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INTERNATIONAL PIPELINE DESIGN CODE COMPARISONS AND THE TREND TOWARDS LIMIT STATE DESIGN

J. T. Powers, Raytheon Engineers & Constructors, 13105 Northwest Freeway, Suite 200, Houston, Texas 77040
Patrick Dalton, Raytheon Engineers & Constructors, 13105 Northwest Freeway, Suite 200, Houston, Texas 77040
Alexander Aynbinder, Gulf Interstate Engineering, 1700 West Loop South, Suite 600, Houston, Texas 77027

ABSTRACT

The methods used for calculating the strength requirements for steel pipelines varies around the world. Pipeline codes developed by the many oil and gas producing nations approach these design criteria differently. Historically, the method of allowable stresses has been predominant. Recently, the concept of limit-state design is being considered by code bodies and included in design code philosophy. This article compares codes that are typically used in the design of oil and gas transmission pipelines and their philosophies, including the concepts of allowable stresses versus allowable strains often associated with limit-state design. The comparisons can provide knowledge to engineers about design possibilities based more upon the properties of the materials than has been done in the past. This can result in reduced wall thicknesses and savings in costs. Also included is a discussion of how the nonlinear behavior of materials can be incorporated into new designs and analyses of existing systems.

INTRODUCTION

Most codes used in the design of oil and gas transmission pipelines (hereafter referred to as "design codes") have existed for years, maturing and growing with the oil and gas industries from rather simplistic guidelines to sophisticated design and regulation tools. Most of these codes were based on setting limits on the allowable stresses permitted in the pipe materials. As the quality and reliability of pipe materials improved, designers began examination of more sophisticated design techniques that better described the physical state of the pipe stresses and strains. Now that the oil and gas industries are moving to harsher environments and conditions, these techniques, known as limit-state design, take on even more significance. At ambient temperatures and in unexceptional conditions, there is little difference between the two design methods. However, the designs can be substantially different for pipelines laid in complicated environments (e.g., thaw settlement or frost heave areas) and for pipelines in the Arctic or transporting hot product. Further, we believe that the principles discussed in this paper are as applicable to the re-evaluation of pipelines as to the design of new systems.

This article is concerned with the design of pipelines, not their regulation. For example, although the U.S. Department of Transportation regulates gas transmission pipelines under Title 49, US Code of Federal Regulations, Part 192, this article concentrates on the code used for the design of the pipelines, the U.S. industry standard ASME B31.8. This article does not attempt to review all the legal requirements within the countries covered by the codes listed below, but to summarize the current status of the design codes.

CODES CONSIDERED

This article compares the following Codes:

ASME B31.4-92 U.S. Code: Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohols

ASME B31.8-92 U.S. Code: Gas Transmission and Distribution Piping Systems

CSA Z662-94 Canadian Standard: Oil and Gas Pipeline Systems

BS 8010: Section 2.8: 1992 British Standard: Code of Practice for Pipelines - Section 2.8 Steel for Oil and Gas

BS 8010: Part 3: 1993 British Standard: Code of Practice for Pipelines - Part 3. Pipelines subsea; design, construction and installation

NEN 3650 - 1992 Dutch Standard: Requirements for Steel Pipeline Transportation Systems

CEN/TC 234 WG 3 - 1993 Draft of the European Committee for Standardization: Pipelines for Gas Transmission

SNIP 2.05.06-85 Former Soviet Union Code: Transmission Pipelines

ISO TC 67 SC2 Draft of the International Organization for Standardization: Pipeline Transportation Systems for the Petroleum and Natural Gas Industries

CODES STRUCTURES

The structure of international pipeline codes for the transportation of hydrocarbons is mixed. Some incorporate the design requirements for both liquids and gases into a single code. Within the single code, the type of fluid is categorized and the design based upon fluid and/or location categorization. This is true of the British code BS 8010: Section 2.8: 1992, the Former Soviet Union (FSU) code SNIP 2.05.06-85, CSA Z662

94, and the proposed international code from the International Organization for Standardization (ISO). The ASME codes and the proposed CEN standard for pipelines for gas transmission still maintain separate documents for the transportation of liquids versus gases.

The British have separate codes for onshore and offshore pipelines, where the ASME codes use separate chapters of the same document. ASME B31.8 has already incorporated the offshore chapter into the code for gas pipelines and ASME B31.4 is planning on doing so in the next issue. The Canadian code has a chapter which covers offshore pipelines for both liquids and natural gas. SNIP 2.05.06-85 only covers onshore pipelines. The Danish codes pertain to both onshore and offshore pipelines. The proposed ISO code will cover both onshore and offshore pipelines.

This structure is of interest due to its lack of consistency. While all onshore code systems have their roots in allowable stress design, the offshore codes were quicker to embrace the alternative designs based on strain-limits. However, where the text addressing strain-limits is found varies from code system to code system.

CONSIDERATION OF STRESSES

Historically, most codes for the design of pipeline systems have been based on designing the system so that the pipe's stresses do not exceed certain maximums. For example, the allowable hoop stress arising from pressure must remain below a certain fractional limit of the pipe's yield strength. The maximum allowable combined equivalent stress (e.g., that resultant stress that considers the combination of the hoop stress and the longitudinal stresses resulting from the combined effects of pressure and temperature) must remain below another limit, generally higher than that for the hoop stress alone.

Allowable Hoop Stresses

All international pipeline systems designed to the national codes such as the American ASME B31.4 or B31.8 or the British Code BS 8010, have limits on the allowable hoop stress (circumferential stress), σ_{ha} that results from the system's operating pressure. This limit is generally a fraction of the specified minimum yield strength (*SMYS*), although the FSU code SNIP 2.05.06-85 uses a fraction of the ultimate tensile stress. The fraction multiplier of the SMYS is characteristically called the *design factor*. The allowable stress limit usually does not exceed 72% of *SMYS*, and is dependant upon the type of pipeline system, its proposed location, and the design code used. The recently released issue of ASME B31.8 allows a design factor of 0.8 in limited circumstances for gas pipelines. The new Canadian code uses a constant design factor of 0.8 but multiplies this by another factor (the location factor) that is less than or equal to one.

For most pipelines, the calculation of the hoop stress is based on equations similar in form to Equation 1, although the exact equations vary from code to code.

$$\sigma_h = PD/2t \tag{1}$$

where

P = internal pressure
D = pipe diameter
t = pipe wall thickness

The equations for offshore are similar but also take into account the external pressure on the pipeline. In the ASME, the Canadian, and the Dutch codes, the hoop stress is determined using the design pressure and the pipe's nominal outside diameter. The FSU code SNIP 2.05.06-85 uses the pipe's inside diameter and a nominal wall thickness. The British code for onshore pipelines has two formulas, the more exact Lamé formula that considers the effect of radial stress for thick walled pipes ($D/t \le 20$), and a simplified formula that uses only outside diameter for thinner wall pipes. In the British codes, when $D/t > 20$, the thin wall formula never differs from the more exact thicker wall formula by more than 5%. The ISO code proposes to use the value equal to the nominal outside diameter minus the minimum wall thickness for D. The proposed CEN code uses the mean diameter of the pipe (or that equal to the inside diameter plus twice the minimum wall thickness if the inside diameter is preset) for the value of D.

Most codes use the nominal design wall thickness for the value of t in Equation 1. However, both the proposed ISO and CEN codes will use the minimum wall thickness for this value. The proposed ISO Code and the British Standards state that the nominal wall thickness less any allowance for manufacturing and corrosion shall always be greater than the minimum wall thickness. The CEN code presents a table of absolute minimum wall thicknesses based upon diameter, but does not define explicitly minimum wall thickness.

Table 1 presents a summary of how the various codes address hoop stress.

Allowable Equivalent Stresses

When combined stress analysis is based on traditional elasticity models, the equivalent or combined stress (the maximum allowable stress value due to pressure, other loads, and thermal effects), σ_{eqv} is often permitted to be a higher fraction of SMYS than the design factor associated with the hoop stress; for example, in ASME B31.4 and BS 8010 Section 2.8

(and in B31.8 for offshore gas transmission systems) it may equal 90% of SMYS.

Even for codes using allowable stress criteria, the method used to calculate the equivalent stress varies from code to code. When considering restrained pipelines, BS 8010, the proposed ISO and CEN codes, and the Dutch code all use Von Mises' formula for calculating the equivalent stress as does the offshore chapter of ASME B31.8 [Equation 2]. However, the Canadian code as well as ASME B31.4 use the more traditional maximum shear theory of failure (Tresca's criterion) where the compressive stress adds directly to the hoop stress to increase the equivalent tensile stress available to cause yielding [Equation 3]. The Canadian offshore chapter uses the Von Mises criterion. The Dutch and British codes permit either criterion to be used.

Von Mises Equivalent Stress Criteria

$$\sigma_{eqv} = \sqrt{(\sigma_h^2 + \sigma_l^2 - \sigma_h\sigma_l + 3\tau^2)} \qquad (2)$$

where

σ_h = hoop stress,
σ_l = longitudinal stress (negative in compression)
τ = shear stress,

and

Tresca Equivalent Stress Criteria

$$\sigma_{eqv} = \sigma_h - \sigma_l \quad (\sigma_l \text{ is negative in compression}) \qquad (3)$$

The allowable stress criterion aims to prevent unsafe designs by accounting for a variety of possible occurrences with a minimal number of variables, most notably the design factor. The simplicity of the method is one of its attractions as well as detractions. The design factors tend to be more conservative than necessary, and the methods traditionally have not taken into account actual material properties. The *limit state design* approach considers the loading on the pipeline, estimates the limit states (unacceptable pipeline conditions) that such loading could produce (based on the actual materials behavior) and applies the appropriate safety margins to avoid such limit states (Klever, Palmer, et al., 1994).

Table 2 summarizes how the various codes address the combination of biaxial stresses into an equivalent stress or stress intensity. This table also illustrates that not all codes establish criteria for equivalent stress (i.e., where the biaxial stresses considered are the hoop and longitudinal stresses), especially for unrestrained sections of pipelines. For example, the US and Canadian Codes have limits for a different combination of stresses that occur in pipelines without substantial axial restraint. These codes limit the expansion stresses due to thermal effects. The expansion stress combines the bending and torsional stresses. These codes limit not only the expansion stress, but also other stress combinations, such as a) the longitudinal pressure stress and the total bending stress due to sustained force and wind loading (in the Canadian code), b) the longitudinal stresses from pressure and sustained external loads as well as from pressure, sustained external loads, and occasional loads (in the case of ASME B31,4), and c) the longitudinal stresses i] from pressure, ii] from sustained external loads, and iii] from pressure, sustained external loads, and occasional loads (in the case of ASME B31.8).

LIMIT STATE DESIGN OF PIPELINES

As the need and opportunity for pipelines to be operated at higher temperatures and in more exotic locations, the limitations of allowable stress designs have become clear and engineers and code writing committees are reevaluating these methods, in part based on the following considerations. The hoop stress criterion can always be satisfied by increasing wall thickness. However, for restrained pipelines, because the axial compressive stress is partly determined by temperature, beyond a certain temperature the wall thickness must be increased (Klever, Palmer, et al., 1994 and Aynbinder, Powers, et al., 1995) so that the equivalent stress remains below the allowable maximum. In fact, satisfying the equivalent stress criterion at high temperature may not be possible no matter the wall thickness chosen (Klever, Palmer, et al., 1994).

The trend of pipeline codes is to permit designs based upon limit-state designs. The restriction on an allowable stress for the hoop stress readily lends itself to a "burst" limit state. In the design of pipelines, a strain-limit criterion is increasingly being substituted for the equivalent stress criterion. Also, where allowable stress codes generally consider a material's properties to be linear (i.e., the relationship between stress and strain is constant), strain-limit codes generally support calculations that consider the materials' actual, nonlinear behavior.

The pipeline codes generally typify the limit states into two categories. The *Ultimate Limit States* are those where the pipeline has, in one way or another, failed, e.g., leaking, rupture, or burst. The *Serviceability Limit States* are those where one of the operators' requirements is no longer met, such as the pipe has changed shape so that it is no longer inspectable, or, for offshore pipelines, there has been moderate upheaval buckling that makes the pipe vulnerable to anchors or trawlgear (Klever, Palmer, et al., 1994 and Nielsen, Bryndum, et al., 1994).

Codes that now permit alternative strain-limited design include ASME B31.8-92 Offshore Chapter, BS 8010: Part 3: 1993, NEN 3650, the draft of CEN/TC 234 WG 3 - 1993, and the draft of ISO's pipeline code.

In the application of strain limited design, it is more typical for the pipe steel's actual properties to be considered. Although it is more typical for elastic-plastic theories to be applied to strain-limited design, there is no reason they cannot be applied to the codes that are based on allowable stress.

In strain-based design, the wall thickness is still determined based on the hoop stress criterion. However, the equivalent stress criterion is replaced with the strain-limit criterion. This results in larger acceptable temperature differentials without increases in pipe wall thicknesses. This can result in substantial savings in steel, transportation, and welding costs.

MATERIALS PROPERTIES

For a variety of reasons, not the least being simplicity, pipeline design according to allowable stress codes such as ASME B31.4 and B31.8 has generally used linear elastic material properties. However, because the allowable value of the equivalent stress for a pipeline system designed according to these codes can exceed the steel's actual proportionality limit, there is no reason not to consider the nonlinear, elastic-plastic property of the material in pipeline stress analysis. The former Soviet Union transmission pipeline code, SNIP 2.05.06-85 takes these considerations one step further, requiring the designer to consider the nonlinear characteristics of the steel pipe when performing pipeline stress analysis.

Experience has shown that the proportional limit (the linear relationship between the stress and strain) for steel used in pipe fabrication is very close to the value $0.7SMYS$. If the equivalent stress is $0.9SMYS$, the maximum allowed by ASME B31.4 and BS 8010: Section 2.8, then a linear relationship between stress and strain would give an elastic strain of approximately 0.19% for Grade X60 steel. The actual strain produced by a stress of $0.90SMYS$ is closer to 0.28%, a difference of 1.5 times. If the stress is actually equal to *SMYS* (defined by API SPEC 5L (1995) as a total strain of 0.5%) the difference increases even further, approaching twice that predicted using a linear model.

Remembering that when the stress is increased beyond the proportional limit, a nonlinear relationship between the stress and strain begins, we note that in practice, the actual strains in pipes subject to allowable operating conditions are between 0.20 and 0.45%. Thus, consideration of the nonlinear mechanical properties of the steel is very important in pipeline stress analysis and may be incorporated in pipeline design as suggested by Palmer back in 1991.

Design using elastic-plastic theory begins with the choice of a function to represent the stress-strain diagram in the area of small elastic-plastic deformation and then to use this diagram as the basis for the stress analysis (Aynbinder, Powers, et al., 1995).

By using nonlinear material considerations, a pipeline design method is available (Aynbinder, Powers, et al., 1995) that can result in thinner walls for pipelines transporting hot or temperate products in the Arctic and hot products in other regions. Previous papers (Klever, Palmer, et al., 1994 and Aynbinder, Powers, et al., 1995) have shown how the change in wall thickness with an increasing positive temperature differential differs markedly whether linear and nonlinear solutions are used. These methods can result in larger acceptable temperature differentials when applied under allowable stress codes.

CONCLUSIONS

The major pipeline codes in the world today are inconsistent in scope and the manner in which they handle stress criteria and design limitations. The trend in pipeline codes is consolidation to fewer codes and more detailed analysis based on limit-state design while still permitting simplified designs based on allowable stresses in certain circumstances. The interest in the limit-state design approach has renewed interest in designs that consider the elastic-plastic characteristics of the pipe steel. The renewed interest in elastic-plastic design can be applied to allowable stress codes as well as the limit-state design codes.

By using nonlinear, elastic-plastic considerations, a pipeline design method is available (Aynbinder, Powers, et al., 1995) that can result in thinner walls for pipelines transporting hot or temperate products in the Arctic and hot products in other regions. If the product is gas, according to the method in Reference 3, the temperature to which gas must be chilled in Arctic regions can be increased, reducing gas-chilling loads and costs. The elastic plastic designs, already accepted in limit-state design approaches, can result in lower capital, construction, and operating costs.

REFERENCES

American Petroleum Institute, 1995, SPEC 5L-95, "Specification for Line Pipe."

Aynbinder, A., Powers, J., and Dalton, P., 1995, "Pipeline Design Method Can ReduceWall Thickness, Costs," *Oil and Gas Journal*, February 20, pp. 70-77.

Klever, Frans J., Palmer, Andrew C., and Kyriakides, Stelios, 1994, "Limit-State Design of High Temperature Pipelines," *1994 OMAE - Volume V, Pipeline Technology*., pp. 77-95.

Nielsen, Niels-Jorgen Rishoj, Bryndum, Mads B., and Braestrup, Mikael W., 1994, "Marine Pipeline Stability: The Danish Code Approach," *1994 OMAE - Volume V, Pipeline Technology*., pp. 257-265.

Palmer, A., 1991, "Limit State Design of Pipelines and Its Incorporation in Design Codes," *The Society of Naval Architects and Marine Engineers Design Criteria and Codes Symposium.*

Table 1. Codes comparisons. Hoop stress due to pressure

Code	Hoop Stress Equation(s)	Allowable hoop stress	
		bases	Factors considered
ASME B31.8	$\sigma_h = PD/2t$ D = outside t = nominal	SMYS	design factor ($0.4 \leq F \leq 0.8$) based on location longitudinal joint factor temperature derating factor
ASME B31.4	$\sigma_h = PD/2t$ D = outside t = nominal	SMYS	design factor is 0.72 weld joint factor
CSA-Z662-94 Oil & Gas	$\sigma_h = PD/2t$ D = outside t = nominal	SMYS	design factor location facxtor ($0.50 \leq L \leq 1.0$) joint factor temperature derating factor
BS 8010: Section 2.8 Onshore	$\sigma_h = PD/2t$ $(D/t>20)$, or Lamé's $\sigma_h = P(D^2+D_i^2)/(D^2-D_i^2)$ for $(D/t \leq 20)$ D = outside D_i = inside t = minimum	SMYS	design factor is 0.72 for most liquids, but is always in the range $0.30 \leq F \leq 0.72$ "The nominal wall thickness . . . minus the specified manufacturing tolerance on wall thickness should not be less than the design thickness . . . used in the calculation . . . " § 2.8.3.1
BS 8010: Part 3 Offshore	$\sigma_h = (P_i - P_o)D/2t$ for $(D/t>20)$, or Lamé's $\sigma_h = (P_i - P_o)\dfrac{(D^2+D_i^2)}{(D^2-D_i^2)}$ for $(D/t \leq 20)$ D = outside D_i = inside t = minimum	SMYS	design factor is 0.72 for seabed pipelines
CEN/TC 234 WG 3	σ_h = $PD/2t$ D = mean t = minimum	SMYS	utilization factor is either 0.67 or 0.72 for underground sections and stations
NEN 3650	σ_h = $PD/2t$ D = outside t = nominal	SMYS	0.72 for field sections and pipeline corridors, range for other areas is ($0.55 \leq F \leq 0.66$)
SNIP 2.05-06-85	σ_h = $PD/2t$ D = inside t = nominal	SMUS	location factor material dependant reliability coefficients safety factor
ISO TC 67 SC2	σ_h = $PD/2t$ D = nominal OD - t_{min} t = minimum	SMYS	design factor ($0.43 \leq F \leq 0.83$) based on location and fluid category

Table 2. Codes comparison. Equivalent stresses criteria.

Code	Equation(s) Used	bases	Factor	Limit Comments (Allowable Equivalent Stress)
ASME B31.8(Onshore)				Not explicitly addressed, no limit given
ASME B31.8 Offshore	Tresca or Von Mises	SMYS	0.90	"... the **combined stress** shall not exceed the value given by. . . (Tresca combined stress condition) ...Alternatively...(Von Mises ombine stress condition) ... may be used for limiting longitudinal stress values. . ."
				"A842.23. Alternate design for strain. In situations where the pipeline experiences a predictable noncyclic displacement of its support... the longitudinal & combined stress limits need not be used . . . "
ASME B31.4 (Restrained Pipelines)	Tresca	SMYS	0.90	"according to the commonly used maximum shear theory of failure, this compressive stress adds directly . . . As specified. . . the equivalent tensile stress shall not be allowed to exceed 90%. . ."
CSA-Z662-94 (onshore chapter)	Tresca	SMYS	0.90	Equivalent stresses due to pressure and temperature differential
			1.00	Equivalent stresses due to pressure and temperature differential and bending moment
BS 8010 : Section 2.8: 1992	Von Mises	SMYS	0.90	"The equivalent stress should not exceed the allowable equivalent stress given in . . .The equivalent stress should be calculated using the Von Mises equivalent stress criteria. . ."
BS 8010 : Part 3 : 1993	Von Mises	SMYS	0.96	"Equivalent stresses resulting from functional and environmental or accidental loads for seabed pipelines"
				"The limit on equivalent stress recommended in 4.2.5.4 may be replaced by a limit on allowable strain provide that all [four] of the ...conditions are met."
CEN/TC 234 WG 3	Tresca or Von Mises	SMYS	0.72	If the analysis is based on elasticity theory...The maximum **stress resultant** shall not exceed . . . A more sophisticated analysis may be carried out using elastic-plastic or plastic analysis.
NEN 3650	Tresca or (Huber-Hencky) Von Mises	SMYS, SMUS	min. (SMYS, 0.75SMUS)	There are additional limit values for Strain, Alternating yield, fatigue, deformation, progressive plastic failure (for pipelines where the temp range is > 150 C), and displacement
SNIP 2.05.06-85 factor ranges $0.6 \le m \le 0.9$ $1.34 \le k_1 \le 1.55$ $1.1 \le k_2 \le 1.2$ $1.0 \le k_2 \le 1.15$	Von Mises (buried)	SMUS	$m/k_1 k_n$	Considers equivalent stress (using plastic analysis) due to factored loads in combination.
		SMYS	$m/(0.9)k_n$	Considers equivalent stress (using elastic analysis) due to normative loads in combination.
	Von Mises (above ground)	SMYS	$m/k_2 k_n$	Considers equivalent stress (using plastic analysis) due to factored loads in combination.
				The fraction coefficients consider: Location/category (m), pipe materials (k_1,k_2), and a reliability coefficient for pipeline characteristics: for gas it depends on pressure and diameter, for oil it is diameter-dependent (k_n)
ISO TC 67 SC2	Von Mises	SMYS	1.00	Construction, environmental, and accidental load combinations
			0.90	Functional and environmental load combinations
			1.00	Functional, environmental, and accidental load combinations
				This code states that above criteria for allowable equivalent stress may be replaced in certain code-defined conditions by a permissible strain criterion.