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STRAIN-BASED PIPELINE DESIGN CRITERIA REVIEW

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ABSTRACT

The new Canadian limit states pipeline design standard (CSA Z662-96, Appendix C - Limit States Design) incorporates deformation or strain-based design criteria to prevent pipe rupture and or buckling and limit ovality due to bending. These criteria are different and in some instances, much more conservative than those contained in the Canadian offshore pipeline design standard (chapter 11 of CSA Z662-96) and similar standards used in other countries. This study was completed to review the ovality, buckling (including wrinkling) and rupture criteria included in current Canadian pipeline design standards (CSA Z662-96) and define its basic differences with respect to other standards.

The deformation or strain based design criteria formulations in Z662 are compared with those contained in design standards, industry association recommendations and classification society rules from Norway, Britain, Germany, Australia and the USA to illustrate their differences and relative levels of conservatism. In addition, current and on-going research efforts were reviewed to identify the state-of-the-art in pipeline strain-based design, since this research could form the basis for future amendments to existing pipeline design standards.

Based on the findings of this review, recommended changes to the limit states pipeline design formulation are given to better reflect the strain-based (non-linear or post-yield) design and assessment approaches included in the Canadian offshore or foreign pipeline design approaches. In addition, an analytical basis for pipeline ovality and buckling design criteria are recommended.

INTRODUCTION

Existing design standards, including the Canadian Standards Association Oil and Gas Pipeline Systems standard (CSA Z662-96), perform structural design based primarily on yield strength based criteria. This approach to design was considered acceptable for steels with a well defined yield point and a significant amount of post yield ductility and strength. The behavior of these steels could be reasonably modeled as an elastic-perfectly plastic material, similar to that shown in Figure 1(a).

Pipeline design criteria and material specifications based almost solely on steel yield strength drove the steel production industry to develop alloying and or controlled rolling processes capable of supplying higher yield strength steels. As a result, modern steels display stress-strain behaviors similar to those shown in Figure 1(b), which are markedly different than their predecessors (Figure 1(a)). The mechanical behavior feature which differentiates the modern steels from their predecessors is the lack of a well defined yield point. The lack of a yield point has necessitated the use of fictitious yield point measures (i.e. 0.2% offset or 0.5% strain under load).

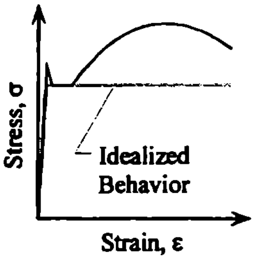

Figure 1(a): Yield Point Definition

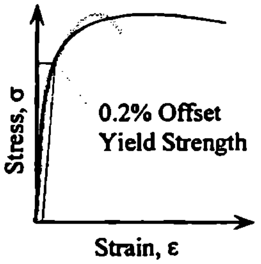

Figure 1(b): Modern Steel Behavior

A drive towards more economic designs and a better understanding of the pipe materials led to the development of design criteria based on inelastic (post yield) failure. The implementation of post yield stress design approaches has been accomplished in the form of a delayed yield type criteria. While this design approach accounts for the observed difference between a pipe's actual failure stress and the material's yield strength, it does not acknowledge the difference between material ductilities.

The two materials, whose stress strain behaviors are shown in Figure 1(b), both have the same yield and ultimate strengths and thus flow stresses, although they display quite different post-yield behaviors. The difference between these two materials is their ductility which can be represented by their uniform strains (strain at the maximum load, UTS) or their work hardening characteristics (load carrying capacity increase per unit plastic strain).

An acknowledgment of the need to ensure ductility and to better distinguish between steels with differing work hardening behaviors, has led to the inclusion of additional design and material specification requirements which consider a material's ductility expressed in terms of minimum material tensile strain at failure (total elongation), maximum yield to tensile ratio and or maximum allowable design strain.

A variety of strain or ductility based design criteria have been developed by researchers and incorporated into design standards. For example, the current draft of the CSA Oil and Gas Pipeline Systems design standard - limit states design requirements (CSA-Z662, Appendix C) and the Norwegian, Det Norske Veritas (DNV) Rules for Submarine Pipelines-1981, both incorporate different strain-based design criteria. In the DNV rules the allowable tensile strain is limited to a maximum of 2%, while, Appendix C of CSA-Z662 limits the tensile strain to 0.5%. The DNV strain limitation is a function of the pipe geometry (diameter and thickness) and strain history, whereas, the Z662 requirement is essentially an arbitrary and conservative value which is constant for all pipe configurations.

Review Scope

The objective of this paper is to review strain-based design limits applicable to pipelines, current research efforts in this area and compare these with the requirements included in the current edition of the Canadian Oil and Gas Pipeline System limit states design requirements (CSA-Z662, Appendix C). In order to evaluate and compare the appropriateness of the strain-based design criteria applied to Canadian pipelines, strain based design criteria research and the design standards listed in Table 1 were reviewed.

Strain or deformation based design criteria are generally presented in terms of design requirements which are intended to preclude the following three limit states: (1) ovality, (2) buckling and, (3) rupture. Pipe wrinkling is viewed as a form of buckling caused by pipe flexural deformation in this review.

The review reported here is limited to the application of these design limit states based on the assumption of a defect-free homogeneous pipe material. It should be noted that although most of the current pipeline design standards are moving towards a limit states format, which would deal explicitly with each of the above limit states. Current workmanship requirements simply restrict the physical manifestations of these limit states.

CSA-Z662 STRAIN-BASED DESIGN CRITERIA

CSA-Z662

The current oil and gas pipeline design criteria (Z662-96) only allows elastic pipeline design. Pipe wall stresses must remain below the minimum specified yield stress of the pipe material. Since elastic strains are generally treated as being directly proportional to elastic stresses, the stress criteria outlined in this standard could be rewritten in terms of strain. The only direct references to strain or deformation limits are given in clause 6.2.3 dealing with maximum allowable cold bend deflection and clause 6.3.3 which limits the maximum allowable dent depth.

The 1.5° maximum allowable cold bend deflection within an axial distance equal to the pipe outside diameter, for pipes with outside diameters greater than 323.9mm, is intended to prevent compressive failures (e.g., buckling, wrinkling or ovality) and implies a maximum allowable nominal strain of 1.31%.

Table 1: Scope of Design Standard Review

Origin	Pipeline	Offshore Pipelines	Materials
Canada	CSA Z662-96 CSA Z662-96 App. C	CSA Z662-96 Section 11	CSA Z245.1-93 CSA Z662-96
Norway		DNV -1982*	DNV -1982*
Britain	BS 8010: Part 1: 1993	BS 8010: Part 3: 1993	BS 8010: Part 2: 1993
Germany		GL - Code III/4 - 1995*	
Australia	AS 2885-1987	AS 1958-1981	AS 2018-1981
USA	ASME PD Vol. 55* ASME PD Vol. 69* API 5L:1991*	API RP 1111-1993*	

* Note: These are rules of practice produced by industry associations and classification societies.

CSA-Z662 Section 11-Offshore Pipelines

In an effort to harmonize the offshore and onshore pipeline design standards, the previously stand alone offshore pipeline design standard was included as Section 11 of CSA-Z662-1994.

The construction and installation requirements (cl. 11.2.4.2.1.1.2) limit the permissible installation strain (elastic plus plastic) in the pipe wall, in any plane of orientation, to a maximum of 0.025 (2.5%). This strain criteria, stated in terms of a principal strain which considers all of the strain components (hoop, longitudinal, shear), is included to permit reel barge pipe laying and considers the extra restraint against buckling afforded by the tension on the line when it is being placed. It is implicit in this requirement that the base material and weld metal are homogeneous and free of any significant flaws. Even though a maximum total strain of 2.5% is permitted, the notes attached to this design criteria clearly indicate that other limit states such as buckling or ovality may control the design of the pipe. In addition, the appropriateness of the pipe base or weld materials for this relatively high strain application must be demonstrated, and the mechanical and geometric effects of the installation process must be considered in the design and analysis of the pipe for other installation and operational limit states.

For typical operational or design loads the design strength criteria are based on an effective stress formulation (cl. 11.2.4.2.3.1) which must be less than an elastic allowable stress (cl. 11.2.4.2.3.3). This effective stress formulation (Hüber, Von Mises and Hencky yield criterion) provides the designer with a rational and effective criterion for evaluating the complex multi-axial stress states associated with pipeline design.

The effects of infrequent, strain controlled loading due to frost heave, subsidence, or earthquake are compared against a 2.5% strain limit (cl. 11.2.4.2.2.4), in any plane of orientation in the pipe wall, less any strain residual from installation. This deformation allowance for infrequent and potentially severe load events allows plasticity when other limit states are not violated and includes the residual strains associated with the installation process. If this design condition is used in an ECA (Engineering Critical Assessment) situation, care should be taken here to include the residual strains from similar previous events which induced plastic deformations. This requirement is necessary since the total permanent deformation a material may sustain is limited and cumulative over the life of the pipe structure. In addition, the effects of repeated high strain loads on the material and geometric properties of the pipe structure should be recognized in the application of subsequent structural analysis.

CSA-Z662 Appendix C - Draft Version

Rupture. The limit states formulation of the Canadian pipeline design standard, Appendix C, allows both elastic (cl. C5.2) and plastic (cl. C5.3) analysis techniques to be used in the design or analysis of pipeline systems. Although both elastic and plastic design are allowed, no material resistance factors are proposed for limit states other than those associated with material yielding. The non-linear stress-strain behavior of pipeline steels are represented by Ramberg-Osgood or a bi-linear material models including temperature de-rating factors.

The limit states formulation precludes pipeline rupture with a strain-based criteria (cl. C6.3.1) limiting the tensile stress due to primary or secondary loads to 70% of a pipe wall or weldment critical tensile strain. The critical tensile strain is taken as 0.75% unless fracture mechanics approaches or physical testing are used to establish a higher critical strain limit taking into account flaws and metallurgical damage in the welds and heat-affected zones. The nominal critical strain limit of 0.75% ensures that the design of pipeline systems remain elastic, unless more detailed means of justifying a higher critical strain are used, by virtue of the fact that a strain limit of 0.0075 × 0.7 ($\phi_\varepsilon\ \varepsilon_t^{crit}$) equals 0.005, the nominal yield strain generally used by industry. Unfortunately, no guidance is given on the extent or size of physical or metallurgical damage which must be considered in what amounts to a damage tolerant design approach. It is not specified whether the critical strain derived from fracture mechanics based analyses is the local (crack tip) or nominal critical strain.

This limit state fails to properly differentiate between longitudinal, hoop and principal strains. For instance the strain limits, based on some preliminary work by FTL and Graville Associates [11] towards the development of a strain-based ligament extension model indicated that the longitudinal or hoop failure strains at defects would be very different and thus should not be assumed to be the same. Therefore, it is suggested that the note indicating that experience gained from reel barge operation ($\varepsilon_t^{max} \le \varepsilon_t^{crit} = 2.5\%$) should only be applied to the longitudinal deformation of "defect-free" pipe systems.

Buckling. The limit state used in Appendix C to preclude local buckling (cl. C6.3.3.2) is a strain-based limit on the longitudinal or hoop compressive strain to 80% of the critical buckling strain. The critical compressive strain capacity of the pipe wall, ε_c^{crit}, may be determined through analytic methods and or physical tests, taking into account internal and external pressure, the effect of line depressurization, initial imperfections, residual stresses and the shape of the material stress-strain curve. When primary loads dominate the behavior, the ultimate longitudinal compressive strain is taken as the strain coincident with the attainment of peak load capacity of the member or may be estimated using the following empirical formula:

$$\varepsilon_c^{crit} = 0.5\frac{t}{D} - 0.0025 + 3000\left(\frac{(p_i - p_e)D}{2tE_s}\right)^2$$

Ovality. The limit state equation used to limit ovality due to bending, Δ_θ, (cl C6.3.3.3) where:

$$\Delta_\theta = 2\left(\frac{D_{max} - D_{min}}{D_{max} + D_{min}}\right) \leq \Delta_\theta^{crit}$$

is a characterization of the greatest acceptable pipe deformation. The critical or limit ovality may be taken as 0.03 or determined through detailed analysis and or physical testing which take into account internal and external pressure, initial imperfections, residual stresses and the shape of the material stress-strain curve. When it can be shown that premature collapse will not occur as a result of excessive deformation, the critical ovality deformation may be increased up to 0.06 or a value derive analytically or experimentally, such that unhindered passage of internal inspection devices is still assured.

COMPARISON OF STRAIN-BASED DESIGN CRITERIA

A review of pipeline design standards from various countries and on-going technical investigations, which may serve as the basis for further code developments, is used to demonstrate the application of strain based failure criteria and highlight areas for improvement in the Canadian pipeline limit states design standard. The discussion is presented in terms of the three primary limit states: ovality, rupture and buckling. It should be noted that while the general trend in code development is towards limit states design, not all of the reviewed standards have been updated to a limit states format and thus will not explicitly handle each limit state.

Ovality

When all of the strain-based ovality criteria are compared, see Table 2, it is noted that design standards limit ovality using one or more of the following three general approaches:

- A general requirement that ovality should not promote structural failure or affect pipeline operation including maintenance and inspection
- Limit the maximum ovality to a fixed percentage
- Provide a means of calculating ovality and relating its effects to other ultimate limit states (i.e. buckling, yielding) or serviceability limit states (i.e. inspectability or flow restriction).

Table 2: Pipe Ovality Limit Comparison (in percent)

Source	Ref.	Pipe OD [mm]				
		323.8	353.6	406.4	457	507
CSA Z662	[1]	General Integrity / Operational Requirement				
CSA Z662 - Sec 11	[1]	General Integrity / Operational Requirement				
CSA Z662 - App. C *	[1]	3.0 (6.0)				
DNV	[3]	2.0				
BSi	[4]	General Integrity / Operational Requirement				
GL	[5]	General Integrity / Operational Requirement				
SAA †	[6,7]	2.5				
API ‡	[8]	6.2	5.5	5.8	5.9	6.1
Murray et. al.¥	[10]	4.3	4.7	5.3	5.9	6.5

* Number in brackets indicates upper bound of behavior if it can be demonstrated that the behavior does not affect pipeline operation or maintenance or promote failure.

† Also refers to API Limits

‡ Inferred from minimum cold bend radius using a 10mm wall thickness and the BSi ovality formulation.

¥ Ovality which produces the yield level hoop stresses in the pipe, assuming a yield strength of 480MPa (70ksi) and a wall thickness of 10mm.

Most standards, including Z662, incorporate the general requirement that the designer ensure that ovality does not cause operational problems or promote failure. This approach is acceptable in that it leaves the means of evaluating the extent and effects of ovality up to the user.

Design requirements which limit ovality to a single fixed percentage for all pipes are more conservative for pipes with lower D/t ratios (smaller diameter or thicker walled) or higher strength. Those design standards which currently provide a range of ovality limits consider only pipe diameter as a significant factor influencing ovality and thus do not allow users to optimize their design in terms of wall thickness or material strength.

Only BS8010 includes a means of estimating ovality, but does not indicate the maximum allowable limit. This formulation may be used to relate the minimum bend radius and pipe D/t ratio to the resulting ovality as shown in Figure 2. This figure describes the relationship between pipe geometry, bend radius and the degree of ovality which is produced, but does not help in predicting the interaction between the degree of ovality and the stresses it creates.

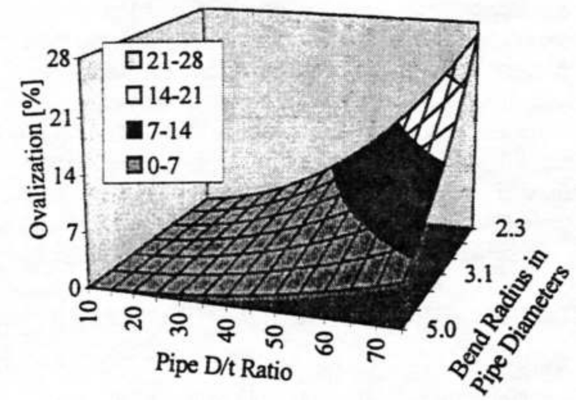

Figure 2: Ovality as a function of
Pipe Minimum Bend Radius and D/t Ratio

The formulation presented by Murray et. al.[10] identifies a means of assessing the hoop stress associated with the ovality process (σ_o) which may be compared to the yield stress (σ_y) to develop a limit state equation of the form:

$$\lambda\sigma_o \leq \phi\,\sigma_y$$

where λ and ϕ are the appropriate partial safety factors. Alternatively, the longitudinal bending strain and hoop ovality strain may be combined to compare with the 2.5% allowable principal strain requirement presented in Appendix C of CSA Z662.

In addition, the degree to which ovality affects other limit states (i.e., buckling, yielding, etc.) should be considered. Based on Walker's [9] work, 30% of the total ovality should be expected to remain after the flexural load is removed from the pipe.

Approaches like those presented above enable the inclusion of ovality as a strength and or stability limit state, but its inclusion would not alleviate the necessity to also incorporate a statement which requires the designer to ensure that pipeline maintenance (internal inspection) is not affected by the degree of pipe ovality.

Rupture.

When all of the strain-based rupture criteria are compared, see **Table 3**, it is noted that design standard rupture limits, with the exception of CSA Z662-Appendix C, take one of the following three general forms:

- No explicit strain limit since the design approach is strictly elastic, therefore, stresses and strains are directly proportional
- Limit the maximum effective or principal strain to a fixed percentage
- Provide individual limits for strains in the hoop and longitudinal directions.

In a general design situation, there is no significant benefit or operational reason for gross section pipe strains in the hoop direction to exceed the yield strain. In comparison, longitudinal strains due to pipe bending either due to installation or in-service events (i.e., unexpected soil movement) may warrant the use of the post yield capacity of the pipe material. Based on this reasoning design standards which permit non-linear design practice imply either an effective or principal strain approach or set individual limits on strains in the hoop and longitudinal directions. When individual limits are set for the hoop and longitudinal strains, the hoop strain is limited to the yield strain, prior to the application of the material partial safety factor, while plasticity is allowed in the longitudinal direction to allow relatively large bending deformations.

When the relatively high bending strains in the longitudinal direction are permitted, attention should be paid to the resulting secondary effects including: ovality, material property changes, promotion of buckling, girth weld deformation leading to ductility concerns and the other affected limit states should consider these effects.

Table 3: Pipe Rupture Strain Limit Comparison

Source	Ref.	Strain Limit
CSA Z662	[1]	No Explicit Limit (Elastic Analysis)
CSA Z662 - Sec 11 *	[1]	2.5% Principal Strain
CSA Z662 - App. C †	[1]	0.53% (2.5%)
DNV ‡	[3]	0.2% (2.0%) Plastic Longitudinal Strains
BSi **	[4]	0.1% Plastic Equivalent Strain
GL ††	[5]	D/t Dependent Longitudinal Strains < 1.0% or < 1.5% for controlled deformation or < 2.0% for local discontinuities
SAA	[6,7]	No Explicit Limit (Elastic Analysis)
API	[8]	No Explicit Limit (Elastic Analysis)
Graville et. al. ‡‡	[11]	$\varepsilon_h^{max} = 0.1838 - 0.1783\ \sigma_y/\sigma_u$

* Applies to installation and or infrequent loads

† Value in brackets is a suggested maximum based on observed pipe behavior which may be used if it is shown that it will not promote failure or interfere with pipeline operation.

‡ 0.2% residual longitudinal strains but allows 2.0% local longitudinal strains.

** reference zero strain level does not include any residual strains from construction, installation or pressure testing. This strain limit is strictly for operating pressures and thermal strains.

†† allows higher longitudinal strain levels for displacement controlled deformations and local strain concentrations.

‡‡ Instability hoop strain due to pipe internal pressure.

Buckling.

When all of the strain-based buckling criteria are compared, see Table 4, it is noted that design standard buckling or wrinkling formulations are expressed in one of the following three general formats:

- No explicit strain limit since the design approach is strictly elastic, therefore, stresses and strains are directly proportional.
- Limit the maximum effective or principal strain to a fixed percentage
- Provide individual limits for strains in the hoop and longitudinal directions.

Since there are so many analytical models predicting the local and beam like buckling behavior of pipe sections, most design standards allow the designer the freedom to select the most appropriate approach. In addition, buckling is a pipe failure mode which is primarily governed by the geometry of the pipe (i.e. D/t ratio) and occurs in the elastic behavior range of the pipe material. For this reason, with the exception of those pipe sections which have low D/t ratios, buckling will be an elastic failure mode which could be modeled with equal validity in terms of the material stress or strain.

Two buckling limit state features which should be of interest are the consideration of initial pipe ovality and direct means of estimating the strain which will initiate wrinkling. The initial ovality consideration in a buckling formulation is of significance if the pipe has previously experienced a flexural load resulting in permanent deformations whether due to installation or an infrequent (unforeseen) load scenario. The residual ovality will reduce the residual compressive strength of the pipe section. The buckling limit state in the British standard includes a minimum initial ovality, to account for pipe out of roundness which corresponds to industry fabrication tolerances.

CONCLUSIONS AND RECOMMENDATIONS

Ovality

Ovality is considered to be primarily a serviceability limit state in that it may restrict the operation and/or inspection (pigging) of the pipeline. A secondary effect of ovality is its potential to promote buckling and or pipe rupture, thus degrading the structural integrity of the pipe.

It is felt that with the understanding of the pipe ovality process afforded by analytical and experimental studies which have produced predictive models, ovality criteria expressed in terms of a fixed percentage for all pipes should be revised. This revision is necessary to acknowledge the influences of pipe geometry, flexural loads or deformations, pipe mechanical properties and initial ovality (out of roundness) on the ovality of a pipe section.

Table 4: Buckling Strain Limit Comparison

Source	Ref.	Strain Limit
CSA Z662	[1]	No explicit limit (elastic analysis)
CSA Z662 - Sec 11	[1]	No explicit limit (elastic analysis)
CSA Z662 - App. H *	[1]	Local buckling & wrinkling
DNV †	[3]	No explicit limit (elastic analysis)
BSi	[4]	Flexural & axial load buckling including ovality
GL	[5]	Same limit as rupture criteria
SAA	[6,7]	No explicit limit (elastic analysis)
API	[8]	No explicit limit (elastic analysis)
Walker	[9]	Analytical function of D/t and initial ovality
Murray et. al.	[10]	Wrinkling strain limit to prevent coating loss
Langner	[12]	Empirical strain formulation in terms of D/t

* Analytical formulation for local buckling and a requirement to preclude wrinkling. May exceed buckling limit with sufficient proof that pipe integrity and serviceability will not be affected.

† Includes interaction formula to consider combined buckling modes. Buckling formulations are included in an appendix as recommended limit states.

The revised ovality criteria could take the form of a limit state equation governing the response of the pipe to various load scenarios. An alternative approach would be to formulate a limit state in terms of flexural strain by assuming a yield strain of 0.5% and an initial out of roundness consistent with pipe fabrication tolerances. The resulting permanent ovality limit state would be expressed in terms of the applied flexural strain and pipe geometry. The formulations presented by Murray et. al. or BS8010 would be a suitable basis for the development of this new ovality criteria.

If an ovality limit state formulation is undesirable, the current workmanship criteria should be reviewed to consider pipe geometry.

Rupture

The CSA Z662 Section 11 strain-based design rupture criteria, allows a similar amount of strain as other design approaches formulated in a similar fashion (i.e. effective or principal stress criteria). If the limit states appendix is to adopt this limit on principal strain, the current wording of the strain-based rupture criteria should be revised.

Consideration should be given to the alternative design approach which limits the hoop stress or strain to the yield level but allows 2 to 2.5% total strain in the longitudinal direction. The application of a design criteria such as this might be limited to installation and to infrequent load or deformation events.

In addition, care should be taken to identify the point in a pipe's life-cycle at which the reference strain is assumed to be zero. It is recommended that the baseline for plastic strain accumulation be identified as the condition of the pipe prior to installation. This assumption makes the material properties used in the design approach consistent with the pipe mechanical properties which are measured immediately prior to installation.

Pipeline standards which allow post yield design, should require the pipe material properties (Y/T, elongation and toughness) after plastic deformation to remain in compliance with minimum specified levels and not promote failure. The ability of pipe materials to meet this requirement should be investigated.

Buckling

In the design of pipeline systems a variety of buckling modes (e.g., column (Euler) buckling, local buckling, wrinkling, etc.) should be considered, depending on the pipe loading and initial geometry. Many buckling failure criteria are available to ensure these modes of failure do not manifest themselves. Individual limit state equations will consider some or all of the following effects, depending on the application for which they were developed:

- axial deformations and or loads,
- initial pipe deformations (e.g. ovality),
- flexural deformations and or loads,
- pipe longitudinal curvature,
- internal pressure,
- external pipe pressure, and
- material properties (e.g. SMYS, work hardened properties).

It would be desirable to have a variety of buckling limit state equations available to incorporate varying levels of detail and conservatism in the design process. Since it may not be realistic to expect a design standard to include a selection of criteria for an individual limit state, the designer should be required to consider all forms of buckling and be referred to sources of information on a variety of buckling criteria.

The offshore pipeline design requirements should be merged with the onshore limit states pipeline design requirements to ensure a consistent design approach.

Defect Acceptance or ECA

The design of pipeline systems assumes that the pipelines are homogenous and defect-free and therefore may only consider average strain levels. Once defects or material inhomogeneities (e.g., under or over-matching welds) are recognized, failure criteria may no longer be based on average strains, they must consider local strains or strain concentrations. The strain-based assessment of pipe material and geometric discontinuities deserve further attention to ensure a consistent approach to their assessment.

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