Guidance Document on Strain Based Design

Introduction
Scope

Strain-based design is appropriate where the stresses and strains exceed the proportional limit and where the peak design loads will be reduced when the material strains.

Principles

This document has paragraphs of three types: provisions, notes, and commentary.

Provisions are designed to provide the required framework for pipeline strain-based design and to apply to all cases. Provisions describe requirements of strain-based design that are not expected to change with time or additional engineering data.

Notes are designed to provide technical information based upon current knowledge. As additional information becomes available, the specifics given in notes may need to be updated.

Commentary is designed to provide additional information, such as descriptions of procedures, examples of cases, references to the literature, or options in design.

Where specific descriptions of actions are provided, the verb "shall" is used in provisions, "should" is used in notes, and "may" is used in the commentary.

Exclusions

Design information for pipelines is not included in the guidance document if it is the same both for pipe sections where strain-based design is applied and where it is not applied.

The effect of strain on corrosion and corrosion protection systems is not included in this guidance document.

Causes of Strain
Pressure

Pressure shall be assessed based upon the difference between the external and internal pressure. Pressure loadings shall be assumed to be load controlled, rather than displacement controlled, in the hoop direction.

Soil Movement

Note: Soil movement may generally be considered displacement controlled. However, situations are known where soil induced loadings are load controlled or intermediate between load controlled and displacement controlled.

Restrained Thermal Expansion

Thermal expansion will induce longitudinal strain in the pipe wall when it is restrained. Restrained thermal expansion shall be assumed to be displacement controlled, rather than load controlled.

Bending to Conform to a Curved Surface

Bending strains in pipe against a curved surface shall be assumed to be displacement controlled. Strain in bending may be determined by the curvature of the surface against which the pipe rests.

Commentary: Strains may be higher at areas where the pipe does not rest completely against the surface and these strains may be intermediate between load controlled and displacement controlled.

Primary Loadings

Note: Strain-based methods are not generally applicable to primary loading, that is, load-controlled situations. However, there are many individual instances where a limiting strain will be more appropriate. One example would be a pipeline spanning between two supports and deforming under its weight. This normally load-controlled situation may be more appropriate to assess based on strain, if at a given strain the pipe will be supported at an intermediate point.

Design Limits
Maximum Strain
          Tension

A maximum strain limit in tension shall be applied when no other provision below limits the tensile strain.

Note: A maximum strain limit of 10% (0.1) should be applied in the absence of additional engineering information.

          Compression

A maximum strain limit in compression shall be applied when no other provision below limits the compressive strain.

Note: A maximum strain limit of 10% (0.1) should be applied in the absence of additional engineering information.

Global Compressive Strain

Pipe sections subject to dominant primary loads in global axial compression shall be designed to prevent longitudinal collapse buckling.

Pipe sections subject to dominant secondary loads in global axial compression shall be designed with account for global buckling in combination with other failure modes.

Pipe sections subject to loading that is intermediate between load control and displacement control in global axial compression should be designed to limit global buckling strains and account for global buckling in combination with other failure modes.

Note: Other failure modes to be assessed should include local buckling, fracture, ductile failure, and cyclic failure modes such as fatigue and ratcheting.

Lateral

The limits on the position of the pipeline after any lateral buckling that is allowed within the design shall be determined and the position shown to be acceptable.

Upward

Where upward buckling will significantly reduce the resistance to additional loading modes, restrictions on global compressive strain shall be defined.

Local Compressive Strain

Pipe sections subjected to axial compressive strain shall be designed to avoid failure by local buckling of the pipe wall.

Note: For situations where primary loads dominate behavior, but strain-based methods are appropriate, the allowable strain should be determined based upon the ultimate longitudinal compressive strain. The ultimate longitudinal compressive strain may be determined based on the following equation for cases with internal overpressure:
$$\varepsilon_{ccrit} = 0.85 \, ([t/D] - 0.01) \, (1 + \sigma_h/Fy) \, \alpha_h^{-1.5} \, \alpha_{gw}$$
where
ε_{ccrit} is the ultimate longitudinal critical strain
σh is the design hoop stress from internal overpressure
α_h is the plastic deformation behavior factor [the maximum allowed yield-to-tensile ratio]
α_{gw} is girth weld factor [1 for plain pipe and, for girth welded pipe, 1 below D/t of 20 and otherwise 1.2-0.01(D/t)]. The ultimate longitudinal strain may be determined based on the following equation for cases with external overpressure:
$$\varepsilon_{ccrit} = 0.85 \, (t/D - 0.01) \, (g_d - p_e/p_c) \, \alpha_{gw}$$
where

g_d is the collapse reduction factor $1/(1-10D_\theta)$

Pe is the external overpressure

Pc is the collapse pressure [see below]. Alternatively, the ultimate longitudinal compressive strain may be determined by analysis methods or physical tests that take into account internal and external pressure, welds and weld residual stresses, and the pipe stress-strain behavior.

Note: For situations where secondary loads dominate behavior, the allowable strain should be in excess of that for primary loads. The amount of this excess should be determined by analysis or physical testing techniques that can account for post-buckling behavior.

Note: For situations that are dominated by behavior intermediate between load controlled and displacement controlled, the allowable strain may be determined based upon the ultimate longitudinal compressive strain. Alternatively, the allowable strain may be in excess of that for primary loads. The amount of this excess should be determined by analysis or physical testing techniques that can account for post-buckling behavior. The assessment must include the effect of the loss of stiffness in the buckled region on the loading system.

Note: Allowable strain should be determined from ultimate compressive longitudinal strain by multiplying by an appropriate resistance factor.

Commentary: The effect of internal overpressure on local buckling resistance has usually been estimated to be a greater effect than given here. Test results from the University of Alberta reported by Dorey et al. 2000 have suggested that these estimates may not be conservative for D/t from 50 to 100. For lower values of D/t the effect of pressure has not been established by experiment, but can be confidently expected to be greater based on finite element models. The ovalization type buckling that tends to occur first for low D/t will be improved more than other buckling modes by internal pressure.

Commentary: The effect of external overpressure on local buckling resistance has been checked against several different design equations.

Commentary: The excess in allowable strain above that for primary loads would not be expected to be more than 0.015 (1.5%) for secondary loading.

Elastic Local Buckling

Note: Elastic local buckling should be checked as a possible mode of failure when D/t>50.

Elastic-Plastic Local Buckling

Note: Several modes of buckling have been observed in pipes under test conditions. Assessments for local wrinkle formation should check all applicable modes, such as

outward, inward, and diamond. Where the capacity is determined by ovalization as at small D/t and the excess capacity for secondary loading is being assessed, buckling by additional modes should be checked.

Plastic Ovalization

Ovalization of the pipe cross-section shall be limited in design to prevent section collapse and allow the unhindered passage of internal inspection devices.

Note: The ovalization deformation should be calculated using the following equation
$D_\theta = 2 (D_{max}-D_{min})/(D_{max}+D_{min})$
Where
D_θ is the ovalization parameter
D_{max} is the maximum outside diameter, and
D_{min} is the minimum outside diameter.

Note: Ovalization deformation should be limited to no more than 0.06 (6%) to allow the passage of internal inspection devices.

Note: Ovalization deformation should be limited to prevent section collapse under external pressure.

Commentary: A simple limit on ovalization for external pressure may be set at ovalization deformation of 0.03 (3%).

Global Tensile Strain

Pipe sections in global axial tension shall be designed to prevent ductile failure.

Note: Global axial tension strain should be limited to 0.025 (2.5%).

Local Tensile Strain

Pipe sections subject to local axial or hoop tensile strain shall be designed to prevent brittle fracture and ductile failure.

Note: Local tensile strain should be limited to 0.10 (10%).

Commentary: Brittle fracture is prevented by limiting the possible combinations of fracture toughness, applied tension stress, local geometry and flaw size. Limiting the range of application to steel pipelines places implicit limits on each of these parameters. Thus it is often sufficient to place additional requirements on only one or two of these parameters to limit the combinations to those that avoid brittle fracture. Alternatively, information correlated to these parameters may be required, such as Charpy V-notch test impact energy, which is correlated to fracture toughness.

Commentary: Ductile failure is prevented by limiting the possible combinations of fracture toughness, applied tension stress, applied tension strain, local material stress-strain behavior, local geometry and flaw size.

Note: When strains in excess of the yield strain are included in design, an engineering critical assessment should be completed.

External Overpressure

Pipe sections subjected to external overpressure shall be designed to prevent local collapse and propagation of that collapse along the pipe.

Note: The buckling propagation pressure may be determined using the following equation:
$$P_{pr}=26SMYS(t/D)^{2.5}$$
Where P_{pr} is the external overpressure at which buckle propagation is expected to begin.

Note: The characteristic resistance for external pressure should be calculated based upon a widely used standard method.

Commentary: Similar but not identical results can be obtained from several standard methods including those in API RP 1111 and DNV 2000. The characteristic resistance for external pressure may be calculated from the following third order equation from DNV 2000:
$$(p_c-p_{el})(p_c^2-p_p^2)=p_c \, p_{el} \, p_p \, f_o \, (D/t)$$
where
p_c is the characteristic resistance
$$p_{el}=2E(t/D)^3 / (1-nu^2)$$
$$p_p=2fy \, \alpha_{fab} \, (t/D)$$
$f_o=(D_{max}-D_{min})/D$ but not less than 0.005.

Note: The external overpressure should not exceed the characteristic resistance multiplied by a safety factor appropriate to the service conditions.

Commentary: While the design equations for external pressure noted above are not based upon strain, the parameters are used below in the assessments of combinations of external pressure and strains in the pipe axis direction.

Commentary: The safety factor on external overpressure for a propagating buckle may be set to 0.8. This multiplier is used by API 1111 for a slightly different propagation pressure equation.

Ratcheting

Pipe sections subjected to multiple cycles of plastic deformation shall be designed to avoid a ratcheting failure. The pipe section shall meet limits on accumulated strain during the initial cycles and shall be elastic on further cycles of loading.

Commentary: Pipe sections with plastic strain histories including both tensile and compressive plastic strain, but in unequal amounts, may be susceptible to ratcheting failure when the strain difference accumulates.

Concentration of Strain

Note: Strain concentrations at changes of section thickness, changes of material grade, transitions to attachments, transitions in coating thickness, and localized areas of transverse loading should be accounted for in assessments of allowable strains, both in tension and compression.

Accumulated Plastic Strain

Accumulated plastic strain is the sum of the plastic strain increments in the strain history, irrespective of sign and direction. The plastic strain increment is the largest amount of plastic strain reached for each part of the history where plastic strain occurs, that is where strain exceeds the proportional limit. The accumulated plastic strain need not include strains induced during linepipe manufacture.

Commentary: Accumulated plastic strain sums the absolute value of both the positive (tensile) and the negative (compressive) plastic strains that may occur at successive parts of the strain history. Accumulated plastic strain is commonly used in the determination of the effect of reeling where cyclic bending plastic strain is counted for the multiple cycles within a reeling/unreeling cycle.

Pipe Material Selection
Dimensions

Note: Pipe sections with accumulated plastic strain in excess of 2% in design should have dimensions of the pipe subjected to tighter tolerances and greater inspection. This should include testing every pipe for pipe end diameter and pipe end out of roundness. Pipe end matching should be practiced to limit wall misalignment across girth welds.

Mechanical Properties

Note: Pipe sections with accumulated plastic strain in excess of 2% in design should have tensile properties of representative pipe material meet three criteria:
      Measured yield strength minus SMYS of no more than 100 MPa,
      Measured yield strength to tensile strength ratio of no more than 0.85, and
      Elongation equal to or exceeding 25%.

Commentary: The material properties in the Note are discussed in DNV 2000. The yield to tensile strength ratio may become difficult to meet on pipe grades above API 5L X65.

Mechanical Properties after Strain Aging Treatment

Note: Pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should have their mechanical properties tested after a strain aging treatment. A strain aging treatment should reach the design accumulated plastic strain through cycles of compressive and tensile strain and then follow with an artificial age at 250C for one hour before additional mechanical testing. The mechanical test results should meet the requirements for the base pipe with the following exceptions:

     Measured yield strength to tensile strength ratio of no more than 0.97, and
     Elongation equal to or exceeding 15%.

Commentary: Requirements for strain aging resistance tend to restrict the pipe material to pipe with improved local buckling resistance. Strain age degradation is correlated to a sharp yield point and long yield plateau, while both of these are correlated with poor local buckling resistance.

Strength Variability

Note: Variability of pipe strength should be allowed for in design.

Girth Weld Material Selection
Mechanical Properties

Weld metal shall meet the minimum mechanical property requirements of the pipe base metal.

Note: The yield strength of the weld metal should be limited to no less than SMYS+80 MPa and no more than SMYS+250 MPa. The yield strength of the weld metal should be further limited for girth welds with accumulated plastic strain in excess of 2% in design to no more than SMYS+200 MPa.

Commentary: Weld metal that has strength properties below the base metal requirements can accumulate local strain. Weld metal that greatly exceeds the base metal in strength may direct concentrated strain into the heat affected zone, most notably under conditions of local stress concentration in the weld area, such as by weld misalignment or local change in coating thickness. If local stress concentrations are minimized in design, girth welds of higher strength may be used.

Mechanical Properties after Strain Aging Treatment

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 2% in design should have the weld mechanical properties tested after a strain aging treatment.

Root Region Mechanical Properties

Commentary: Root regions may be welded with different filler metal from the majority of the weld to improve tie-in performance and resistance to cracking

Strength Variability

Note: Variability of strength of weld metal should be allowed for in design.

Fabrication and Installation
Matching of Diameter, Thickness and Ovality Across Welds

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 2% in design should have the pipe ends matched across a girth weld so that "high-low" across the joint is limited to the lesser of 10% of wall thickness and 3 mm.

Matching of Mechanical Properties across Welds

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 0.02 (2%) in design should avoid larger differences in yield strength across the weld than necessary.

Weight Coating

Note: Weight coating should be designed to provide sufficient strain capacity so that the weight coat is not removed by the action of the design strains.

Commentary: Tests of weight coating strain capacity and the strain capacity of other types of coatings may be completed on plate specimens.

Commentary: Grooving of weight coating has been shown to be effective at increasing strain to failure.

Prevention of Pipe Rotation

Note: Pipe that has been bent with plastic deformation may have a tendency to rotate around its axis under subsequent loadings. Pipe configurations where such rotations would be detrimental should be assessed to demonstrate that any rotations are limited to an acceptable range.

Commentary: Pipe rotation has been recognized in offshore S-lay where plastic strain in induced in bending on the stinger. The suspended span between the stinger and seabed touchdown has low torsional resistance, so the pipe can rotate to place the compression side of the pipe from the stinger bend on the compression side of the bend near the sea floor.

Commentary: Rotations may be detrimental to fittings, such as T's, Y's and elbows, to valves, and to connections to corrosion protection systems.

Inspection
Methods

Note: Girth welds in pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should be inspected with 100% automated ultrasonic testing.

Commentary: Girth welds in pipe sections with plastic strain in excess of 0.005 (0.5%) may need to replace the manual ultrasonic inspection with an automated ultrasonic inspection to achieve reliable detection capabilities for smaller flaws that result from ECA assessments.

Acceptance Criteria

Note: Girth welds in pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should be rejected and repaired or replaced if a flaw or flaws exceeds the allowable flaw size determined in the engineering critical assessment.

Commentary: Inspection acceptance criteria for strains below 0.005 (0.5%) may be obtained from the applicable sections of many standards, such as API 1104 Appendix A and CSA Z662:1999.

Commentary: Inspection acceptance criteria for use with strains intermediate between 0.005 (0.5%) and 0.02 (2%) may be determined based upon an engineering critical assessment, or based upon a generic engineering critical assessment of a more severe case.

Engineering Critical Assessment
Simple Methods Appropriate to Low Strains

Methods available in widely distributed codes and standards applicable to pipelines cover cases of tensile strain up to the yield strain of 0.005 (0.5%). These methods provide for determining acceptable combinations of fracture toughness, applied tension stress, local geometry and flaw size.

Note: Methods described in API 1104 Appendix A, CSA Z662:1999, the EPRG Guidelines, and BS 7910 (all levels) are applicable.

Intermediate Strain Methods

Engineering critical assessment methods used when strains in design are in excess of the yield strain shall be appropriate to the level of strain.

Note: Methods described in BS 7910 are designed primarily for load-controlled situations. Options are described for use in displacement-controlled situations. These options should be used for conditions that are defined to be displacement controlled rather than load controlled or intermediate between the two.

Commentary: The methods in BS 7910 are modifications to methods that use stress as a primary variable. There are methods available that use CTOD and strain as primary parameters, as in Anderson 1985 and Fukijubo et al. 1991. The results from such methods may be compared with those from BS7910.

Accumulated High Strain Methods

Commentary: Engineering critical assessment methods for accumulated plastic strain in excess of 0.02 (2%) have not been widely validated. It is reasonable to believe that these cases may be assessed conservatively by a displacement-controlled assessment using the tension part of the accumulated plastic strain as though it were the monotonic plastic strain of a single partial cycle.

Full-Scale Testing

Note: Representative full-scale testing should be completed for cases with accumulated plastic strain in excess of 0.02 (2%). This testing should be designed to demonstrate sufficient resistance to unstable fracture under the design conditions.

Commentary: Full-scale tests may be performed to demonstrate pipe resistance to one or more of the failure modes described above, or to account for other possible pipe performance issues (coatings, etc.). The design of such tests should recognize that not all failure modes will be tested with the same safety factors during any individual test.

Commentary: Full-scale testing may need to include multiple modes of loading to provide a representative comparison of relative risks between different modes of failure. For instance, comparison of fracture risk from the tension side and buckling risk from the compression side would require a representative balance between the bending and axial strains on the overall pipe cross-section.

Commentary: Testing specifically designed for checking unstable fracture resistance may need to be designed with additional efforts to avoid other failure modes while achieving the required strain at the defect being tested. An example of such testing can be found in Berge et al. 2001. This may involve adding additional axial loading, increasing internal pressure, or spreading the localized loading that occurs on the compression side.

Commentary: Modeling of full-scale tests may be appropriate to predict behavior when designing the test or to understand the behavior observed in the test.

References

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