requirement that *"The sum of longitudinal stresses due to pressure, weight and other sustained loads shall not exceed the allowable stress in the hot condition S_h. Where the sum of these stresses is less than S_h the difference between S_h and this sum may be added to the term $0.25S_h$ in Formula (1) [$S_A = f\,(1.25\ S_c + 0.25\ S_h)$] for determining the allowable stress range S_A. The longitudinal pressure stress S_{lp} shall be determined by dividing the end force due to internal pressure…by the cross-sectional area of the pipe $S_{lp} = P \times d^2 / (D_o^2 - d^2)$."* There is no formula for the other longitudinal stresses. There was no equation to calculate the longitudinal stresses.

The 1977 edition of B31.1 contains the stress equation in its current form,

$$PD/(4\ t_n) + 0.75i\ M_A/Z \le 1.0\ S_h$$

The single stress intensification factor i, maximum of in-plane i_i and out-of-plane i_o was used, and continues to be used in B31.1, for simplicity.

The equations for B31.9 are the same as ASME B31.1.

4.2.2 ASME B31.3

4.2.2.1 Presure Design B31.3

The pressure design equation in B31.3 is identical to B31.1, but with a different design margin against ultimate strength (3 in place of 4) and therefore a different allowable stress.

4.2.2.2 Longitudinal Stresses B31.3

ASME B31.3 refers to longitudinal stress but does not provide an equation. B31 Case 178 "Providing an Equation for Longitudinal Stress for Sustained Loads in ASME B31.3 Construction," approved May 6, 2005, provides the following stress equation for sustained loads.

$$S_L = \sqrt{(|S_a| + S_b)^2 + (2 \times S_t)^2}$$

$$S_b = \frac{\sqrt{(I_i M_i)^2 + (I_o M_o)^2}}{Z}$$

$$S_t = \frac{M_t}{2 \times Z}$$

Z shall be based on the nominal wall thickness less mechanical and corrosion allowances. Case 178 states "in the absence of more applicable data, S_a and S_t need not be intensified,"

4.2.3 ASME B31.4

4.2.3.1 Pressure Design B31.4

The pressure design equation of B31.4 differs from B31.1 and B31.3, and is based on an allowable stress of 0.72 SMYS (specified minimum yield stress). The origin of the 0.72 factor may stem from the fact that line pipe was mill tested at 90% SMYS, and this value was then reduced for 12.5% mill tolerance and 10% for waterhammer allowance (as was and still is the practice in AWWA), resulting in an allowable stress of 90% SMYS × 0.875 / 1.1 = 72% SMYS.

4.2.3.2 Longitudinal Stresses B31.4

The liquid pipeline code B31.4 does not provide an explicit equation for longitudinal stresses due to sustained loads in above-ground pipelines and piping systems, but it requires the sum of longitudinal stresses due to sustained loads not to exceed 75% of 0.72 SMYS.

Another sustained load for buried pipelines is the soil load, which is not addressed in this report.

4.2.4 ASME B31.8

4.2.4.1 Pressure Design B31.8

The pressure design equation is similar to B31.4 but the 0.72 factor is replaced by a location-dependent class, where the location class depends on factors such as the population density in the vicinity of the pipeline route.

4.2.4.2 Longitudinal Stresses B31.8

For longitudinal stresses, B31.8 sums algebraically the pressure-induced longitudinal stress, plus the thermal expansion-induced longitudinal stress, plus the axial force-induced longitudinal stress, plus the moment-induced longitudinal stress. The latter is calculated as described for B31.3, with in-plane ii and out-of plane io stress intensification factors applied to their respective moments and no stress intensification factor applied to torsion.

The design stress equations for unrestrained pipe (i.e. above ground pipe) in ASME B31.8 are

$$S_L = S_P + S_X + S_B \leq 0.75 \times SMYS \times T$$

The longitudinal stress due to internal pressure S_P is

$$S_P = 0.5 \times S_H = 0.5 \times \frac{P \times D}{2 \times t}$$

ASME B31.8 is the only code which explicitly calls out the stress due to axial loading S_X other than thermal expansion and pressure is

$$S_X = \frac{R}{A}$$

The nominal bending stress in straight pipe or long-radius bends due to weight or other external loads is

$$S_B = \frac{M}{Z}$$

The nominal bending stress in fittings and components due to weight and other external loads is

$$S_B = \frac{M_R}{Z}$$

Where,

$$M_R = \sqrt{(0.75 \times i_i \times M_i)^2 + (0.75 \times i_o \times M_o)^2 + M_i^2}$$

4.2.5 ASME B31.7

Between 1969 and 1971, nuclear power plant piping systems were designed to ASME B31.7, the precursor to the piping rules of ASME III piping design sections (ASME III NB/NC/ND-3600). ASME B31.7 adopted the equations of B31.1 for Class 2 and 3 piping.

4.2.6 ASME III Division 1 for Class 2 and 3 Piping

4.2.6.1 Pressure Design ASME III NC/ND-3600

The pressure design equation of ASME III NC/ND-3600 (Class 2 and 3 piping systems) is the same as B31.1, and has remained unchanged. The 1999 addendum of ASME III reduced the design margin against ultimate strength (increased the allowable stress S) from 4 to 3.5.

4.2.6.2 Sustained Longitudinal Stresses ASME III NC/ND-3600

The Winter 1972 Addenda of ASME III introduced the sustained load stress equation

$$\frac{P \times D}{4 \times t} + 0.75i \times \frac{M_A}{Z} \leq \alpha \times S_h$$

Changes to this equation were introduced starting in 1978 and completed in the 1981 winter addenda. The winter 1981 addenda introduced the B_1 and B_2 stress indices in Class 2 and 3 design equations for sustained loads, labeled Design Condition.

$$B_1 \times \frac{P \times D}{2 \times t} + B_2 \times \frac{M_A}{Z} \leq \beta \times S_h$$

The 1977 allowable stress αS_h and βS_h are given in Table 1. The deadweight load is considered a Design Load and the allowable stress is $1.5 \times S_h$. As explained by Rodabaugh and Moore (1982), $\beta \times S_h$ limits for occasional loads with β equal to or greater than 1.8 were too large to prevent collapse, and additional yield-based stress limits were introduced in ASME III Winter 1981, stating that $\beta \times S_h$ shall not exceed $1.5S_y$ (level B), $1.8S_y$ (level C) and $2S_y$ (level D).

Table 1 - Allowable Stress Factors ASME III 1977 αS_h and βS_h

Service Level	α	β
Design and Level A	1.5	1.0
Level B	1.5	1.2
Level C	2.25	1.8
Level D	3.0	2.4

The 2004 and subsequent editions of ASME III permits larger allowable stresses for "reversed dynamic loads" (seismic) provided the allowable stress for weight loads is reduced from $1.5 \times S_h$ to $0.5 \times S_h$.

4.3 Comparison

The different equations and different allowables between codes result in differences in design margins, as illustrated in Figure 1.

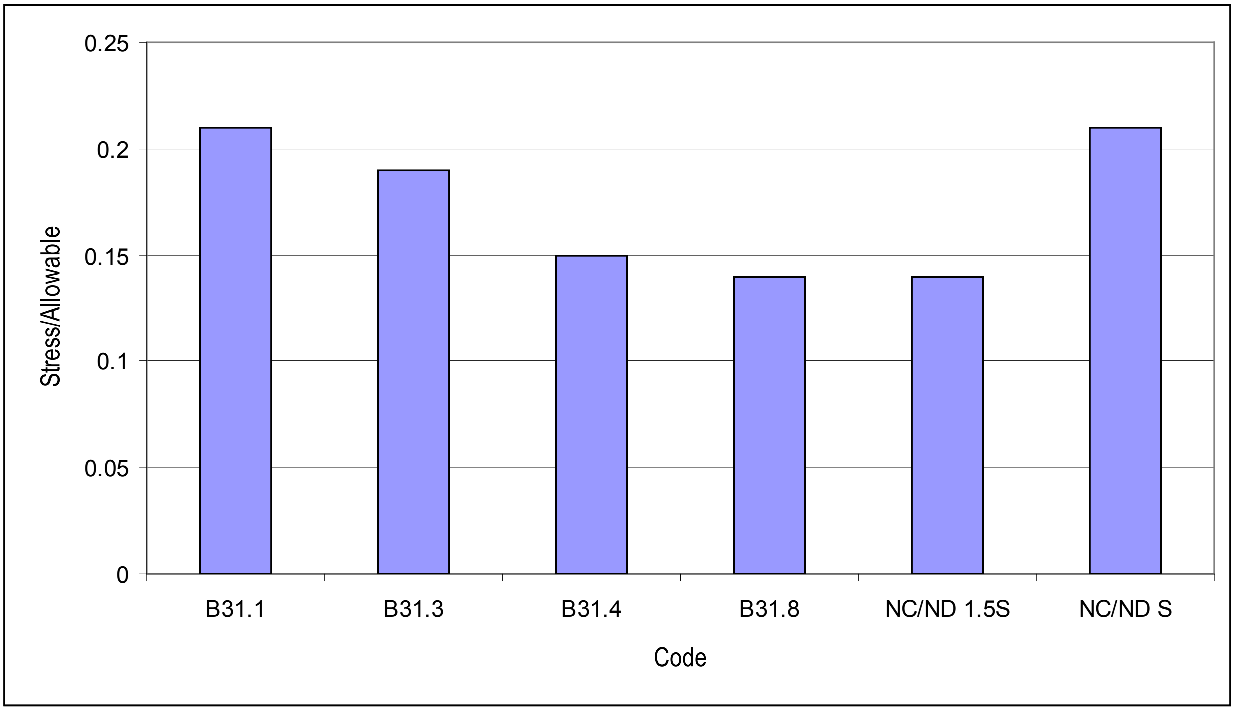

Figure 1 - Example Comparison of Margins Sustained Stress / Allowable

The example in Figure 1 corresponds to a long radius elbow in a horizontal water-filled 3 in. sch. 40 ASTM A 106 Grade B carbon steel pipe (3.5 in. OD × 0.216 in. wall). The loads from deadweight are M_o (out-of-plane moment in the horizontal elbow) of 2900 in-lb, with the other loads and moments, including the axial force, being zero. The system design pressure is 500 psi and its design temperature is 100^{o}F. The design stress ratios are

For B31.1 (and B31.9),

$$\left(\frac{P \times D}{4 \times t} + 0.75i \times \frac{\sqrt{M_i^{\ 2} + M_o^{\ 2} + M_t^{\ 2}}}{Z}\right) / (S_h = 17{,}500)$$

For B31.3 (in this case, with no axial force),

$$\left(\frac{P \times D}{4 \times t} + \frac{\sqrt{(I_i M_i)^2 + (I_o M_o)^2 + M_t^{\ 2}}}{Z}\right) / (S_h = 20{,}000)$$

For B31.4,

$$\left(\frac{P \times D}{4 \times t} + \frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2 + M_t^{\ 2}}}{Z}\right) / (0.72 \times SMYS = 0.72 \times 35{,}000)$$

For B31.8,

$$\left(\frac{P \times D}{4 \times t} + \frac{R}{A} + \frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2 + M_t^2}}{Z}\right) / (0.75 \times SMYS = 0.75 \times 35{,}000)$$

For ASME III NC/ND,

$$\left(B_1 \times \frac{P \times D}{2 \times t} + B_2 \times \frac{\sqrt{M_i^2 + M_o^2 + M_t^2}}{Z}\right) / (1.5 \times 20{,}000)$$

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6 SUSTAINED STRESS INDICES DATA

6.1 The Meaning of the Stress Intensification Factor i

The stress intensification factor (SIF) "i" used in ASME B31 has two sources: experimental fatigue tests and theoretical peak stresses. There is no experimental data on "sustained stress multipliers," instead, stress indices (applicable to sustained stresses rather than SIF) are based on theoretical or numerical solutions as described in Section 6.2.

6.1.1 Experimental Fatigue Tests

The experimental SIF originated from Markl's fatigue tests which had a practical intent: to simplify the design for flexibility of large diameter, hot lines. Markl introduced the concept of stress intensification factor for flexibility analysis in order to *"reduce the complex problem of providing adequate flexibility in a piping system"* (Markl, 1955). He defined the SIF as "*the ratio of the bending moment producing fatigue failure in a given number of cycles in a straight pipe of nominal dimensions, to that producing failure in the same number of cycles in the part under consideration*."

Almost the same definition can be found today in ASME III NC/ND-3600 (Appendix E to this report) which defines the SIF as the *"ratio of the bending moment producing fatigue failure in a given number of cycles in a straight pipe with a girth butt weld to that producing failure in the same number of cycles in the fitting or joint under consideration."*

6.1.2 Theoretical Peak Stress

The SIFs also have a theoretical basis related to static loading. In the case of a fitting subject to a static bending moment, the SIFs denote the stress ratio of the actual peak stresses in the fitting to those developed in a straight butt-welded pipe. Table 2 lists the theoretical SIFs (peak stress divided by M/Z) for an elbow subject to in-plane and out-of-plane bending. It is the theoretical static moment SIFs, in the form $i = \text{constant}/h^{2/3}$ developed by Hovgaard, Wahl and others in the 1920s and 1930s, which guided Markl in selecting the parameter i_i and i_o to trend the experimental fatigue results. Rodabaugh and George established similar theoretical SIFs $c_i = 1.89 / h^{2/3}$ and $c_o = 1.62 / h^{2/3}$.

Table 2 - Theoretical and Experimental SIFs for an Unpressurized Pipe Bend

Bending Plane	Theoretical SIF for Static Load on an Elbow		Experimental SIF from Cyclic Tests of an Elbow
	Longitudinal Stress	Circumferential Stress	
In-Plane Bending	$m_i = 0.84 / h^{2/3}$	$c_i = 1.80 / h^{2/3}$	$i_i = 0.9 / h^{2/3}$
Out-of-Plane Bending	$m_o = 1.08 / h^{2/3}$	$c_o = 1.50 / h^{2/3}$	$i_o = 0.75 / h^{2/3}$

6.1.3 Experimental and Theoretical SIF

For practical reasons, since in many cases butt weld locations are unknown at the design stage, rather than comparing the fitting to a straight pipe, Markl compared the fitting to a butt weld, and therefore,

$$i = \text{Peak Stress in Component} / \text{Peak Stress in Butt Weld}$$

$$i = \text{Peak Stress in Component} / 2 \times \text{Nominal Stress in Straight Pipe}$$

$$i = \text{Peak Stress in Component} / 2 \times (M/Z)$$

The factor 2 in "2 x Nominal Stress in Straight Pipe" comes from Markl observing that using a fatigue strength reduction factor of 2 for a weld achieved agreement with the base case of no weld.

The SIF is equivalent to the fatigue strength reduction factor which is conservatively approximated by peak stress in Div 2 and Section III.

$$i = (P_L + P_b + Q + F) / (M/Z)$$

The theoretical SIFs for bends were developed on the basis of assumptions which explain some of the discrepancies with the experimental results: constant curvature, constant cross-sectional properties, isotropic and homogeneous material, ideal, notch-free material, elastic material. plane sections remain plane (theory of elasticity), neutral axis retains its original length (pure bending, away from ends), longitudinal and circumferential stresses are principal stresses (pure bending, away from ends), bending moment constant over the length of the bend, radial and longitudinal strains are uniform through the wall thickness (approximation, better for large radius bends such as 5D bends), circumferential strains produce pure bending, are zero at the mid-wall (approximation, better for large radius bends such as 5D bends), bend radius much larger than the pipe radius (R/r > 10), wall thickness much smaller than pipe radius (thin wall, D/t > 20).

The experimental cyclic-fatigue-based SIFs i_i and i_o are half the theoretical static peak-stress-based c_i and c_o. Therefore, the peak stress due to a static in-plane or out-of-plane bending moment applied to a bend is

$$\sigma_{\text{peak circumferential},i} = c_i \times (M/Z)_i \approx 2 \times i_i \times (M/Z)_i$$

$$\sigma_{\text{peak circumferential},o} = c_o \times (M/Z)_o \approx 2 \times i_o \times (M/Z)_o$$

While, for longitudinal stresses the theoretical peak-stress-based m_i amd m_o factors are equal to i_i and $1.4i_o$ respectively

$$\sigma_{\text{peak longitudinal},i} = m_i \times (M/Z)_i \approx i_i \times (M/Z)_i$$

$$\sigma_{\text{peak longitudinal},o} = m_o \times (M/Z)_o \approx 1.4 \times i_o \times (M/Z)_o$$

In summary, the Stress Intensification Factors (SIF) are fatigue-based factors used to determine fatigue life of the component, but they are also based on the theoretical peak stresses in the component. As stated in Rodabaugh and Moore (1984), "*There does not appear to be a good reason, however, to use the stress intensification i-factors to evaluate primary loadings.*"

6.2 The Meaning of the ASME III Stress Index B

Stress indices were first introduced for nuclear pressure vessels in the first edition of ASME III, in 1963. They were defined as the ratio of the pressure-induced stress components σ_t (hoop), σ_n (axial) and σ_r (radial) in a nozzle to the membrane stress in the cylindrical shell PD/2t.

In 1969, stress indices B, C and K for piping components were introduced in B31.7 for Class 1 nuclear piping design, and then transferred in 1971 to ASME III NB-3600. In B31.7 1969, the B index was described as "*based on limit load analysis*" and was a simplified means of preventing gross plastic deformation of the pipe cross-section under applied loads, weight, earthquake, etc.). The B31.7 1969 allowable stress for the stress equations with B indices was 1.5S.

The C and K indices were based on the vessel design-by-analysis rules of ASME III: the C index was to parallel the Section III primary + secondary stress, and the K index was to parallel the ASME III peak stress. Therefore, the product C × K would then lead to a primary + secondary + peak stress which is used in fatigue analysis of pressure vessels, and which is therefore related to Markl's fatigue-based SIF, as will be discussed later.

ASME III NB-3682 states, "*The general definition of a stress index for mechanical loads is:*

$$B, C, K \text{ or } i = \sigma / S$$

where

S = nominal stress, psi (MPa), due to load L

σ = elastic stress, psi (MPa), due to load L

For B indices, σ represents the stress magnitude corresponding to a limit load. For C or K indices, σ represents the maximum stress intensity due to load L. For i factors, σ represents the principal stress at a particular point, surface and direction due to load L. The nominal stress S is defined in detail in the tables of stress indices."

ASME III NC/ND-3600 relates the SIF to stress indices C and K in the following manner. *"Analytical determination of stress intensification factors may be based on the empirical relationship*

$$i = C2 \times K2 / 2, \text{ but not less than } 1.0$$

where C2 and K2 are stress indices for Class 1 piping products or joints."

The B_1 and B_2 stress indices reflect the ability of pipe components and fittings to carry an applied load without gross plastic deformation. The B_2 index is the ratio of the limit moments for a straight pipe over the limit moment for the component, and are obtained by theoretical or numerical (FEA) solutions.

$$B_2 = \frac{M_{LM-straight}}{M_{LM-component}}$$

The B_2 index is larger than the SIF, as illustrated in Figure 2 and Figure 3.

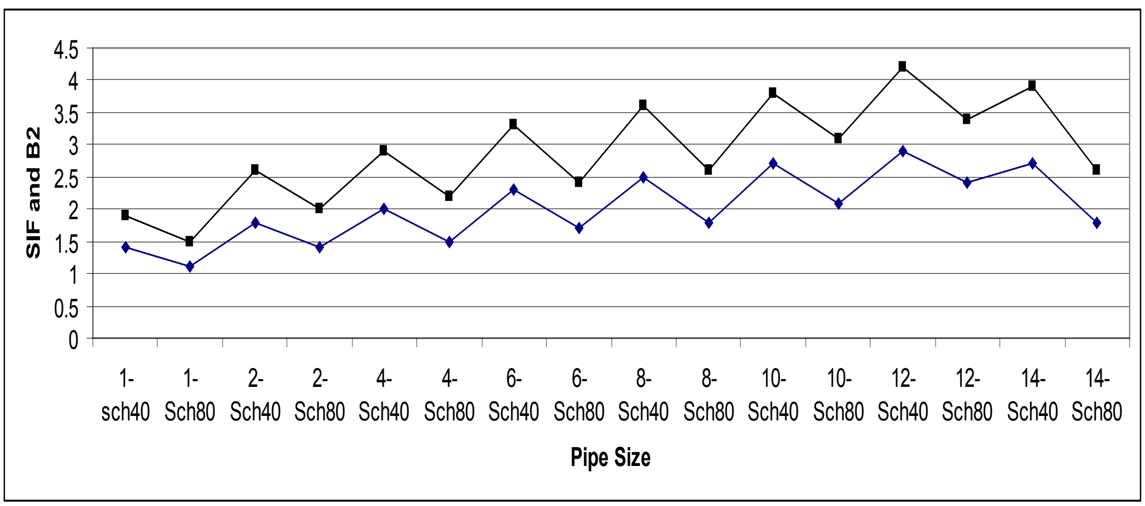


Figure 2 - SIF i (Lower Curve) and Stress Index B_2 for 1.5D B16.9 Elbow

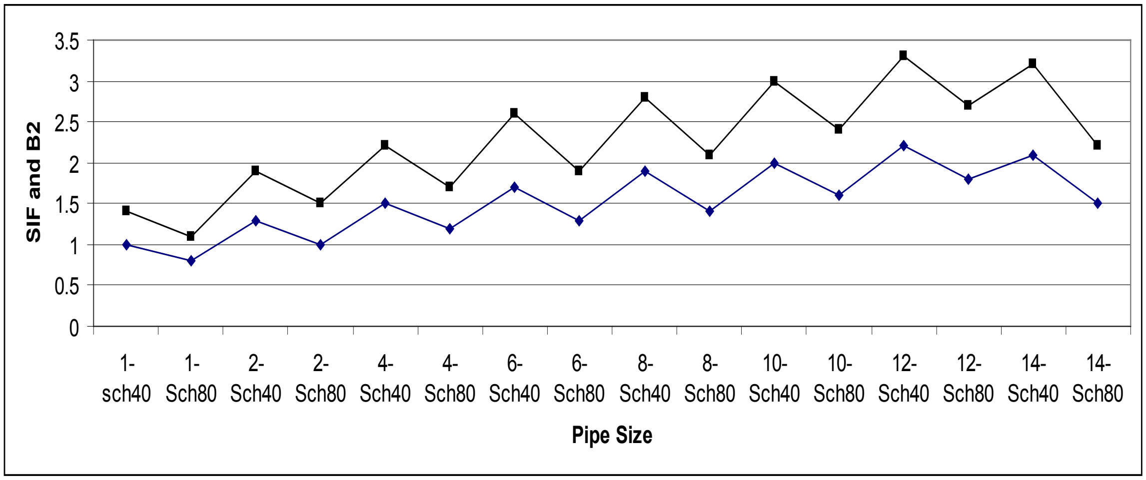


Figure 3 - SIF i (Lower Curve) and Stress Index B_2 for Equal Leg Tee

7 OPTIONS AND RECOMMENDATIONS

7.1 Option 1 Continue as is

7.1.1 Description

B31.1 remains

$$\frac{P \times D}{4 \times t} + 0.75i \times \frac{M}{Z} \le S_h$$

B31.3 remains (case 178)

$$S_L = \sqrt{(|S_a| + S_b)^2 + (2 \times S_t)^2}$$

$$S_a = \frac{F_a}{A_p}$$

$$S_b = \frac{\sqrt{(I_i M_i)^2 + (I_o M_o)^2}}{Z}$$

$$S_t = \frac{M_t}{2 \times Z}$$

Case 178 states "in the absence of more applicable data, S_a and S_t need not be intensified."

B31.4 remains

Longitudinal stress ≤ 0.72 SMYS

B31.8 remains

$$S_L = S_P + S_X + S_B \le 0.75 \times S \times T$$

$$S_P = 0.5 \times S_H = 0.5 \times \frac{P \times D}{2 \times t}$$

$$S_X = \frac{R}{A}$$

$$S_B = \frac{M}{Z}$$

$$S_B = \frac{M_R}{Z}$$

$$M_R = \sqrt{(0.75 \times i_i \times M_i)^2 + (0.75 \times i_o \times M_o)^2 + M_i^2}$$

ASME III NC/ND-3600 remains

$$B_1 \times \frac{P \times D}{2 \times t} + B_2 \times \frac{M_A}{Z} \leq 1.5 \times S_h$$

Or, if the larger ASME III NC/ND allowable stresses are permitted for reverse dynamic loads, then

$$B_2 \times \frac{M_A}{Z} \leq 0.5 \times S_h$$

7.1.2 Advantages

- No need to change code books
- Familiar equations
- Basis for current designs remain unchanged.

7.1.3 Disadvantages

- Lack of consistency between industries
- Prevention of plastic instability under sustained loads analyzed using equations based on fatigue rules (use of SIF rather than B indices).

7.2 Option 2 Consistent Equations with B Indices

7.2.1 Description

All codes adopt, for above-ground piping systems, the following stress equation for sustained loads.

$$B_1 \times \frac{P \times D}{2 \times t} + B_2 \times \frac{M_A}{Z} \leq S_h$$

This is the ASME III NB/NC equation but with an allowable stress S_h rather than $1.5S_h$ because, in practice, a well supported system is achieved with a stress limit of S_h rather than $1.5 \times S_h$. Since pipeline designers are more accustomed to an allowable stress based on yield, the allowable stress S_h would be replaced by 2/3 SMYS for pipelines.

7.2.2 Advantages

- Prevention of plastic instability under sustained loads analyzed using the correct limits (Rodabaugh and Moore, 1984) rather than equations based on fatigue rules (use of B_i indices rather than SIF).
- Consistent approach among codes.

7.2.3 Disadvantages

- Unfamiliar equations to all but nuclear power plant designers
- With the allowable stress set at S_h (or 2/3 SMYS), this equation will lead to lower design margins than current sustained stress equation in some cases, as illustrated in Figure 1, where the proposed equation and allowable correspond to the last bar (“NC/ND S”).

7.3 Option 3 Adopt B31.3 Case 178

7.3.1 Description

$$S_L = \sqrt{(|S_a| + S_b)^2 + (2 \times S_t)^2}$$

$$S_a = \frac{F_a}{A_p}$$

$$S_b = \frac{\sqrt{(I_i M_i)^2 + (I_o M_o)^2}}{Z}$$

$$S_t = \frac{M_t}{2 \times Z}$$

Case 178 states "in the absence of more applicable data, S_a and S_t need not be intensified."

7.3.1.1 Option 3a

It has been proposed that S_a and S_b be combined by SRSS for fittings where the the maxima occur at different locations, and therefore:

$$\sqrt{S_a{}^2 + S_b{}^2 + 4 \times S_t{}^2} \le S_h$$

Where S_a is the absolute sum of he intensified axial pressure stress and the intensified axial force stress

$$S_a = i_P \times \frac{P \times D}{2 \times t} + i_{ax} \times \frac{F_{ax}}{A}$$

and

$$S_b = \frac{\sqrt{(I_i \times M_i)^2 + (I_o \times M_o)^2}}{Z}$$

$$S_t = \frac{M_t}{2 \times Z}$$

This option 3a deserves further discussion within ASME B31 Mechanical Design Committee.

7.3.2 Advantages

- Introduces axial load effects
- Combines axial pressure-force stresses by SRSS with axial moment stresses since they do not occur at the same point in the component

- Consistent approach among codes
- Uses SIF more familiar than B indices.

7.3.3 Disadvantages

- Need to develop i_{ax} and i_P (although the latter may be B_1)
- New, unfamiliar equations
- Uses i_i, i_o, which are fatigue-based rather than sustained load-based.

7.4 Recommendation for Sustained Loads

Sustained load limits should be based on the prevention of excessive deformation (sag), excessive weight on supports, excessive reactions at equipment nozzles and excessive stresses, well below plastic deformation let alone collapse or failure.

Regarding the prevention of excessive stresses, a combination of Options 3 and 4 is recommended. It would consist of applying the stress equations of Option 4 but with the B indices of Option 3. For sustained loads this takes the form:

$$\sqrt{S_a^2 + S_b^2 + 4 \times S_t^2} \le S_h$$

$$S_a = B_1 \times \frac{P \times D}{2 \times t} + B_3 \times \frac{F_{ax}}{A}$$

$$S_b = \frac{\sqrt{(B_{2i} \times M_i)^2 + (B_{2o} \times M_o)^2}}{Z}$$

$$S_t = \frac{M_t}{2 \times Z}$$

The B_3 stress indices would have to be developed, and additional stress indices B_1 and B_2 for sizes and fittings encountered outside the nuclear power industry would have to be developed to support B31.3, B31.4, B31.8 and B31.9 designs.

The separate treatment of hoop effects (t_{min}) and sustained load axial stress effects that has always been followed in the design of piping systems, has proven through experience to be adequate, and should be retained.

APPENDIX A: ASME B31.1, 2007 SUSTAINED STRESS EQUATIONS

104.1.2 Straight Pipe Under Internal Pressure

The minimum thickness of pipe wall is

$$t = \frac{P \times D_o}{2 \times (S \times E + P \times y)} + A$$

102.4.5 Bending

The minimum wall thickness for bends is

$$t = \frac{P \times D_o}{2 \times (S \times E / I + P \times y)} + A$$

where, at the intrados

$$I = \frac{4 \times (R / D_o) - 1}{4 \times (R / D_o) - 2}$$

and, at the extrados

$$I = \frac{4 \times (R / D_o) + 1}{4 \times (R / D_o) + 2}$$

and, on the side walls

$$I = 1$$

102.3.2 Limits of Calculated Stresses Due to Sustained Loads and Thermal Expansion

(D) Longitudinal Stresses. The sum of the longitudinal stresses S_L due to pressure, weight and other sustained loads shall not exceed the allowable stress in the hot condition S_h. Where the sum of these stresses is less than S_h, the difference may be used as an additional thermal expansion allowance, which is the second term on the right side of Eq. (13) of para. 104.8.3.

The longitudinal pressure stress S_{lp} shall be determined by either of the following equations.

$$S_{lp} = \frac{P \times D}{4 \times t_n}$$

$$S_{lp} = \frac{P \times d_n^2}{D_n^2 - d_n^2}$$

104.8.1 Stress Due to Sustained Loads

The effects of pressure, weight and other sustained mechanical loads shall meet the requirements of Eq. (11).

$$S_L = \frac{P \times D_o}{4 \times t_n} + 0.75 \times i \times \frac{M_A}{Z} \le S_h \qquad (11A)$$

104.8.3 Thermal Expansion Stress Range

The effects of thermal expansion shall meet the requirements of Eq. (13).

$$S_E = \frac{i \times M}{Z} \leq S_A + f \times (S_h - S_L) \qquad (13A)$$

$$S_A = f \times (1.25 \times S_C + 0.25 \times S_h) \qquad (1)$$

A = additional thickness for threading, grooving, mechanical strength, corrosion and erosion

D_o = outside diameter of pipe

E = joint efficiency

P = internal design pressure

M_A = resultant moment loading on cross section due to weight and other sustained loads, in-lb

M_C = range of resultant moments due to thermal expansion, in.-lb. Also include moments effects of anchor displacement due to earthquake if anchor displacement effects were omitted from Eq. (12) (see para. 104.8.4).

R = bend radius

y = coefficient

Z = section modulus, in^3

i = stress intensification factor. The product 0.75i shall never be taken as less than 1.0

S_L = sum of the longitudinal stresses due to pressure, weight and other sustained loads

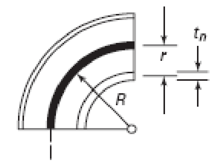
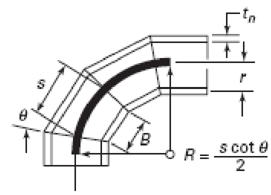
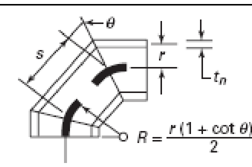
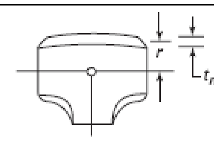
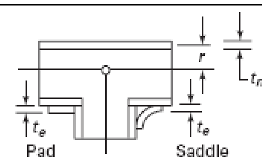
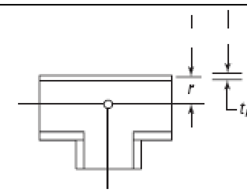
S_c = basic material allowable stress at minimum (cold) temperature from the Allowable Stress Tables

S_h = basic material allowable stress at maximum (hot) temperature from the Allowable Stress Tables

f = stress range reduction factor for cyclic conditions for total number N of full temperature cycles over total number of years during which system is expected to be in operation, from Table 102.3.2(C).

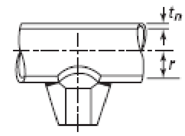
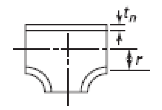
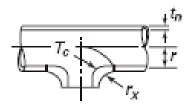
ASME B31.1 Appendix D

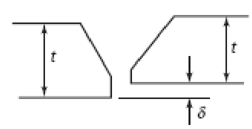
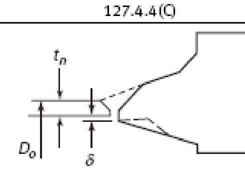
Table D-1 Flexibility and Stress Intensification Factors

Description	Flexibility Characteristic h	Flexibility Factor k	Stress Intensification Factor i	Sketch
Welding elbow or pipe bend [Notes (1), (2), (3), (9), (13)]	$\frac{t_n R}{r^2}$	$\frac{1.65}{h}$	$\frac{0.9}{h^{2/3}}$	
Closely spaced miter bend [Notes (1), (2), (3), (13)] $s < r(1 + \tan\theta)$ $B \geq 6\,t_n$ $\theta \leq 22\frac{1}{2}$ deg.	$\frac{s t_n \cot\theta}{2r^2}$	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	
Widely spaced miter bend [Notes (1), (2), (4), (13)] $s \geq r(1 + \tan\theta)$ $\theta \leq 22\frac{1}{2}$ deg.	$\frac{t_n (1 + \cot\theta)}{2r}$	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	
Welding tee per ASME B16.9 [Notes (1), (2), (10)]	$\frac{4.4 t_n}{r}$	1	$\frac{0.9}{h^{2/3}}$	
Reinforced fabricated tee [Notes (1), (2), (5), (10)]	$\frac{\left(t_n + \frac{t_e}{2}\right)^{5/2}}{r\,(t_n)^{3/2}}$	1	$\frac{0.9}{h^{2/3}}$	
Unreinforced fabricated tee [Notes (1), (2), (10)]	$\frac{t_n}{r}$	1	$\frac{0.9}{h^{2/3}}$	

ASME B31.1 Appendix D

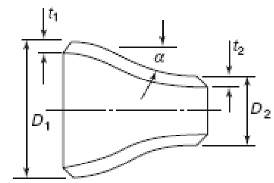
Table D-1 Flexibility and Stress Intensification Factors (Cont'd)

Description	Flexibility Characteristic h	Flexibility Factor k	Stress Intensification Factor i	Sketch
Branch welded-on fitting (integrally reinforced) per MSS SP-97 [Notes (1), (2)]	$\frac{3.3t_n}{r}$	1	$\frac{0.9}{h^{2/3}}$	
Extruded outlet meeting the requirements of para. 104.3.1(G) [Notes (1), (2)]	$\frac{t_n}{r}$	1	$\frac{0.9}{h^{2/3}}$	
Welded-in contour insert with $r_x \geq D_{ob}/8$ $T_c \geq 1.5\ t_n$ [Notes (1), (2)]	$4.4\frac{t_n}{r}$	1	$\frac{0.9}{h^{2/3}}$	

Description	Flexibility Factor k	Stress Intensification Factor i	Sketch
Branch connection [Notes (1), (6)]	1	For checking branch end $1.5\left(\frac{R_m}{t_{nh}}\right)^{2/3}\left(\frac{r'_m}{R_m}\right)^{1/2}\left(\frac{t_{nb}}{t_{nh}}\right)\left(\frac{r'_m}{r_p}\right)$	See Fig. D-1
Butt weld [Note (1)] $t \geq 0.237$ in.,	1	1.0 [Note (12)]	
Butt weld [Note (1)] $t \geq 0.237$ in., $\delta_{max} \leq 1/16$ in., and $\delta_{avg}/t \leq 0.13$	1	1.0 [Note (12)]	
Butt weld [Note (1)] $t \geq 0.237$ in., $\delta_{max} \leq 1/8$ in., and δ_{avg}/t = any value	1	1.9 max. or $[0.9 + 2.7(\delta_{avg}/t)]$, but not less than 1.0 [Note (12)]	
Butt weld [Note (1)] $t \geq 0.237$ in., $\delta_{max} \leq 1/16$ in., and $\delta_{avg}/t \leq 0.33$	1		
Fillet welds	1	2.1; or 1.3 for fillet welds as defined in Note (11)	See Figs. 127.4.4(A), 127.4.4(B), and 127.4.4(C)
Tapered transition per para. 127.4.2(B) and ASME B16.25 [Note (1)]	1	1.9 max. or $1.3 + 0.0036\frac{D_o}{t_n} + 3.6\frac{\delta}{t_n}$	

ASME B31.1 Appendix D

Table D-1 Flexibility and Stress Intensification Factors (Cont'd)

Description	Flexibility Factor k	Stress Intensification Factor i	Sketch
Concentric reducer per ASME B16.9 [Note (7)]	1	2.0 max. or $0.5 + 0.01\alpha \left(\frac{D_2}{t_2}\right)^{1/2}$	
Threaded pipe joint, or threaded flange	1	2.3	...
Corrugated straight pipe, or corrugated or creased bend [Note (8)]	5	2.5	...

ASME B31.1 Appendix D Notes

Table D-1 Flexibility and Stress Intensification Factors (Cont'd)

NOTES:

(1) The following nomenclature applies to Table D-1:

- B = length of miter segment at crotch, in. (mm)
- D_o = outside diameter, in.
- D_{ob} = outside diameter of branch, in. (mm)
- R = bend radius of elbow or pipe bend, in. (mm)
- r = mean radius of pipe, in. (mm) (matching pipe for tees)
- r_x = external crotch radius of welded-in contour inserts, in. (mm)
- s = miter spacing at center line, in. (mm)
- T_c = crotch thickness of welded-in contour inserts, in. (mm)
- t_n = nominal wall thickness of pipe, in. (mm) (matching pipe for tees)
- t_r = reinforcement pad or saddle thickness, in. (mm)
- α = reducer cone angle, deg.
- δ = mismatch, in. (mm)
- θ = one-half angle between adjacent miter axes, deg.

(2) The flexibility factors k and stress intensification factors i in Table D-1 apply to bending in any plane for fittings and shall in no case be taken less than unity. Both factors apply over the effective arc length (shown by heavy center lines in the sketches) for curved and miter elbows, and to the intersection point for tees. The values of k and i can be read directly from Chart D-1 by entering with the characteristic h computed from the formulas given.

(3) Where flanges are attached to one or both ends, the values of k and i in Table D-1 shall be multiplied by the factor c given below, which can be read directly from Chart D-2, entering with the computed h: one end flanged, $c = h^{1/6}$; both ends flanged, $c = h^{1/3}$.

(4) Also includes single miter joints.

(5) When $t_e > 1.5t_n$, $h = 4.05t_n/r$.

(6) The equation applies only if the following conditions are met.

(a) The reinforcement area requirements of para. 104.3 are met.

(b) The axis of the branch pipe is normal to the surface of run pipe wall.

(c) For branch connections in a pipe, the arc distance measured between the centers of adjacent branches along the surface of the run pipe is not less than three times the sum of their inside radii in the longitudinal direction or is not less than two times the sum of their radii along the circumference of the run pipe.

(d) The inside corner radius r_1 (see Fig. D-1) is between 10% and 50% of t_{nh}.

(e) The outer radius r_2 (see Fig. D-1) is not less than the larger of $T_b/2$, $(T_b + y)/2$ [shown in Fig. D-1 sketch (c)], or $t_{nh}/2$.

(f) The outer radius r_3 (see Fig. D-1) is not less than the larger of:

(1) $0.002\theta d_o$;

(2) $2(\sin\theta)^3$ times the offset for the configurations shown in Fig. D-1 sketches (a) and (b).

(g) $R_m/t_{nh} \le 50$ and $rt_m/R_m \le 0.5$.

(7) The equation applies only if the following conditions are met:

(a) Cone angle α does not exceed 60 deg., and the reducer is concentric.

(b) The larger of D_1/t_1 and D_2/t_2 does not exceed 100.

(c) The wall thickness is not less than t_1 throughout the body of the reducer, except in and immediately adjacent to the cylindrical portion on the small end, where the thickness shall not be less than t_2.

(8) Factors shown apply to bending; flexibility factor for torsion equals 0.9.

(9) The designer is cautioned that cast butt welding elbows may have considerably heavier walls than those of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(10) The stress intensification factors in the Table were obtained from tests on full size outlet connections. For less than full size outlets, the full size values should be used until more applicable values are developed.

(11) A stress intensification factor of 1.3 may be used for socket weld fitting if toe weld blends smoothly with no undercut in pipe wall as shown in the concave, unequal leg fillet weld of Fig. 127.4.4(A).

(12) The stress intensification factors apply to girth butt welds between two items for which the wall thicknesses are between $0.875t$ and $1.10t$ for an axial distance of $\sqrt{D_o t}$. D_o and t are nominal outside diameter and nominal wall thickness, respectively. δ_{avg} is the average mismatch or offset.

(13) In large diameter thin-wall elbows and bends, pressure can significantly affect magnitudes of k and i. Values from the table may be corrected by dividing k by

$$\left[1 + 6\left(\frac{P}{E_c}\right)\left(\frac{r}{t_n}\right)^{7/3}\left(\frac{R}{r}\right)^{1/3}\right]$$

and dividing i by

$$\left[1 + 3.25\left(\frac{P}{E_c}\right)\left(\frac{r}{t_n}\right)^{5/2}\left(\frac{R}{r}\right)^{2/3}\right]$$

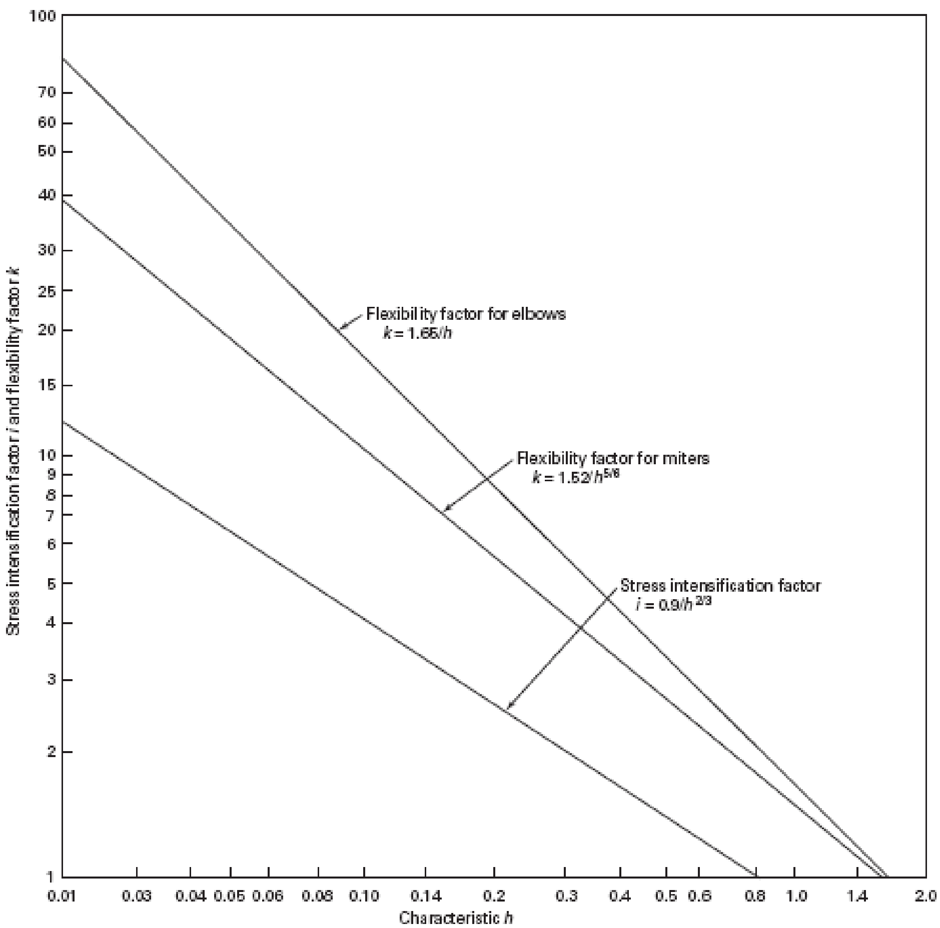


Chart D-1 Flexibility Factor *k* and Stress Intensification Factor *i*

APPENDIX B: ASME B31.3, 2004 SUSTAINED STRESS EQUATIONS

304.1.2 Straight Pipe Under Internal Pressure

Same as B31.1

304.2.1 Pipe Bends

Same as B31.1

302.3.5 Limits of Calculated Stresses Due to Sustained Loads and Displacement Strains

(c) Longitudinal Stresses SL. The sum of the longitudinal stresses S_L *in any component in a piping system, due to sustained loads such as pressure and weight, shall not exceed the product* S_h *W;* S_h *and W are defined in (d) and (e) below. The weld joint strength reduction factor, W, may be taken as 1.0 for longitudinal welds. The thickness of pipe used in calculating SL shall be the nominal thickness, T, minus mechanical, corrosion and erosion allowance, c, for the location under consideration. The loads due to weight should be based on the nominal thickness of all system components unless otherwise justified in a more rigorous analysis.*

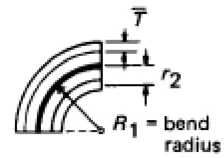
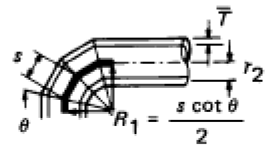
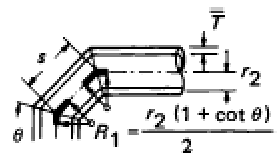
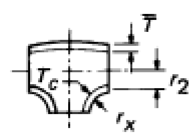
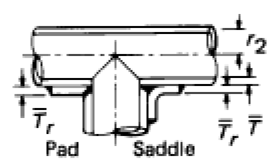
Appendix S Piping System Stress Analysis Examples – This Appendix was introduced in the 2004 edition. Note (1) of Appendix S states, *"ASMEB31.3 does not address the issue of using a stress intensification factor as the stress index to be applied to piping components for sustained loads; stress intensification factors are based on fatigue test results. Establishing the proper index is the responsibility of the designer. This example uses 0.75 times the stress intensification factor for the sustained case."*

Sustained stresses due to the axial force, internal pressure and intensified bending moment in this example are combined to determine the sustained longitudinal stress, S_L. The sustained load case excludes thermal effects and includes the effects of internal pressure [*P*1 = 3450 kPa (500 psi)], pipe weight, insulation weight and fluid weight on the piping system.

Nominal section properties are used to generate the stiffness matrix and sustained loads for the computer model in accordance with para. 319.3.5. The nominal thickness, less allowances, is used to calculate the section properties for the sustained stress, S_L, in accordance with para. 302.3.5(c).

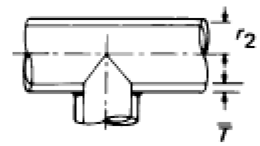
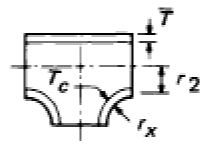
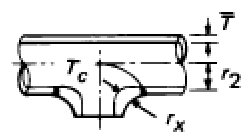
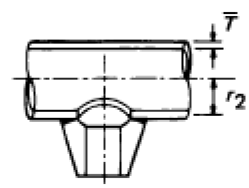
ASME B31.3, 2004 Appendix D

Table D300[1] Flexibility Factor, k, and Stress Intensification Factor, i

Description	Flexibility Factor, k	Stress Intensification Factor [Notes (2), (3)] Out-of-Plane, i_o	In-Plane, i_i	Flexibility Characteristic, h	Sketch
Welding elbow or pipe bend [Notes (2), (4)-(7)]	$\frac{1.65}{h}$	$\frac{0.75}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{\bar{T} R_1}{r_2^2}$	
Closely spaced miter bend $s < r_2 (1 + \tan\theta)$ [Notes (2), (4), (5), (7)]	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{\cot\theta}{2}\left(\frac{s\bar{T}}{r_2^2}\right)$	
Single miter bend or widely spaced miter bend $s \geq r_2 (1 + \tan\theta)$ [Notes (2), (4), (7)]	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{1 + \cot\theta}{2}\left(\frac{\bar{T}}{r_2}\right)$	
Welding tee per ASME B16.9 [Notes (2), (4), (6), (11), (13)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4} i_o + \frac{1}{4}$	$3.1 \frac{\bar{T}}{r_2}$	
Reinforced fabricated tee with pad or saddle [Notes (2), (4), (8), (12), (13)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4} i_o + \frac{1}{4}$	$\frac{(\bar{T} + \frac{1}{2}\bar{T}_r)^{2.5}}{\bar{T}^{1.5} r_2}$	

ASME B31.3, 2004 Appendix D

Table D300[1] Flexibility Factor, k, and Stress Intensification Factor, i (Cont'd)

Description	Flexibility Factor, k	Stress Intensification Factor [Notes (2), (3)] Out-of-Plane, i_o	In-Plane, i_i	Flexibility Characteristic, h	Sketch
Unreinforced fabricated tee [Notes (2), (4), (12), (13)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$\frac{\bar{T}}{r_2}$	
Extruded welding tee with $r_x \geq 0.05\ D_b$, $T_c < 1.5\ \bar{T}$ [Notes (2), (4), (13)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$\left(1 + \frac{r_x}{r_2}\right)\frac{\bar{T}}{r_2}$	
Welded-in contour insert [Notes (2), (4), (11), (13)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$3.1\frac{\bar{T}}{r_2}$	
Branch welded-on fitting (integrally reinforced) [Notes (2), (4), (9), (12)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$3.3\frac{\bar{T}}{r_2}$	

ASME B31.3, 2004 Appendix D

Description	Flexibility Factor, k	Stress Intensification Factor, i [Note (1)]
Butt welded joint, reducer, or weld neck flange	1	1.0
Double-welded slip-on flange	1	1.2
Fillet welded joint, or socket weld flange or fitting	1	Note (14)
Lap joint flange (with ASME B16.9 lap joint stub)	1	1.6
Threaded pipe joint or threaded flange	1	2.3
Corrugated straight pipe, or corrugated or creased bend [Note (10)]	5	2.5

ASME B31.3, 2004 Appendix D

Table D300[1] Flexibility Factor, k, and Stress Intensification Factor, i (Cont'd) **(04)**

NOTES:

(1) Stress intensification and flexibility factor data in Table D300 are for use in the absence of more directly applicable data (see para. 319.3.6). Their validity has been demonstrated for $D/\overline{T} \le 100$.

(2) The flexibility factor, k, in the Table applies to bending in any plane. The flexibility factors, k, and stress intensification factors, i, shall not be less than unity; factors for torsion equal unity. Both factors apply over the effective arc length (shown by heavy centerlines in the sketches) for curved and miter bends, and to the intersection point for tees.

(3) A single intensification factor equal to $0.9/h^{2/3}$ may be used for both i_i and i_o if desired.

(4) The values of k and i can be read directly from Chart A by entering with the characteristic h computed from the formulas given above. Nomenclature is as follows:

D_b = outside diameter of branch
R_1 = bend radius of welding elbow or pipe bend
r_x = see definition in para. 304.3.4(c)
r_2 = mean radius of matching pipe
s = miter spacing at centerline
$\overline{T}$ = for elbows and miter bends, the nominal wall thickness of the fitting
= for tees, the nominal wall thickness of the matching pipe
T_c = crotch thickness of branch connections measured at the center of the crotch where shown in the sketches
$\overline{T}_r$ = pad or saddle thickness
θ = one-half angle between adjacent miter axes

(5) Where flanges are attached to one or both ends, the values of k and i in the Table shall be corrected by the factors C_1, which can be read directly from Chart B, entering with the computed h.

(6) The designer is cautioned that cast buttwelded fittings may have considerably heavier walls than that of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(7) In large diameter thin-wall elbows and bends, pressure can significantly affect the magnitudes of k and i. To correct values from the Table, divide k by

$$1 + 6\left(\frac{P}{E}\right)\left(\frac{r_2}{\overline{T}}\right)^{7/3}\left(\frac{R_1}{r_2}\right)^{1/3}$$

divide i by

$$1 + 3.25\left(\frac{P}{E}\right)\left(\frac{r_2}{\overline{T}}\right)^{5/2}\left(\frac{R_1}{r_2}\right)^{2/3}$$

For consistency, use kPa and mm for SI metric, and psi and in. for U.S. customary notation.

(8) When $\overline{T}_r$ is $> 1\frac{1}{2}\,\overline{T}$, use $h = 4\,\overline{T}/r_2$.

(9) The designer must be satisfied that this fabrication has a pressure rating equivalent to straight pipe.

(10) Factors shown apply to bending. Flexibility factor for torsion equals 0.9.

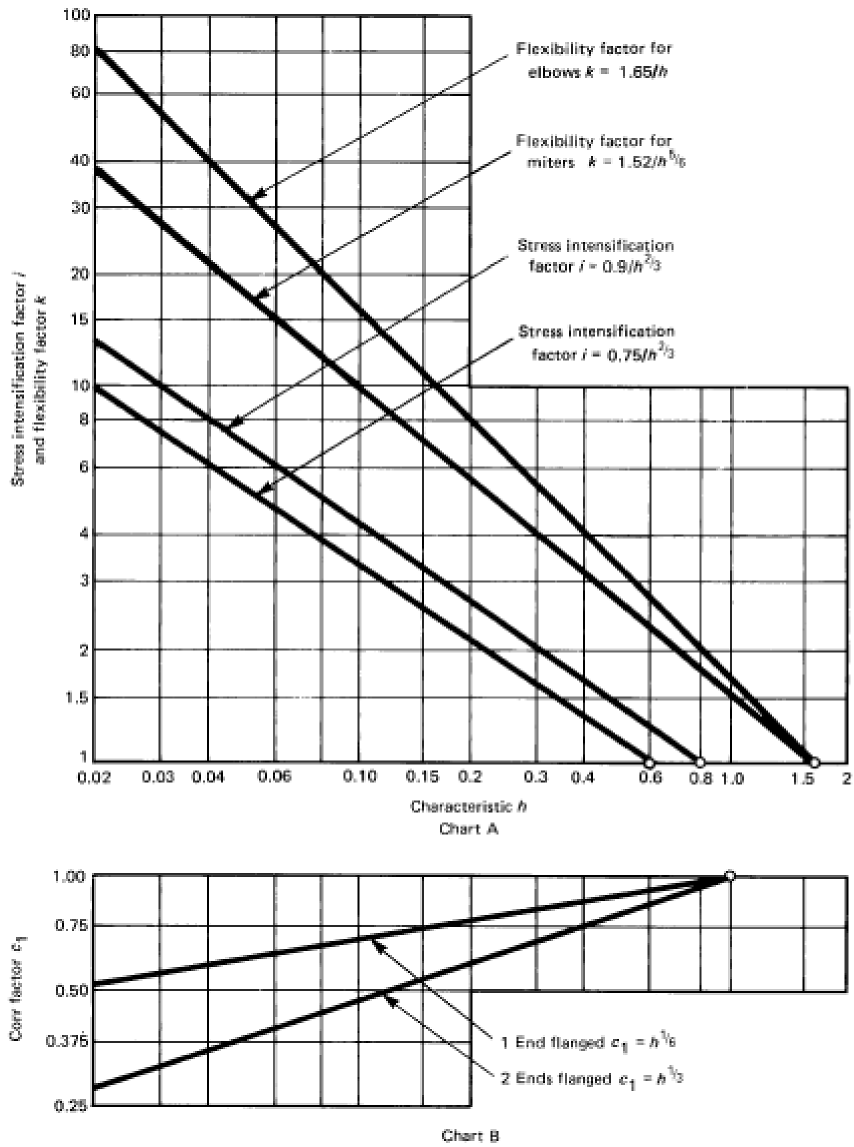
(11) If $r_x \ge \frac{1}{8} D_b$ and $T_c \ge 1.5\overline{T}$, a flexibility characteristic of $4.4\,\overline{T}/r_2$ may be used.

(12) The out-of-plane stress intensification factor (SIF) for a reducing branch connection with branch-to-run diameter ratio of $0.5 < d/D < 1.0$ may be nonconservative. A smooth concave weld contour has been shown to reduce the SIF. Selection of the appropriate SIF is the designer's responsibility.

(13) Stress intensification factors for branch connections are based on tests with at least two diameters of straight run pipe on each side of the branch centerline. More closely loaded branches may require special consideration.

(14) 2.1 max. or $2.1\,\overline{T}/C_x$, but not less than 1.3. C_x is the fillet weld leg length (see Fig. 328.5.2C). For unequal leg lengths, use the smaller leg for C_x.

ASME B31.3, 2004 Appendix D



APPENDIX C: ASME B31.4, 200 SUSTAINED STRESS EQUATIONS

404.1.2 Straight Pipe Uunder Internal Pressure

$$t = \frac{P \times D}{2 \times (0.72 \times SMYS \times E)} + A$$

P = internal design pressure

D = outside diameter of pipe

E = weld joint factor

SMYS = specified minimum yield strength

A = threading, grooving, corrosion and erosion allowance

49 CFR 195 Pressure Design

The ASME B31.4 pressure design equation is also contained in Code of Federal Regulations 49 CFR 195.106.

404.2.1 Pipe Bends

Same as straight pipe

402.3.2 Limits of Calculated Stresses Due to a Sustained Loads and Thermal Expansion

(d) Additive Longitudinal Stresses. The sum of the longitudinal stresses due to pressure, weight and other sustained external loadings [see para. 419.6.4(c)] shall not exceed 75% of the allowable stress value specified for $\mathbf{S_A}$ in (c) above.

419.6.4 Stress Values

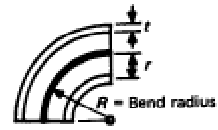
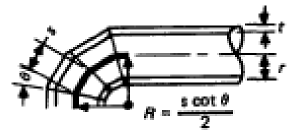
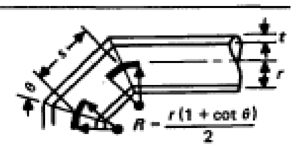
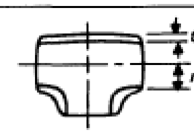
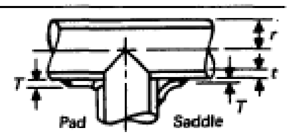
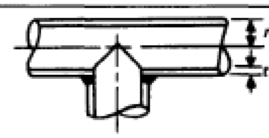
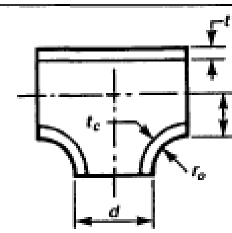
The sum of the longitudinal stresses due to pressure, weight and other sustained external loadings shall not exceed $0.75S_A$ in accordance with para. 402.3.2(d).

49 CFR 195.110 External Loads Design

a) Anticipated external loads (e.g.), earthquakes, vibration, thermal expansion and contraction must be provided for in designing a pipeline system. In providing for expansion and flexibility, section 419 of ASME/ANSI B31.4 must be followed.

b) The pipe and other components must be supported in such a way that the support does not cause excess localized stresses. In designing attachments to pipe, the designer must compute, and compensate for, the added stress to the wall of the pipe.

ASME B31.4, 2002, 419.6.4

		Stress Intensification Factor			
Description	Flexibility Factor k	i_i (1)	i_o (2)	Flexibility Characteristic h	Sketch
Welding elbow,[3, 4, 5, 6, 7] or pipe bend	$\frac{1.65}{h}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.75}{h^{2/3}}$	$\frac{tR}{r^2}$	
Closely spaced miter bend,[3, 4, 5, 7] $s < r(1 + \tan\theta)$	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.75}{h^{2/3}}$	$\frac{\cot\theta}{2}\,\frac{ts}{r^2}$	
Widely spaced miter bend,[3, 4, 7, 8] $s \ge r(1 + \tan\theta)$	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.75}{h^{2/3}}$	$\frac{1 + \cot\theta}{2}\,\frac{t}{r}$	
Welding tee[3, 4] per ASME B16.9	1	$0.75 i_o + 0.25$	$\frac{0.9}{h^{2/3}}$	$4.4\,\frac{t}{r}$	
Reinforced tee[3, 4, 9] with pad or saddle	1	$0.75 i_o + 0.25$	$\frac{0.9}{h^{2/3}}$	$\frac{(t + 1/2\ T)^{5/2}}{t^{3/2}\ r}$	
Unreinforced fabricated tee[3, 4]	1	$0.75 i_o + 0.25$	$\frac{0.9}{h^{2/3}}$	$\frac{t}{r}$	
Extruded welding tee[3, 4, 11] $r_o \ge 0.05d$ $t_c < 1.5t$	1	$0.75 i_o + 0.25$	$\frac{0.9}{h^{2/3}}$	$\left(1 + \frac{r_o}{r}\right)\frac{t}{r}$	

ASME B31.4, 2002, 419.6.4

Description	Flexibility Factor k	Stress Intensification Factor i_i (1)	Stress Intensification Factor i_o (2)	Flexibility Characteristic h	Sketch
Butt welded joint, reducer, or welding neck flange	1	1.0		...	...
Double welded slip-on flange	1	1.2		...	...
Fillet welded joint (single welded), or single welded slip-on flange	1	1.3		...	...
Lapped flange (with ANSI B16.9 lap-joint stub)	1	1.6		...	...
Threaded pipe joint, or threaded flange	1	2.3		...	...
Corrugated straight pipe, or corrugated or creased bend[10]	5	2.5		...	...

ASME B31.4, 2002, 419.6.4 Notes:

(1) In-plane.

(2) Out-of-plane.

(3) For fittings and miter bends, the flexibility factors kand stress intensification factors, i, in the Table apply to bending in any plane and shall not be less than unity; factors for torsion equal unity. Both factors apply over the effective arc length (shown by heavy center lines in the sketches) for curved and miter elbows, and to the intersection point for tees.

(4) The values of k and i can be read directly from Chart A by entering with the characteristic h computed from the equations given, where

R = bend radius of welding elbow or pipe bend, in.

T = pad or saddle thickness, in.

d = outside diameter of branch

r = mean radius of matching pipe, in.

r_o = see Note (11)

s = miter spacing at center line

t = nominal wall thickness of: part itself, for elbows and curved or mitered bends; matching pipe, for welding tees; run or header, for fabricated tees (provided that if thickness is greater than that of matching pipe, increased thickness must be maintained for at least one run O.D. to each side of the branch O.D.).

t_c = the crotch thickness of tees

θ = one-half angle between adjacent miter axes, deg.

(5) Where flanges are attached to one or both ends, the values of k and i in the Table shall be corrected by the factors C_1 given below, which can be read directly from Chart B, entering with the computed h; one end flanged $h^{1/6} \geq 1$; both ends flanged, $h^{1/3} \geq 1$

(6) The engineer is cautioned that cast butt welding elbows may have considerably heavier walls than that of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(7) In large diameter thin wall elbows and bends, pressure can significantly affect the magnitude of flexibility and stress intensification factors. To correct values obtained from Table for the pressure effect, divide:

$$\text{Flexibility factor } k = 1 + 6 \times \frac{P}{E_C} \times \left(\frac{r}{t}\right)^{7/3} \times \left(\frac{R}{r}\right)^{1/3}$$

$$\text{Stress intensification factor } i = 1 + 3.25 \times \frac{P}{E_C} \times \left(\frac{r}{t}\right)^{5/2} \times \left(\frac{R}{r}\right)^{2/3}$$

where

Ec = cold modulus of elasticity

P = gage pressure

(8) Also includes single miter joint:

(9) When T > 1½t use h = 4.05 t/r

(10) Factors shown apply to bending; flexibility factor for torsion equals 0.9

(11) Radius of curvature of external contoured portion of outlet measured in the plane containing the axes of the run and branch. This is subject to the following limitations.

(a) minimum radius r_o, the lesser of 0.05d or 38 mm (1.5 in.);

(b) maximum radius r_o shall not exceed:

(1) for branches DN200 (NPS 8) and larger, 0.10d+ 13 mm (0.50 in);

(2) for branches less than DN200 (NPS 8), 32 mm (1.25 in.); requirements of (a) and (b) above;

(c) when the external contour contains more than one radius, the radius on any arc sector of approximately 45 deg. shall meet

(d) machining shall not be employed in order to meet the above requirements.

APPENDIX D: ASME B31.8, SUSTAINED STRESS EQUATIONS

841.11 Steel Pipe Design Formula

The nominal wall thickness of the pipeline is

$$t = \frac{P \times D}{2 \times SMYS \times F \times E \times T}$$

P = internal pressure

D = outside diameter of pipe

SMYS = specified minimum yield strength

F = design factor, function of location class, and includes under-thickness tolerance

T = temperature derating factor

E = longitudinal joint factor

49 CFR 192 Pressure Design

The ASME B31.8 pressure design equation is also contained in Code of Federal Regulations 49 CFR 192.105.

833 DESIGN FOR LONGITUDINAL STRESS

833.1 Restraint

(a) The restraint condition is a factor in the structural behavior of the pipeline. The degree of restraint may be affected by aspects of pipeline construction, support design, soil properties and terrain. Part 833 is applicable to all steel piping within the scope of B31.8. For purposes of design, this Code recognizes two axial restraint conditions, "restrained" and "unrestrained." Guidance in categorizing the restraint condition is given below.

(b) Piping in which soil or supports prevent axial displacement of flexure at bends is "restrained." Restrained piping may include the following.

(1) straight sections of buried piping

(2) bends and adjacent piping buried in stiff or consolidated soil

(3) sections of above-ground piping on rigid supports

(c) Piping that is freed to displace axially or flex at bends is "unrestrained." Unrestrained piping may include the following.

(1) above-ground piping that is configured to accommodate thermal expansion or anchor movements through flexibility

(2) bends and adjacent piping buried in soft or unconsolidated soil

(3) an unbackfilled section of otherwise buried pipeline that is sufficiently flexible to displace laterally or which contains a bend

(4) pipe subject to an end cap pressure force.

833.2 Calculation of Longitudinal Stress in Components

(a) The longitudinal stress due to internal pressure in restrained pipelines is

$$S_p = 0.3\ S_H$$

where S_H is the hoop stress, psi

(b) The longitudinal stress due to internal pressure in unrestrained pipeline is

$$S_p = 0.5\ S_H$$

where S_H is the hoop stress, psi

(c) The longitudinal stress due to thermal expansion in restrained pipe is

$$S_T = E\ \alpha\ (T_1 - T_2)$$

where

E = the elastic modulus, psi, at the ambient temperature

T_1 = the pipe temperature at the time of installation, tie-in or burial, 1/°F

T_2 = the warmest or coldest pipe operating temperature, °F

α = the coefficient of thermal expansion, 1/°F

If a section of pipe can operate either warmer or colder than the installed temperature, both conditions for T2 may need to be examined.

(d) The nominal bending stress in straight pipe or large-radius bends due to weight or other external loads is

$$S_B = M / Z$$

where

M = the bending moment across the pipe cross section, lb-in.

Z = the pipe section modulus, in^3

(e) The nominal bending stress in fittings and components due to weight or other external loads is

$$S_B = M_R / Z$$

where M_R is the resultant intensified moment across the fitting or component. The resultant moment shall be calculated as

$$M_R = [(0.75\ i_i\ M_i)^2 + (0.75\ i_o\ M_o)^2 + M_t^2\ ]^{1/2}, \text{ lb-in.}$$

M_i = in-plane bending moment, lb-in.

M_t = torsional moment, lb-in.

M_o = out-of-plane bending moment, lb-in.

i_i = in-plane stress intensification factor from Appendix E

i_o = out-of-plane stress intensification factor from Appendix E

The product $0.75i \geq 1.0$

(f) The stress due to axial loading other than thermal expansion and pressure is

$$S_X = R / A$$

where

A = pipe metal cross sectional area, in.^{2}

R = external force axial component, lb

833.3 Summation of Longitudinal Stress in Restrained Pipe

(a) The net longitudinal stresses in restrained pipe are

$$S_L = S_P + S_T + S_X + S_B$$

Note that S_L, S_T, S_X, or S_B can have negative values.

(b) The maximum permitted value of |SL| is 0.9ST, where S is the specified minimum yield strength, psi, per para. 841.11(a), and *T* is the temperature derating factor per para. 841.116.

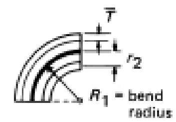
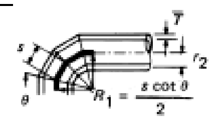
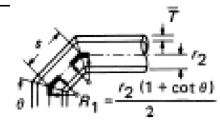
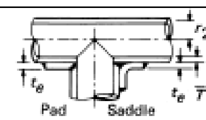
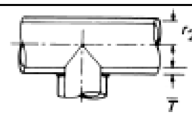
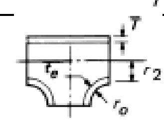
(c) Residual stresses from construction are often present, for example, bending in buried pipelines where spanning or differential settlement occurs. These stresses are often difficult to evaluate accurately, but can be disregarded in most cases. It is the engineer's responsibility to determine whether such stresses should be evaluated.

49 CFR 192 Requirements for Longitudinal Stresses

192.159 Each pipeline must be designed with enough flexibility to prevent thermal expansion or contraction from causing excessive stresses in the pipe or components, excessive bending or unusual loads at joints, or undesirable forces or moments at points of connection to equipment, or at anchorage or guide points.

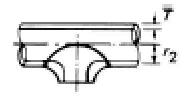
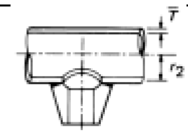
Appendix D ASME B31.8, 2003

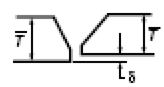
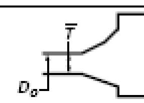
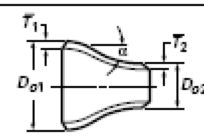
Table E1
Flexibility Factor, k, and Stress Intensification Factor, i

Description	Flexibility Factor, k	Stress Intensification Factor, i [Notes (1) and (2)] Outplane, i_o	Inplane, i_i	Flexibility Characteristic, h	Sketch
Welding elbow or pipe bend [Notes (1)–(5)]	$\frac{1.65}{h}$	$\frac{0.75}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{\bar{T} R_1}{r_2^2}$	
Closely spaced miter bend [Notes (1), (2), (3), and (5)] $s < r_2 (1 + \tan\theta)$	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{\cot\theta}{2}\frac{\bar{T}s}{r_2^2}$	
Single miter bend or widely spaced miter bend $s \geq r_2 (1 + \tan\theta)$ [Notes (1), (2), and (5)]	$\frac{1.52}{h^{5/6}}$	$\frac{0.9}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{1+\cot\theta}{2}\frac{\bar{T}}{r_2}$	
Welding tee per ANSI B16.9 with $r_o \geq d/8$ $T_c \geq 1.5\,\bar{T}$ [Notes (1), (2), and (6)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$4.4\frac{\bar{T}}{r_2}$	
Reinforced fabricated tee with pad or saddle [Notes (1), (2), (7), (8), and (9)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$\frac{(\bar{T} + \frac{1}{2}t_e)^{5/2}}{\bar{T}^{3/2} r_2}$	
Unreinforced fabricated tee [Notes (1), (2), and (9)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$\frac{\bar{T}}{r_2}$	
Extruded outlet $r_o \geq 0.05d$ $T_c < 1.5\,\bar{T}$ [Notes (1), (2), and (6)]	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$	$\left(1 + \frac{r_o}{r_2}\right)\frac{\bar{T}}{r_2}$	

Appendix D ASME B31.8, 2003

Table E1
Flexibility Factor, k, and Stress Intensification Factor, i (Cont'd)

Description	Flexibility Factor, k	Stress Intensification Factor, i [Notes (1) and (2)] Outplane, i_o	Stress Intensification Factor, i [Notes (1) and (2)] Inplane, i_i	Flexibility Characteristic, h	Sketch
Welded-in contour insert $r_o \geq d/8$ $T_c \geq 1.5\,\bar{T}$ [Notes (1), (2), and (10)]	1	$\dfrac{0.9}{h^{2/3}}$	$\frac{3}{4}\,i_o + \frac{1}{4}$	$4.4\,\dfrac{\bar{T}}{r_2}$	
Branch welded-on fitting (integrally reinforced) [Notes (1), (2), (9), and (11)]	1	$\dfrac{0.9}{h^{2/3}}$	$\dfrac{0.9}{h^{2/3}}$	$3.3\,\dfrac{\bar{T}}{r_2}$	

Description	Flexibility Factor, k	Stress Intensification Factor, i	Sketch
Buttweld [Notes (1) and (12)] $\bar{T} \geq 0.237$ in., $\delta_{max.} \leq \frac{1}{16}$ in., and $\delta_{avg}/\bar{T} \leq 0.13$	1	1.0	
Buttweld [Notes (1) and (12)] $\bar{T} \geq 0.237$ in., $\delta_{max.} \leq \frac{1}{8}$ in., and $\delta_{avg}\,\bar{T}$ = any value	1	1.9 max. or $[0.9 + 2.7(\delta_{avg}/\bar{T})]$, but not less than 1.0	
Buttweld [Notes (1) and (12)] $\bar{T} \leq 0.237$ in., $\delta_{max.} \leq \frac{1}{16}$ in., and $\delta_{avg}/\bar{T} \leq 0.33$			
Tapered transition per ANSI B16.25 [Note (1)]	1	1.9 max. or $1.3 + 0.0036\,\dfrac{D_o}{\bar{T}} + 3.6\,\dfrac{\delta}{\bar{T}}$	
Concentric reducer per ANSI B16.9 [Notes (1) and (13)]	1	2.0 max. or $0.5 + 0.01\alpha\left(\dfrac{D_{o2}}{\bar{T}_2}\right)^{1/2}$	

Appendix D ASME B31.8, 2003

Table E1
Flexibility Factor, *k*, and Stress Intensification Factor, *i* (Cont'd)

Description	Flexibility Factor, *k*	Stress Intensification Factor, *i*
Double-welded slip-on flange [Note (14)]	1	1.2
Socket welding flange or fitting [Notes (14) and (15)]	1	2.1 max or 2.1 $\overline{T}/C_x$ but not less than 1.3
Lap joint flange (with ANSI B16.9 lap joint stub) [Note (14)]	1	1.6
Threaded pipe joint or threaded flange [Note (14)]	1	2.3
Corrugated straight pipe, or corrugated or creased bend [Note (16)]	5	2.5

Table E1
Flexibility Factor, *k*, and Stress Intensification Factor, *i* (Cont'd)

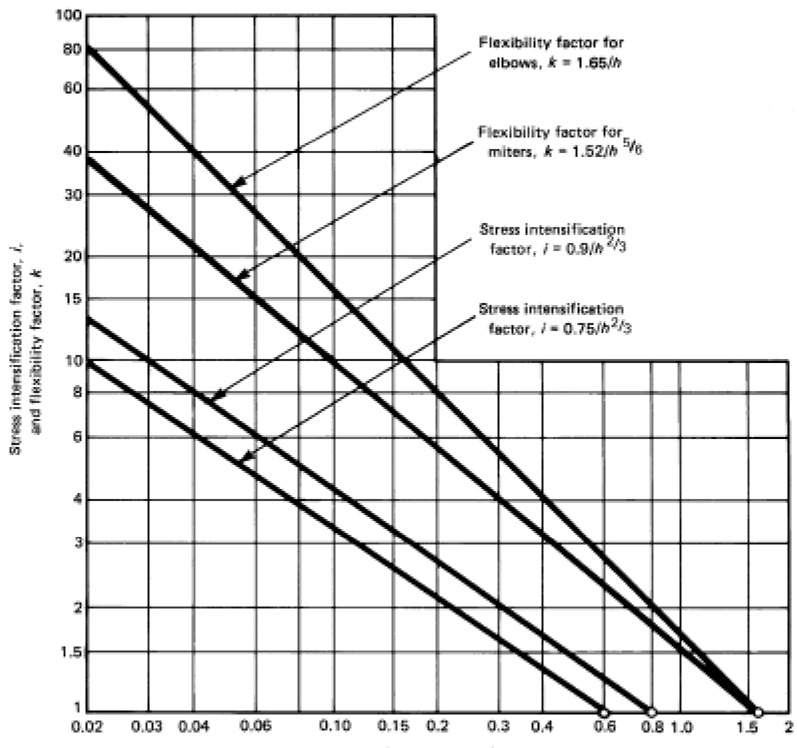


Chart A

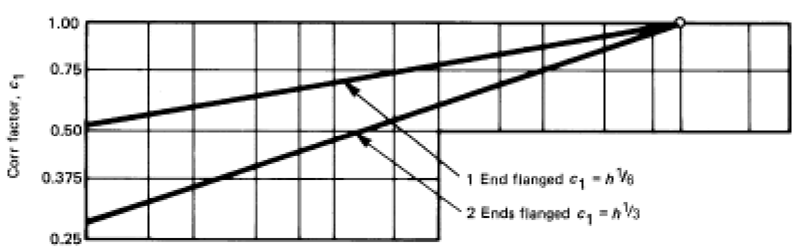


Chart B

Appendix D ASME B31.8, 2003

Notes to Table E1

NOTES:

(1) The nomenclature is as follows:

R_1 = bend radius of welding elbow or pipe bend, in. (mm)
$\overline{T}$ = nominal wall thickness of piping component, in. (mm)
= for elbows and miter bends, the nominal wall thickness of the fitting, in. (mm)
= for welding tees, the nominal wall thickness of the matching pipe, in. (mm)
= for fabricated tees, the nominal wall thickness of the run or header (provided that if thickness is greater than that of matching pipe, increased thickness must be maintained for at least one run outside diameter to each side of the branch outside diameter), in. (mm)
T_c = the crotch thickness of tees, in. (mm)
d = outside diameter of branch, in. (mm)
r_o = radius of curvature of external contoured portion of outlet, measured in the plane containing the axes of the header and branch, in. (mm)
r_2 = mean radius of matching pipe, in. (mm)
s = miter spacing at centerline, in. (mm)
t_e = pad or saddle thickness, in. (mm)
θ = one-half angle between adjacent miter axes, deg

(2) The flexibility factor, k, applies to bending in any plane. The flexibility factors, k, and stress intensification factors, i, shall not be less than unity; factors for torsion equal unity. Both factors apply over the effective arc length (shown by heavy centerlines in the sketches) for curved and miter bends and to the intersection point for tees.

The values of k and i can be read directly from Chart A by entering with the characteristic, h, computed from the formulas given.

(3) Where flanges are attached to one or both ends, the values of k and i shall be corrected by the factors, C_u, which can be read directly from Chart B, entering with the computed h.

(4) The designer is cautioned that cast buttwelded fittings may have considerably heavier walls than that of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(5) In large diameter thin-wall elbows and bends, pressure can significantly affect the magnitudes of k and i. To correct values from the table, divide k by

$$\left[1 + 6\left(\frac{P}{E_e}\right)\left(\frac{r_2}{\overline{T}}\right)^{7/8}\left(\frac{R_1}{r_2}\right)^{1/3}\right]$$

divide i by

$$\left[1 + 3.25\left(\frac{P}{E_e}\right)\left(\frac{r_2}{\overline{T}}\right)^{5/2}\left(\frac{R_1}{r_2}\right)^{2/3}\right]$$

where
E_e = cold modulus of elasticity
P = gage pressure

(6) If the number of displacement cycles is less than 200, the radius and thickness limits specified need to be met. When the radius and thickness limits are not met and the number of design cycles exceeds 200, the out-plane and in-plane stress intensification factors shall be calculated as $1.12/h^{2/3}$ and $(0.67/h^{2/3}) + \frac{1}{4}$, respectively.

(7) When $t_e > 1\frac{1}{2}\overline{T}$, use $h = 4.05\overline{T}/r_2$.

(8) The minimum value of the stress intensification factor shall be 1.2.

(9) When the branch-to-run diameter ratio exceeds 0.5 and the number of design displacement cycles exceeds 200, the out-plane and in-plane stress intensification factors shall be calculated as $1.8/h^{2/3}$ and $(0.67/h^{2/3}) + \frac{1}{4}$, respectively, unless the transition weld between the branch and run is blended to a smooth concave contour. If the transition weld is blended to a smooth concave contour, the stress intensification factors in the table still apply.

(10) If the number of displacement cycles is less than 200, the radius and thickness limits specified need not be met. When the radius and thickness limits are not met and the number of design displacement cycles exceeds 200, the out-plane and in-plane stress intensification factors shall be calculated as $1.8/h^{2/3}$ and $(0.67/h^{2/3})$.

(11) The designer must be satisfied that this fabrication has a pressure rating equivalent to straight pipe.

(12) The stress intensification factors apply to girth butt welds between two items for which the wall thicknesses are between $0.875\overline{T}$ and $1.10\overline{T}$ for an axial distance of $\sqrt{D_o \overline{T}} \cdot D_o$ and $\overline{T}$ are nominal outside diameter and nominal wall thickness, respectively. δ_{avg} is the average mismatch or offset.

(13) The equation applies only if the following conditions are met.

(a) Cone angle α does not exceed 60 deg, and the reducer is concentric.
(b) The larger of $D_{o1}\sqrt{\overline{T}}$ and $D_{o2}\sqrt{\overline{T}}$ does not exceed 100.
(c) The wall thickness is not less than $\overline{T}_1$ throughout the body of the reducer, except in and immediately adjacent to the cylindrical portion on the small end, where the thickness shall not be less than $\overline{T}_2$.

Appendix D ASME B31.8, 2003

Notes to Table E1 (Cont'd)

(14) For some flanged joints, leakage may occur at expansion stresses otherwise permitted herein. The moment to produce leakage of a flanged joint with a gasket having no self-sealing characteristics can be estimated by the equation.

$$M_L = (C/4)\ (S_b A_b - PA_b)$$

A_b = total area of flange bolts, in.^{2} (mm^3)
A_p = area to outside of gasket contact, in.^{2} (mm^2)
C = bolt circle, in. (mm)
M_L = moment to produce flange leakage, in.-lb (mm·N)
P = internal pressure, psi (MPa)
S_b = bolt stress, psi (MPa)

(15) C_x is the fillet weld length. For unequal lengths, use the smaller leg for C_x.

(16) Factors shown apply to bending. Flexibility factor for torsion equals 0.9.

APPENDIX E: ASME III NC/ND-3600 SUSTAINED STRESS EQUATIONS

NC-3640 Pressure Design of Piping Products

$$t_m = \frac{P \times D_o}{2 \times (S + P \times y)} + A$$

t_m = minimum required wall thickness, in. (mm). If pipe is ordered by its nominal wall thickness, the manufacturing tolerance on wall thickness must be taken into account. After the minimum pipe wall thickness t_m is determined, this minimum thickness shall be increased by an amount sufficient to provide the manufacturing tolerance allowed in the applicable pipe specification or required by the process. The next heavier commercial wall thickness shall then be selected from standard thickness schedules such as contained in ANSI B36.10M or from manufacturers' schedules for other than standard thicknesses

P = internal Design Pressure, psi (MPa)

D_o = outside diameter of pipe, in. (mm). For design calculations, the outside diameter of pipe as given in tables of standards and specifications shall be used in obtaining the value of t_m. When calculating the allowable pressure of pipe on hand or in stock, the actual measured outside diameter and actual measured minimum wall thickness at the thinner end of the pipe may be used to calculate this pressure.

S = maximum allowable stress for the material at the Design Temperature, psi (MPa) (Section II, Part D, Subpart 1, Tables 1A and 1B)

A = an additional thickness, in. (mm): *(a)* to compensate for material removed or wall thinning due to threading or grooving required to make a mechanical joint. The values of *A* listed in Table NC-3641.1 (a)-1 are minimum values for material removed in threading. *(b)* to provide for mechanical strength of the pipe. Small diameter, thin wall pipe or tubing is susceptible to mechanical damage due to erection, operation and maintenance procedures.

Accordingly, appropriate means must be employed to protect such piping against these types of loads if they are not considered as Design Loads. Increased wall thickness is one way of contributing to resistance against mechanical damage. *(c)* to provide for corrosion or erosion. Since corrosion and erosion vary widely from installation to installation, it is the responsibility of designers to determine the proper amounts which must be added for either or both of these conditions.

NC-3652 Consideration of Design Conditions

The effects of pressure, weight and other sustained mechanical loads must meet the requirements of Eq. (8):

$$B_1 \times \frac{P \times D}{2 \times e_n} + B_2 \times \frac{M_A}{Z} \le 1.5 \times S_h \qquad (8)$$

B_1, B_2 = primary stress indices for the specific product under investigation [Fig. NC-3673.2(b)-1]

P = internal Design Pressure, psi (MPa)

Do = outside diameter of pipe, in. (mm)

tn = nominal wall thickness, in. (mm)

MA = resultant moment loading on cross section due to weight and other sustained loads, in.-lb (N·m) (NC-3653.3)

Z = section modulus of pipe, in.^{3} (mm^3)

Sh = basic material allowable stress at Design Temperature, psi (MPa)

NC 3672.2 Basic Assumptions and Requirements

(d) Stress intensification factors are identified herein by i. The definition of a stress intensification factor is based on fatigue bend testing of mild carbon steel fittings and is:

$$iS = 245{,}000\ N^{-0.2}$$

where

S = amplitude of the applied bending stess at the point of failure, psi (MPa)

N = number of cycles to failure

i = stress intensification factor = ratio of the bending moment producing fatigue in a given number of cycles in a straight pipe with a girth butt weld to that producing failure in the same number of cycles in the fitting or joint under consideration.

(e) For piping products or joints not listed in Fig. NC-3673.2(b)-1, flexibility or stress intensification factors shall be established by experimental or analytical means.

(f) Experimental determination of flexibility factors shall be in accordance with Appendix II, II-1900. Experimental determination of stress intensification factors shall be in accordance with Appendix II, II-2000.

(g) Analytical determination of flexibility factors shall be consistent with the definition above.

(h) Analytical determination of stress intensification factors may be based on the empirical relationship

$$i = C2 \times K2\ /2, \text{ but not less than } 1.0$$

where C2 and K2 are stress indices for Class 1 piping products or joints from NB-3681(a)-1, or are determined as explained below.

Analytical determination of stress intensification factors shall be correlated with experimental fatigue results. Experimental correlation may be with new test data or with test data from similar products or joints reported in literature. Finite element analyses or other stress analysis methods may be used to determine C2; however, tests or established stress concentration factor data should then be used to determine K2.

(i) For certain piping products or joints the stress intensification factor may vary depending on the direction of the applied moment, such as in an elbow or branch connection. For these cases, the stress intensification factor used in Eqs. (10), (10a) and (11) of NC-3653.2 shall be the maximum stress intensification factor for all loading directions as determined in accordance with (f) or (h) above.

(j) Stress intensification factors determined in accordance with (f) above shall be documented in accordance with Appendix II, II-2050. The test report may be included and certified with the Design Report (NCA-3551.1 and NCA-3555) for the individual piping system or a separate report furnished (II-2050).

(k) Stress intensification factors determined in accordance with (h) above shall be documented in a report with sufficient detail to permit independent review. The review shall be performed by an engineer competent in the applicable field of design in accordance with Appendix XXIII. The report shall be included and certified as part of the design report for the piping system (NCA-3551.1 and NCA-3555).

ASME III NC-3600

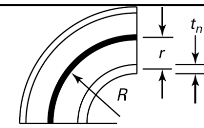
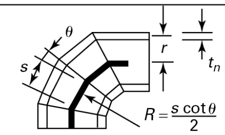
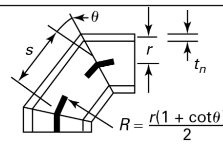
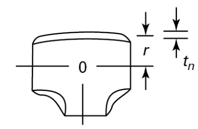
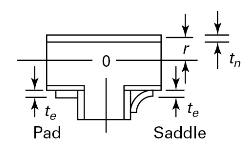
	Primary Stress Index					
Description	B_1	B_2	Flexibility Characteristic h	Flexibility Factor k	Stress Intensification Factor i	Sketch
Welding elbow or pipe bend [Notes (4) and (5)]	$0.4\,h - 0.1 \le 0.5$ and > 0	$\dfrac{1.30}{h^{2/3}}$	$\dfrac{t_n R}{r^2}$	$\dfrac{1.65}{h}$	$\dfrac{0.9}{h^{2/3}}$	
Closely spaced miter bend [Note (4)] $s < r\,(1 + \tan\theta)$	[Note (6)]	[Note (6)]	$\dfrac{s t_n \cot\theta}{2r^2}$	$\dfrac{1.52}{h^{5/6}}$	$\dfrac{0.9}{h^{2/3}}$	
Widely spaced miter bend [Notes (4) and (7)] $s \ge r\,(1 + \tan\theta)$	[Note (6)]	[Note (6)]	$\dfrac{t_n\,(1 + \cot\theta)}{2r}$	$\dfrac{1.52}{h^{5/6}}$	$\dfrac{0.9}{h^{2/3}}$	
Welding tee per ANSI B16.9 [Note (8)]	0.5	Branch end: $B_{2b} = 0.4\left(\dfrac{r}{t_n}\right)^{2/3}$ Run end: $B_{2r} = 0.5\left(\dfrac{r}{t_n}\right)^{2/3}$	$\dfrac{4.4\,t_n}{r}$	1	$\dfrac{0.9}{h^{2/3}}$ For branch leg of a reduced outlet, use $\dfrac{0.9}{h^{2/3}}\left(\dfrac{T'_b}{T_r}\right)$	
Reinforced fabricated tee [Notes (8)–(10)]	0.5	[Note (6)]	$\dfrac{\left(t_n + \dfrac{t_e}{2}\right)^{5/2}}{r\,(t_n)^{2/3}}$	1	$\dfrac{0.9}{h^{2/3}} \ge 2.1$ For branch leg of a reduced outlet, use $\dfrac{0.9}{h^{2/3}}\left(\dfrac{T'_b}{T_r}\right) \ge 2.1$	

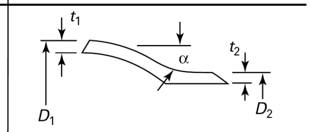
FIG. NC-3673.2(b)-1 STRESS INDICES, FLEXIBILITY, AND STRESS INTENSIFICATION FACTORS [NOTES (1), (2), AND (3)]

ASME III NC-3600

Description	Primary Stress Index		Flexibility Factor k	Stress Intensification Factors i	Sketch
	B_1	B_2			
Branch connection or unreinforced fabricated tee [Notes (8), (10), and (11)]	0.5	Branch leg: for $(r'_m/R_m) \le 0.9$ $B_{2b} = 0.75\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right)^{1/2}\left(\frac{T'_b}{T_r}\right)\left(\frac{r'_m}{r_p}\right)$ for $(r'_m/R_m) = 1.0$ $B_{2b} = 0.45\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{r_p}\right)$ for $0.9 < (r'_m/R_m) < 1.0$, use linear interpolation Run legs: $B_{2r} = 0.9\left(\frac{r'_m}{t_b}\right)^{1/4}$	1	Branch leg: for $(r'_m/R_m) \le 0.9$ $i_b = 1.5\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right)^{1/2}\left(\frac{T'_b}{T_r}\right)\left(\frac{r'_m}{r_p}\right) \ge 1.5$ for $(r'_m/R_m) = 1.0$ $i_b = 0.9\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{r_p}\right) \ge 1.5$ for $0.9 < (r'_m/R_m) < 1.0$, use linear interpolation Run legs: $i_r = 0.8\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right) \ge 2.1$	Fig. NC-3673.2(b)-2
Fillet welded and partial penetration welded branch connections [Notes (8), (10), and (12)]	0.5	Branch leg: $B_{2b} = 2.25\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right)^{1/2}\left(\frac{T'_b}{T_r}\right)\left(\frac{r'_m}{r_p}\right) \ge 1.5$ Run legs: $B_{2r} = 1.3\left(\frac{r'_m}{t_b}\right)^{1/4} \ge 1.5$	1	Branch leg: $i_b = 4.5\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right)^{1/2}\left(\frac{T'_b}{T_r}\right)\left(\frac{r'_m}{r_p}\right) \ge 3.0$ Run legs: $i_r = 0.8\left(\frac{R_m}{T_r}\right)^{2/3}\left(\frac{r'_m}{R_m}\right) \ge 2.1$	Fig. NC-3643.2(b)-2
Girth butt weld	0.5	1.0	1	1.0	
Circumferential fillet welded or socket welded joints [Note (13)]	$0.75\left(\frac{t_n}{C_x}\right) \ge 0.5$	$1.5\left(\frac{t_n}{C_x}\right)$	1	For $C_x \ge 1.09t_n$ $i = 1.3$ For $C_x < 1.09t_n$ $i = 2.1(t_n/C_x) \ge 1.3$	Fig. NC-4427-1 sketches (c-1), (c-2), and (c-3)
Brazed joint	[Note (6)]	[Note (6)]	1	2.1	Fig. NC-4511-1
30 deg tapered transition (ANSI B16.25) $t_n < 0.237$ in.	0.5	1.0	1	*(U.S. Customary Units)* $1.3 + 0.0036\frac{D_o}{t_n} + 0.113/t_n \le 1.9$ *(SI Units)* $1.3 + 0.0036\frac{D_o}{t_n} + 2.87/t_n \le 1.9$	
30 deg tapered transition (ANSI B16.25) $t_n \ge 0.237$ in.	0.5	1.0	1	$1.3 + 0.0036\ D_o/t_n \le 1.9$	

FIG. NC-3673.2(b)-1 STRESS INDICES, FLEXIBILITY, AND STRESS INTENSIFICATION FACTORS [NOTES (1), (2), AND (3)] (CONT'D)

ASME III NC-3600

Description	Primary Stress Index		Flexibility Factor k	Stress Intensification Factors i	Sketch
	B_1	B_2			
Concentric and ecentric reducers (ANSI B16.9) [Note (14)]	0.5 for $\alpha \le 30$ deg 1.0 for 30 deg $< \alpha \le 60$ deg	1.0	1	$0.5 + 0.01\,\alpha \left(\frac{D_2}{t_2}\right)^{1/2} \le 2.0$	
Threaded pipe joint or threaded flange	[Note (6)]	[Note (6)]	1	2.3	
Corrugated straight pipe or corrugated or creased bend [Note (15)]	[Note (6)]	[Note (6)]	5	2.5	

NOTES TO FIG. NC-3673.2(b)-1

(1) The following nomenclature applies:

D_o = nominal outside diameter, in. (mm)
r = mean radius of pipe, in. (mm) (matching pipe for tees and elbows)
r'_m = mean radius of branch pipe, in. (mm)
R = nominal bend radius of elbow or pipe bend, in. (mm)
R_m = mean radius of run pipe, in. (mm)
θ = one-half angle between adjacent miter axes, deg
s = miter spacing at center line, in. (mm)
t_b = thickness in reinforcement zone of branch, in. (mm)
t_e = pad or saddle thickness, in. (mm)
t_n = nominal wall thickness of pipe, in. (mm) [matching pipe for tees and elbows, see Note (5)]
T'_b = nominal wall thickness of branch pipe, in. (mm)
T_r = nominal wall thickness of run pipe, in. (mm)

For Figs. NC-3673.2(b)-2(a) and (b):

$t_b = T_b$ if $L_1 \ge 0.5(2r'_m T_b)^{1/2}$
$= T'_b$ if $L_1 < 0.5(2r'_m T_b)^{1/2}$

For Fig. NC-3673.2(b)-2(c):

$t_b = T'_b + (2/3)y$ if $\theta \le 30$ deg
$= T'_b + 0.385L_1$ if $\theta > 30$ deg

For Fig. NC-3673-2(b)–2(d):

$t_b = T'_b = T_b$

For branch connection nomenclature, refer to Figs. NC-3643.2(b)-2 and NC-3673.2(b)-2.

FIG. NC-3673.2(b)-1 STRESS INDICES, FLEXIBILITY, AND STRESS INTENSIFICATION FACTORS [NOTES (1), (2), AND (3)] (CONT'D)

ASME III NC-3600

NOTES TO FIG. NC-3673.2(b)-1 (CONT'D):

(2) The flexibility factors k, stress intensification factors i, and stress indices B_2 apply to moments in any plane for fittings and shall in no case be taken as less than 1.0. Flexibility factors apply over the effective arc length (shown by heavy center lines in the sketches) for curved and miter elbows, and to the intersection point for tees.

(3) Primary stress indices are applicable to $D_o / t_n \leq 50$ and stress intensification factors are applicable to $D_o / t_n \leq 100$.

(4) Where flanges are attached to one or both ends, the values of k and i shall be corrected by the factor c given below.

(a) One end flanged, $c = h^{1/6}$

(b) Both ends flanged, $c = h^{1/3}$

But after such multiplication, values of k and i shall not be taken as less than 1.0.

(5) The designer is cautioned that cast butt welding elbows may have considerably heavier walls than that of the pipe with which they are used. Large errors may be introduced unless the effect of these greater thicknesses is considered.

(6) B_1 and B_2 primary stress indices for these products are in preparation. In the interim, use $B_1 = 0.5$ and $B_2 = 0.75i$. B_2 shall not be less than 1.0.

(7) Also includes single miter joints.

(8) For checking branch leg stress:

$$Z = \pi (r'_m)^2 T'_b$$

For checking run leg stress:

$$Z = \pi (R_m)^2 T_r$$

(9) When $t_e > 1.5 t_n$, $h = 4.05 t_n / r$.

(10) The equation applies only if the following conditions are met:

(a) The reinforcement area requirements of NC-3643 are met.

(b) The axis of the branch pipe is normal to the surface of the run pipe wall.

(c) For branch connections in a pipe, the arc distance measured between the centers of adjacent branches along the surface of the run pipe is not less than three times the sum of their inside radii in the longitudinal direction or not less than two times the sum of their inside radii along the circumference of the run pipe.

(d) The run pipe is a straight pipe.

(11) If an r_2 radius is provided [Fig. NC-3673.2(b)-2] that is not less than the larger of $T_b/2$, $(T'_b + y)/2$ [sketch (c)], or $T_r/2$, then the calculated values of i_b and i_r may be divided by 2, but with $i_b \geq 1.5$ and $i_r \geq 1.5$.

(12) The equations apply only if $r'_m / R_m \leq 0.5$.

(13) In Fig. NC-4427-1(c-1) and (c-2), C_x shall be taken as X_{min} and $C_x \geq 1.25 t_n$. In Fig. NC-4427-1(c-3), $C_x \geq 0.75 t_n$. For unequal leg lengths, use the smaller leg length for C_x.

(14) The equation applies only if the following conditions are met:

(a) Cone angle α does not exceed 60 deg.

(b) The larger of D_1 / t_1 and D_2 / t_2 does not exceed 100.

(c) The wall thickness is not less than t_1 throughout the body of the reducer, except in and immediately adjacent to the cylindrical portion on the small end, where the thickness shall not be less than t_2.

(d) For eccentric reducers, α is the maximum cone angle.

(15) Factors shown apply to bending; flexibility factor for torsion equals 0.9.

FIG. NC-3673.2(b)-1 STRESS INDICES, FLEXIBILITY, AND STRESS INTENSIFICATION FACTORS [NOTES (1), (2), AND (3)] (CONT'D)

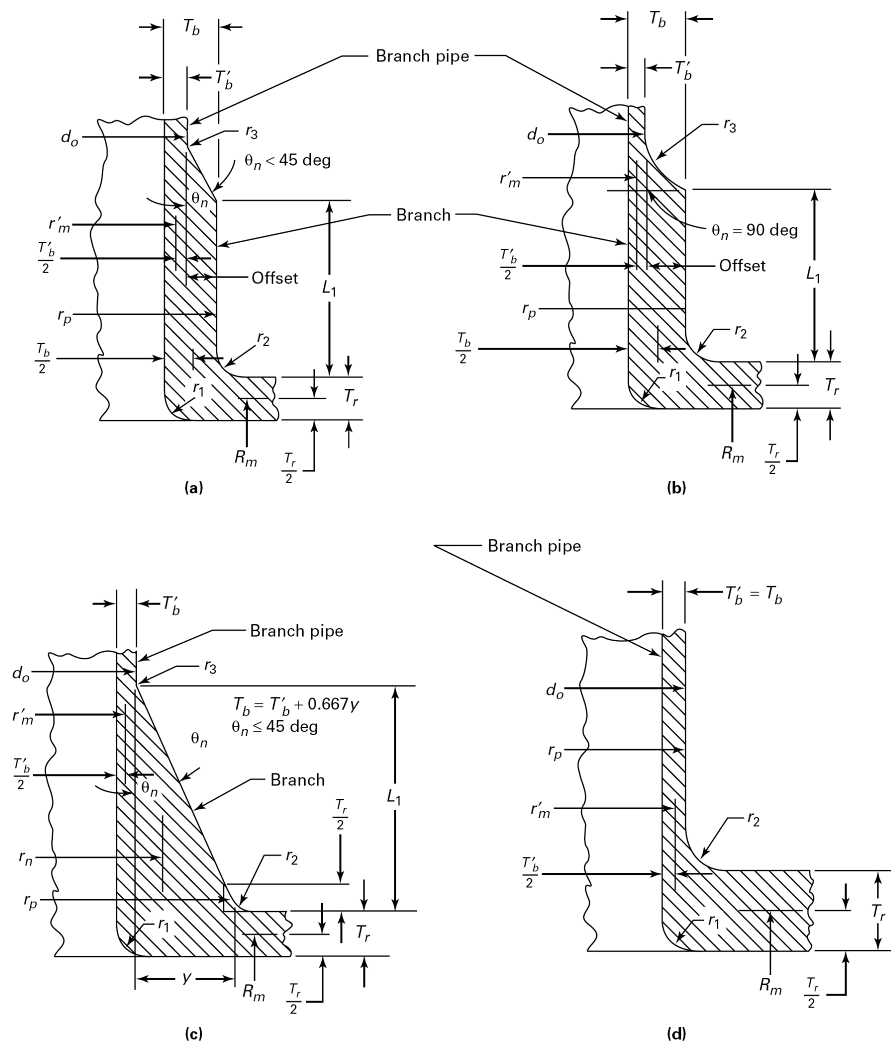
ASME III NB-3600

TABLE NB-3681(a)-1
STRESS INDICES FOR USE WITH EQUATIONS IN NB-3650

Piping Products and Joints [Note (2)]	B_1	C_1 [Note (3)]	K_1 [Note (3)]	B_2	C_2 [Note (3)]	K_2 [Note (3)]	C_3	C'_3	K_3 [Note (3)]	Notes
	Applicable for $D_o/t \le 100$ for C or K Indices and $D_o/t \le 50$ for B Indices									
	Internal Pressure [Note (1)]			Moment Loading [Note (1)]			Thermal Loading			
Straight pipe, remote from welds or other discontinuities	0.5	1.0	1.0	1.0	1.0	1.0	1.0	...	1.0	(4)
Longitudinal butt welds in straight pipe										
(a) flush	0.5	1.0	1.1	1.0	1.0	1.1	1.0	...	1.1	(5)
(b) as-welded $t > 3/16$ in. (5 mm)	0.5	1.1	1.2	1.0	1.2	1.3	1.0	...	1.2	(5)
(c) as-welded $t \le 3/16$ in. (5 mm)	0.5	1.4	2.5	1.0	1.2	1.3	1.0	...	1.2	(5)
Girth butt welds between nominally identical wall thickness items										
(a) flush	0.5	1.0	1.1	1.0	1.0	1.1	0.60	0.50	1.1	(6)
(b) as-welded	0.5	1.0	1.2	1.0	...	1.8	0.60	0.50	1.7	(6)
Girth fillet weld to socket weld, fittings, socket weld valves, slip-on or socket welding flanges	...	...	3.0	...	...	2.0	2.0	1.0	3.0	(7)
NB-4250 Transitions										
(a) flush	0.5	...	1.1	1.0	...	1.1	...	1.0	1.1	(8)
(b) as-welded	0.5	...	1.2	1.0	...	1.8	...	1.0	1.7	(8)
Transitions within a 1:3 slope envelope										
(a) flush	0.5	...	1.2	1.0	...	1.1	...	0.60	1.1	(9)
(b) as-welded	0.5	...	1.2	1.0	...	1.8	...	0.60	1.7	(9)
Butt welding reducers per ASME B16.9 or MSS SP-87	...	...	...	1.0	...	...	1.0	0.5	1.0	(10)
Curved pipe or butt welding elbows	...	...	1.0	...	...	1.0	1.0	0.5	1.0	(11)
Branch connections per NB-3643	0.5	...	2.0	...	...	...	1.8	1.0	1.7	(12)
Butt welding tees	0.5	1.5	4.0	...	...	...	1.0	0.5	1.0	(13)

ASME III NC-3600

2004 SECTION III, DIVISION 1 — NC



GENERAL NOTES:

(a) T_b, θ, r_1, r_2, r_3, r_p, and y are defined in this figure.

(b) Nomenclature

d_o = outside diameter of branch pipe, in. (mm)

r'_m = mean radius of branch pipe, in. (mm)

T'_b = nominal thickness of branch pipes, in. (mm)

R_m = mean radius of run pipe, in. (mm)

T_r = nominal thickness of run pipe, in. (mm)

FIG. NC-3673.2(b)-2 BRANCH CONNECTION NOMENCLATURE

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NOMENCLATURE

A = metal area of the pipe cross section

A_p = metal area of pipe cross section

B_1 = pressure stress index

B_2 = moment primary stress index

C_2 = secondary stress index

c_o and c_i = in-plane and out-of-plane theoretical stress factors

D = outside diameter

d = inside diameter

F = peak stress

F_a = axial force, including force due to internal pressure

I_i = B31.3 in-plane stress index for sustained loads, use 0.75 i_i in the absence of more applicable data

I_o = B31.3 out-of-plane stress index for sustained loads, $0.75 i_o$ in the absence of more applicable data

i_i = in-plane stress intensification factor

i_o = out-of-plane stress intensification factor

K_2 = peak stress index

M_A = moment due to deadweight

M_i = in-plane moment

M_{LM} = limit moment

M_o = out-of-plane moment

M_R = resultant moment

m_i and m_o = in-plane and out-of-plane stress factors

P_b = primary bending stress

P_L = primary local stress

P = pressure

Q = secondary stress

R = axial force

S = allowable stress

S_a = stress due to axial force plus axial stress due to pressure

S_B = bending stress

S_b = bending stress

S_H = hoop stress

S_h = allowable stress at hot temperature

S_L = longitudinal stress

S_P = longitudinal stress due to internal pressure

S_t = torsional stress

S_X = stress due to axial force

t = wall thickness

y = material coefficient

Z = section modulus

β = allowable stress multiplier

σ= stress

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