Report

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Project No. 45892GTH

Strain-Based Design of Pipelines

Submitted to:

U.S. Department of Interior, Minerals Management Service
Herndon, VA

U. S. Department of Transportation, Research and Special Programs Administration
Washington, DC

EWI®

MATERIALS JOINING TECHNOLOGY

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on

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October 8, 2003

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Executive Summary

In recognition of the increasing trend toward strain-based design of pipelines and the need for basic guidance on strain-based design, the Minerals Management Service (MMS) and the Office of Pipeline Safety (OPS) co-funded EWI to provide a general guidance on strain-based design for pipelines both for the on-shore and off-shore environment. The resulting guidance can be found in this report.

Special consideration has been given to the choice and qualification of pipe material, the choice and qualification of girth welding procedures and the demonstration that both pipe and weld areas have sufficient strain capacity to meet the requirements of the design.

The current use of strain-based design has many project-specific components. This limits the ability of a “cookbook” approach where each step can be laid out as part of common design sequence to apply to all areas of pipe strain-based design. This situation would indicate that taking the current state-of-the-art methods and creating a code or standard would be ineffective at covering the range of needs for future pipeline designs. Yet, because there are many choices that are part of a particular pipeline strain-based design, the availability of guidance and recommended practices can help simplify the design and qualification process for many pipelines. Going forward with this approach, the guidance provided in this report could profitably be taken forward by the industry into, for instance, an API-recommended practice.

The primary areas where strain-based design will be used are in design of reeled laying of offshore pipelines, in thermal design of arctic pipelines, in design of types of offshore pipelay systems, in design and assessment of pipelines in areas with significant expected ground movement, and in high-temperature and high-pressure HT/HP pipeline designs.

Pipeline may also have some applications of strain-based design where cyclic loadings cause occasional peak stresses above the pipe yield strength. Here, the cyclic lifetime assessment is improved by using strain ranges for the cycles, instead of stress ranges.

Past design practices have asked designers to determine whether a particular loading was “load controlled” or “displacement controlled” without any other possible choices. Designers today need to recognize that there are a range of intermediate cases between full load control and full displacement control. The behavior of the pipe, particularly its buckling resistance, can change significantly depending upon the designer’s choice of the appropriate intermediate case for design.

Guidance on local buckling compression resistance of pipelines appears to be well founded when using the critical strain. Some changes are recommended here to account better for the effect of internal pressure on the resistance to local compression buckling. The additional strains that can be achieved under partly or fully displacement-controlled loading can provide significant additional capacity.

The methods for assessing tensile failure resistance of pipelines by engineering critical assessment (ECA) become fewer when the plastic strain exceeds 0.005 (0.5%) and fewer still as the strain increases to 0.02 (2%) or more. These ECA methods are used to demonstrate the sizes and types of imperfections that can remain in pipes and welds for high-strain service.

Further study is needed on the effect of pressure, internal or external, on the tensile failure resistance of girth welds in pipelines. Models and experiments done for this project have indicated an important effect of strain concentration around welds with mismatched areas under internal pressure.

Methods of assessing cycles of loading that include plastic strain are available. But the limited number of tests on which they are based may mean that these methods are conservative for many pipeline design situations to which they might be applied.

Design of pipelines to resist ratcheting has become more important recently because of thermal cycle effects on high-temperature pipelines and flowlines. As for other types of cyclic loading, the current design methods are relatively conservative, but have been shifting to allow more cycles of plastic strain.

Abbreviations and Definitions List

Abbreviations

API	American Petroleum Institute
APIA	Australian Pipeline Industry Association
ASTM	American Society for Testing of Materials
AUT	Automated ultrasonic testing
BPV	Boiler and Pressure Vessel
BS	British Standard
CSA	Canadian Standards Association
CTOD	Crack-tip opening displacement (a measure of toughness)
D/t	Diameter-to-thickness ratio
DNV	det Norske Veritas (Norwegian ship and equipment classification society)
EBW	Electron beam welded
ECA	Engineering critical assessment
ELI	Extra-low interstitial
EPRG	European Pipeline Research Group
ERW	Electric resistance welded (a solid-state weld process used to join the edges of a single piece to make pipe)
EWI	Edison Welding Institute
FAD	Failure assessment diagram
FL	Fusion line
GC-HAZ	Grain-coarsened heat-affected zone
GTAW	Gas tungsten arc welding
HAZ	Heat-affected zone (area adjacent to a weld affected by the weld's heat)
HFW	High-frequency welded
HT/HP	High temperature and high pressure
J	A measure of toughness
J-R	A measurement of toughness appropriate to ductile crack growth
KI	Critical stress intensity factor (a measure of toughness)
LBW	Laser welded
Mk	Stress concentration due to local weld shape that changes through the part thickness
MMS	Minerals Management Service
OPS	Office of Pipeline Safety
R6	A fracture assessment technique developed for the British utility industry
SAW	Submerged arc welding

SCF	Stress-concentration factor
SENB	Single-edge notch bend
SMYS	Standard Minimum Yield Strength
TMCP	Thermomechanical-controlled processing
UOE	U'ed, O'ed and Expanded (a description of a pipe making process where the plate is rounded into a U shape, then an O shape and the expanded to the correct diameter)
WES	Japan's Welding Engineering Society
Y/T	Yield strength-to-tensile strength ratio

Definitions

Strain-Based Design – This is a design method that places a limit on the strains at the design condition rather than the stresses.

Load Control – Load control describes a situation where the combination of load and displacement is controlled by the load variable, where a change in shape will not change the load.

Displacement Control – Displacement control describes a situation where the combination of load and displacement is controlled by the displacement variable, where a change in load will not change the shape.

Reeling – Reeling is a part of a pipeline installation procedure where the pipe is fabricated into a long section, wrapped around a circular reel, transported to the laying site, and then unwound from the reel.

S-Lay – This is a type of offshore pipe laying method where the pipe above the water surface is basically horizontal and has an S-shape below the water surface.

J-Lay – This is a type of offshore pipe laying method where the pipe above the water surface is basically vertical and has a J-shape below the water surface.

Wrinkling – Wrinkling is the formation of ridges and troughs in the pipe wall, which is often the visible consequence of local buckling.

Upheaval Buckling – This is a buckling mode of offshore pipelines where the pipe locally leaves the supporting seafloor and forms an upward kink.

Pull Tube – A pull tube is a tube with at least one bend through which an offshore pipeline is pulled to connect it with a structure such as a platform.

Poisson Loadings – These loadings are loadings induced by the Poisson effect, where a body loaded in one direction will change shape in the perpendicular direction if it is not restrained. This loading occurs in buried pipelines where the hoop stress from pressure loading induces a Poisson loading to keep the pipe the same length.

Overbend – This is the upper part of the suspended pipeline between the layship and the seafloor during S-lay that is curved concave downwards.

Sagbend – This is the lower part of the suspended pipeline between the layship and the seafloor that is curved concave upwards.

Field Bending – Field bending is an on-shore pipeline practice where a pipe bending machine is used at the pipe laying site to allow the laid pipe to fit the local configuration.

Soil Liquifaction – This is the loss of load carrying capacity by the soil due to earthquake shaking.

Ratcheting – Ratcheting is the process of accumulating additional deformation beyond what would occur with static loading only because of a combination of static and cyclic loading.

Upheaval Creep – This is a form of ratcheting of the material surrounding a buried pipeline that allows the pipe to rise toward the surface due to cycles of loading.

Free Span – A free span is a section of pipe that is not supported by the surrounding material, but by the adjacent pipe.

Weight Coating – This coating is an external coating of offshore pipe, usually of concrete, added to reduce the buoyancy of the pipe under water.

Overpressure – This is the difference between the local internal pressure in the pipe and the local external pressure outside the pipe.

Limit State – A limit state is a description of one way that a design may become unacceptable. Several different limit states will usually be checked when judging a design.

Rippling – Rippling is the formation of smooth, widely spaced ridges and troughs in the pipe wall of small magnitude.

Propagating Buckle – A propagating buckling may occur in pipelines with external overpressure when an initial buckle shape can extend along the long direction of the pipe more easily than it can initially be formed.

Tangent Modulus – The tangent modulus is the slope of the stress-strain curve locally at a given combination of stress and strain.

Engineering Critical Assessment – Engineering critical assessment is used to assess imperfections or possible imperfections to determine whether the combination of loading, imperfection, and geometry is tolerable. The methods can be adapted to strain-based design.

Lüders Yielding – Lüders yielding is an uneven yielding phenomenon where areas of yielding originate in individual areas and sweep across the adjacent material. This usually corresponds to a plateau with some roughness in the stress-strain curve just after a sharp yield point.

Ramberg-Osgood – Ramberg and Osgood proposed a simple equation to describe the stress-strain behavior of metals. This equation is often formulated today as:
$\left(\frac{\varepsilon}{e_{y0}}\right)=\left(\frac{\sigma}{\sigma_{y0}}\right)+A\left(\frac{\sigma}{\sigma_{y0}}\right)^{n}$, where ε is the strain and σ is the strain, is applicable to materials with smooth stress-strain curves near yield and uses four parameters set by the material.

Undermatch – Undermatch is a condition where the weld metal strength is known to be less than the adjacent base metal strength.

Overmatch – Overmatch is a condition where the weld metal strength is known to be more than the adjacent base metal strength.

Bauschinger Effect – The Bauschinger effect occurs when strain hardening is directional rather than uniform over all directions. In particular, plastic deformation in one direction can increase the yield strength in that direction, but not increase the yield strength by that amount in the opposite direction.

Neuber Notch – Neuber described the theoretical stress concentration factor K_t in terms of the concentration of stress and the concentration of strain around a notch. The equation used the maximum strain $\varepsilon_{\max}$, the maximum stress $\sigma_{\max}$, the nominal strain ε_{nom}, and the nominal stress σ_{nom} to get $K_t^{2}=\left(\frac{\varepsilon_{\max}}{\varepsilon_{nom}}\right)\left(\frac{\sigma_{\max}}{\sigma_{nom}}\right)$.

Accumulated Plastic Strain – Accumulated plastic strain is plastic strain that has been summed over a given set of processes, such as loading cycles, including as positive both strains in the positive and negative directions.

Strain Aging – Strain aging is a phenomenon in steels where the toughness and strength of a material can be degraded by plastic deformation followed by time at ambient or slightly elevated temperatures.

Crack-Tip Opening Displacement – Crack-tip opening displacement is a measurement of the stretching across the crack tip just before rapid growth starts at the crack that is used as a standard measurement of toughness.

Plastic Collapse – Plastic collapse is a failure mode where the material thickness was insufficient to carry the imposed tensile loading so the material stretched until its capacity was exhausted.

Coiled Tubing – Coiled tubing is tubing that, when not in service, is wound on a reel. This tubing is commonly used in oil and natural gas production wells.

Yield Strength – Qualitatively this is the lowest strength where plastic strain that is permanent dominates over elastic strain that disappears as the loading is removed. For pipeline materials, standards specify the measurement of yield strength as the strength at a strain of 0.005 (0.5%) under specified conditions. Other materials may use other definitions of yield strength.

Tensile Strength – Qualitatively this is the peak strength of the material. For pipelines materials, standards specify the measurement of tensile strength as the largest strength during the test under specified conditions.

Plateau – When used to describe a stress-strain curve, plateau means that a portion of that curve shows no increase in stress while the strain is increasing. This can occur just after the yield point in association with Lüders strain or at higher strains and stresses.

Roundhouse – When used to describe a stress-strain curve, roundhouse means that no plateau occurs near the yield strength, that is that the strains near yield smoothly increase as the stress increases.

Proportional Limit – Qualitatively this is the strength at which plastic strain is first observed as tension increases during a tensile test. This parameter is not commonly measured.

Upper Yield Point – The strength measured at the highest local peak in the stress strain-curve before the strain limit for determining the yield strength has been reached.

Lower Yield Point – The strength measured at the strain limit for determining yield strength when there is also an upper yield point.

Elastic Strain – Elastic strain is mechanical strain that disappears when the loading is removed.

Plastic Strain – Plastic strain is mechanical strain that remains when the loading is removed.

Total Strain – Total strain may be used to describe the combination of elastic and plastic strain or the combination of mechanical and thermal strain.

Mechanical Strain – Mechanical strain is strain created by force or moments currently acting or previously acting on a material.

Thermal Strain – Thermal strain is strain induced by a change of temperature. It is not mechanical strain, as it is induced without the action of forces. Thermal strain may induce forces and thus mechanical strain when displacement is restricted or prevented.

Critical Strain – Critical strain is the mechanical strain in compression at which the peak compression load is reached in a member that buckles.

Buckling – Buckling is deformation in other directions than would occur if the loading were tiny. Different patterns of this deformation, called buckling modes, may be observed.

1.0 Introduction

In recognition of the increasing trend toward strain-based design of pipelines and the need for basic guidance on strain-based design, the Minerals Management Service (MMS) and the Office of Pipeline Safety (OPS) co-funded EWI to provide a general guidance on strain-based design for pipelines both for the on- and off-shore environment. The resulting guidance can be found in this report.

Special consideration has been given to the choice and qualification of pipe material, the choice and qualification of girth welding procedures and the demonstration that both pipe and weld areas have sufficient strain capacity to meet the requirements of the design.

The report has several sections. The main body of the report discusses the background for strain-based design guidance and primarily describes work that is in the published literature. Appendix A provides reports of EWI finite-element modeling and specimen testing regarding the effect of lower strength areas near a girth weld on the tensile strain around the weld. Appendix B provides a summary of the data on combinations of longitudinal compressive strain in the pipe and internal pressure. Appendix C, entitled “Guidance on Strain-Based Design” is designed to provide summary guidance on strain-based design of pipelines. The summary guidance is not expected to stand alone, but rather to be used in conjunction with other information, such as that found in the associated sections of the main report. The Abbreviations and Definitions List provides a list of terms that are abbreviated in the text and also definitions of many of the technical terms used in the report.

The 2-year effort described by this report will be expanded and refined by additional work in this area. EWI and the sponsors of this program expect that a new program will begin where this program has left off.

1.1 Introduction to Strain-Based Design

Safe and conservative methodologies, which are based on limiting the stress in the pipe wall due to service and installation, are available for pipeline design. These stress-based design methods have less widely used counterparts in strain-based design methods. The methods using strain allow selected extensions to the stress-based design possibilities to take advantage of steel’s well-known ability to deform plastically, but remain a stable structure.

Strain-based design is appropriate when the performance limits for the design, in at least one direction, are better described in terms of strain than in terms of stress. A simple example occurs when pipeline is fit to a curved surface. The curve of the surface determines the curve, and thus the strain, in the pipe. Here, the pipe strain is figured directly from the surface curvature rather than going through the stress in the pipe and then back to the strain. This becomes important when the surface curve gets sharp enough that the pipe can yield as it bends to fit the surface. Two pipes with different relations between stress and strain will have the same strain, but differing stresses when fit to the curved surface. If an upper limit were placed on stress, the two pipes would be different in relation to that limit. If the upper limit were placed on strain, the two pipes would be the same in relation to that limit.

The example above has two features that help to define when strain-based design will be valuable. First, the situation must be at least partly displacement-controlled. That is, the pipe deformation will be complete when a given displacement is reached. Here, that displacement limit is given by the curve of the surface. Second, plastic deformation must be part of the design condition. The difference between pipes in the relation between stress and strain during plastic deformation causes strain-based design to give different answers from stress-based design in the plastic deformation regime.

Combinations of some displacement control and plastic deformation can be found in many real pipeline conditions, both at installation and during service. They are, however, only a limited set of conditions and strain-based design cannot “replace” stress-based design.

The resistance of the pipe wall to the hoop stress induced by the internal operating pressure is usually the primary determinant of the required pipe grade and thickness. In a smaller number of cases, the design is limited by the resistance to buckling in compression either from external pressure or from longitudinal loads or transverse moments. Even rarer are cases of designs that are limited by the resistance to failure in tension, that is, by fracture, from longitudinal loads or transverse moments.

Much of the effort in this guidance will be to define methods of demonstrating resistance to high longitudinal strains in tension, due to longitudinal loads or transverse moments. This emphasis comes from two primary sources. First, offshore pipelines are more difficult and expensive to lay, so opportunities to use the longitudinal strain capacity of the pipeline are attractive where they reduce the time required for the pipe-lay operation. Second, offshore pipelines, once laid, are remote, so that remediation for conditions that cause longitudinal strains cannot easily be applied. Conditions that cause longitudinal strain, such as slope instability, seismic sideslip and unsupported spans, need not be more severe offshore to cause the need for designs to account for larger amounts of longitudinal strain.

Pipe-laying operations, in particular, tend to induce plastic strain both in an original direction and in the reverse direction, possibly through multiple cycles. Thus, for pipeline assessment in strain-based design, a method must be defined for accounting for these different strains. DNV 2000[1] accounts for plastic strain by adding plastic strain increments regardless of sign into an accumulated plastic strain. Where needed, a total accumulated strain can be calculated by adding the maximum elastic strain to the total accumulated plastic strain. Accumulated plastic strain is expected to be a conservative measurement of the effect of different increments of plastic strain in cycles. But it is not expected that material has sustained damage that is directly proportional to the accumulated plastic strain.

1.2 Use of Strain-Based Design

Plastic strain has been a factor in pipeline installation for many years. Reeling of small-diameter steel pipes was first practiced in the 1940s. Cold bending of pipes before installation also has a long history of successful usage. Each of these techniques has been extended over the years to higher strength pipe, larger diameters, and more robust equipment. More recently, applications using plastic strain in other parts of installation have been added.

A list of recent pipelines that have used strain-based design is shown in Table 1. That list is only a small sample of the worldwide projects that have used strain-based design.

Cases of in-service plastic strain were also observed through the history of pipeline usage due to soil movement on unstable slopes, mining subsidence, and seismic loadings. Confidence developed from the resistance of steel pipelines to these loadings and the understanding of pipe behavior compared to known strains in installation and test has allowed pipeline designers to include strain-based design for in-service plastic strain.

Steel pipelines have also been reeled from the ocean floor. The 16-in. Argyll flowline was recovered over a length of 4.8 km from 80-m water depth in 1993.[2] A previous experience used reeling to lay and retrieve a 10-in.-diameter Grade X-42 pipeline in 1000 ft of water.

1.3 Observed Problems

Several problems have been observed when laying or operating pipelines with longitudinal strains above the yield strain.

Reeled pipes have been observed to be damaged both by the coiling onto the reel where contact causes local dents,[3] and during the un-coiling from the reel where local buckling failures have been observed several times adjacent to girth welds. The local buckling failures were found between the end transitions of the concrete coating.[4,5]

Problems have also been observed in S-lay of pipelines where plastic strain is introduced while the pipe is on the stinger as it leaves the layship.[6,7] The residual curvature of the pipe can cause the pipe to twist in the unsupported span between the stinger and the seafloor. The longitudinal strain itself is well below the level where it could cause a local problem. However, the twist can cause features of the pipeline that need specific orientations, such as valves, T's and connections to corrosion protection systems to be misoriented, requiring remediation.[8]

Problems in high-strain cold bending are not limited to offshore construction or during reeling. Field bending before laying for on-shore pipelines may also have problems where the compression side of the pipe wrinkles.[9] This is particularly a problem for the higher strength grades of pipeline steel.

Once laid, a pipeline may encounter loadings that take it beyond its capacity for longitudinal strain. Seismic loading in transverse, compressive, and tensile directions has been implicated in pipe failures, as well as other ground motions such as those from movement of unstable slopes.[10] Excessive subsidence in a landfill has also been indicated in at least one failure.[11]

A fracture has been observed without buckling where an initial circumferential crack has grown by environmental mechanisms. Slope movement, partial support by a concrete river weight and an adjacent girth weld were all described as contributing factors to a fracture at St. Norbert, Manitoba in 1996.[12]

1.4 Code Provisions Related to Strain-Based Design

Several codes have provisions that apply to strain-based design of pipelines. These codes can be placed in three general categories: those that provide a comprehensive overall pipeline standard that includes requirements both for stress- and strain-based design (DNV 2000, CSA Z662), those that specifically allow strain-based design but do not provide extensive provisions related to strain-based design (B31.8, API 1104), and those that provide information on strain-based design related to a specific subgroup of pipelines (ABS 2001, API RP 1111).

Further discussion of the particular provisions of these codes can be found below in sections discussing the specific technical issues.

A general idea of the types of provisions that allow strain-based design can be gained from the provision designated A842.23 in B31.8 (1995),[(13)] as follows:

> "In situations where the pipeline experiences a predictable noncyclic displacement of its support (e.g., fault movement along the pipeline route or differential subsidence along the line) or pipe sag before support contact, the longitudinal and combined stress limits need not be used as a criterion for safety against excessive yielding, so long as the consequences of yielding are not detrimental to the integrity of the pipeline. The permissible maximum longitudinal strain depends upon the ductility of the material, any previously experienced plastic strain, and the buckling behavior of the pipe. Where plastic strains are anticipated, the pipe eccentricity, pipe out-of-roundness, and the ability of the weld to undergo such strains without detrimental effect should be considered. Similarly, the same criteria may be applied to the pipe during construction (e.g., pull-tube or bending shoe risers)."

Codes of interest for further study of the history and growth of strain-based design in codes and standards would include the British Standard BS 8010 Part 3, the Dutch standard NEN 3650 Requirements for steel pipeline transportation systems (1992) that allows strain-based design both for construction and operation with a distinction given between alternating plasticity and ratcheting, and the previous editions to DNV 2000. These editions are from 1996[(14)] and 1981.[(15)] The 1996 edition had extensive discussion of strain-based design that was updated for the 2000 edition. DNV 1981 was primarily a stress-based code with limitations to <72% standard minimum yield strength (SMYS) for functional loads and to 96% SMYS for functional plus environmental loads. There were discussions of strain-based criteria, but with little further description of requirements. For installation, four strain-related limits were imposed. The first limited residual longitudinal strain to below 0.002 (0.2%) for areas that are not reeled or pulled through a J-tube or have similar displacement-loading conditions imposed. This limit was for global strain as local strain was limited to 0.02 (2%) at areas of variable stiffness. Permanent curvature methods, such as reeling or J-tube installation could have 0.02 (2%) bending strain, or 1% with bending and straightening.

2.0 Estimation of Maximum Longitudinal Strains

Longitudinal strains must be estimated both for laying and for operational conditions. The cyclic longitudinal strains into the plastic regime should be accounted for, even when they are not up to the maximum strain.

2.1 Displacement Control as it Differs from Load Control

Strain-based design uses the difference between load-controlled situations and displacement-controlled situations to set larger allowable strains for the cases that are not fully load controlled.

Take the example of the moment versus curvature curve shown in Figure 1 from Specimen B5 tested by Zimmerman et al.[16] The part of the curve tested at curvatures less than 0.04 m^{-1} could have been tested either in load control or displacement control. However, at that curvature, the pipe reaches its maximum moment capacity. A continuing increase in bending moment would cause rapid failure, in this case by global buckling. The test could continue to higher curvatures because the test was displacement controlled. In essence, the curvature was set and the applied moment followed.

Displacement-controlled loading can be defined more specifically as a loading that can be reduced to nothing by a change in the shape of the part of interest. By contrast a load-controlled loading cannot be reduced to zero by a simple change in shape.

Displacement control and load control are often considered as though they were the only two options. But a wide variety of intermediate conditions are possible where strain-based design can be used. First, and perhaps simplest, the load-controlled and displacement-controlled loadings can be applied in perpendicular directions. It is relatively easy to imagine a plate with one direction stretched 1 cm and the perpendicular direction stretched by a 10,000-N load. Pipes can also have this kind of loading when internal pressure that causes a load-controlled hoop stress is combined with an axial displacement of the two ends. A bending displacement combined with pressure could also create such as a combination, as was done by Zimmerman et al.[16] on Specimen B4.

Second, load-controlled and displacement-controlled loadings can be combined in the same direction. This can occur when a pipe span is bent by a weight placed at the center and then bent further to reach a given displacement.

More complex cases of combinations of load-controlled and displacement-controlled loadings can be devised for pipes, such as by adding hoop and axial loadings to the previous case.

The loading on a pipeline may be a combination of load and displacement controlled. The pressure loading will be load controlled, but the soil motion around a pipeline will usually cause displacement-controlled moment loading. Laying tension may be a combination of load and displacement control in different situations. Thermal and Poisson loadings are displacement controlled in most situations.

2.2 Limit State Definitions

One of the main changes in civil engineering codes including pipeline codes within the last 30 years has been the introduction of the limit states design philosophy. This philosophy explicitly recognizes that there are many ways that a structure such as a pipeline could fail and that these modes may be more or less severe or more or less likely. The factors of safety for these different modes can be based on these levels of severity and likelihood as well as the specific parameters that cause the limit state to be reached.

DNV 2000(1) uses four categories for limit states beyond which the structure no longer satisfies the requirements:

- Serviceability limit state
- Ultimate limit state
- Fatigue limit state
- Accidental limit state.

Within each of these broad categories there can be many types of failure mode. For instance, the ultimate limit state category can include bursting, fracture from a pipe wall flaw, local buckling that blocks the pipe in cross-section, load-controlled global buckling that crushes the pipe along its length, and several others. The serviceability limit state can include problems that partially block the flow or prevent pigs from traveling along the pipeline, such as local ovalization of a given amount. The fatigue limit state is separate, since an acceptable loading for one cycle may not be acceptable for many cycles. The accidental limit state is separate from the others because of its different likelihood.

Local buckling is one case where some amount of shape change may be below the serviceability limit state, another amount may be between the serviceability limit state and the ultimate limit state, and a larger amount may reach the ultimate limit state.

2.3 Installation Strains

Strains during installation can usually be placed into one of three categories: strains before the pipe is released (reeling strains), strains as the pipe is released (overbend in S-lay), and strains at the area of laying (sagbend in S-lay).

Efforts to extend the capability of existing layships to more severe situations can increase the plastic strain on any of these three. The most obvious areas are in the reeling and in the overbend on S-lay.

It is common to account for the reeling strains based upon the pipe nearest the reel, with the smallest radius of curvature. The other plastic parts of the reeling process must be included in the analysis, such as plastic curvature along the shoe and within the straighteners.

As discussed below, the longitudinal strains may need to be increased by a strain concentration factor at or adjacent to girth welds.

Pipe sections that include other items than standard pipe; for instance buckle arrestors or cathodic protection anodes, may need a special assessment for the laying process. Additional strain concentrations may occur at the transitions.

Laying strains can also be considered in terms of whether they fit a description of load controlled or displacement controlled. The discussions earlier about the range of intermediate states also comes into play here. One standard estimate if only two possibilities are considered would place reeling in displacement control, the sagbend in S-lay under load control, and the pipe on the stinger as under displacement control. Other estimates would put the sagbend under displacement control, viewing the position of the layship as a critical parameter. A closer look may find that each of these cases may be intermediate between complete load control and complete displacement control. For instance, the pipe may not sit perfectly against the curvature of the reel, causing strains that have a local component of load control. Considering the pipe on the S-lay stinger as under displacement control must be tempered by the recognition that the stinger does not support the pipe continuously but only over discrete lengths. Also, the axial force applied by the tensioners is load controlled, although it creates only a fraction of the total peak stress as the pipe is bent over the stinger. In the sagbend a portion of the bending strain can be considered as displacement controlled, based for instance on layship position.

2.3.1 Cold Field Bending

Field bending of pipe has been used for many years to allow the pipeline to fit the contours and geography of the area where it is being laid. Three standard curvatures for these bends are most prevalent: 3, 1.5, and 1 degree/diameter.

A simple model assuming uniform bending deformation without additional ovality would predict strains at the outer fiber of 5.2% for the 3-degree/diameter bend, 2.6% for the 1.5-degree/diameter bend, and 1.7% for the 1-degree/diameter bend. The 3-degree/diameter bend has primarily been used for the very lowest strength pipe to ASTM A53B, A 106 B or API 5L X-42. Some API 5L X-70 pipe or stronger pipe cannot be bent even to the 1-degree/diameter curvature without the formation of wrinkles on the compression side.

The problems with wrinkling of pipe during cold field bending have been described as variable, with often only some of the pipe within a given lot or heat showing wrinkles for a given bend radius.

Some effort has recently been made to provide rational allowable limits for the size of the wrinkles. The allowable limits on the wrinkles are not set by burst pressure, on which the wrinkles have been observed to have little effect.(17) Olson, Clark, and Odom(18) have demonstrated that longitudinal cyclic loading may cause a fatigue crack to grow at the wrinkle.

A study by APIA(19,20) examined buckling during cold field bending and provided estimation methods both for what conditions initiate buckles and what conditions cause buckles to be of a rejectable size. They use an extension of the tangent modulus theory of buckling to describe initiation. They plotted the compressive stress strain curve and a critical stress curve as a function of the strain. The critical stress curve comes from the equation

$$\sigma_{cr} = \frac{t}{r}\sqrt{\frac{E_l E_h}{3\left(1-\nu^2\right)}}$$

where r is the mean pipe radius, ν is Poissons ratio, E_l and E_h are moduli, in the longitudinal and hoop directions respectively. They chose to use the elastic modulus for the hoop direction, but the tangent modulus, the slope of the stress-strain curve at a given strain, as the modulus in the longitudinal direction. The initiation stress and strain for buckling can be determined as the smallest strain at which the two stress curves cross. The tangent modulus method suggests that materials with yield plateaus can buckle very early compared to materials with smoothly rising stress-strain curves.

2.4 Environmental and Operational Conditions

2.4.1 Buried Pipelines

Pipelines can be exposed to axial strain due to movement of the surrounding material in many geologic settings. Pipelines can be caused to strain by movements at the same level as the pipe, such as a slope instability or soil liquefaction during an earthquake event, above the pipe such as a landslide or mudflow landing on the area of the line, or below the pipe such as mining subsidence.

Estimates for limiting values of axial strain in any particular geologic setting may be subject to large uncertainties. To overcome this for general design, standards are defined to give maximum expected values. Japanese standards have been defined for both temporary ground deformation such as seismic wave motion during an earthquake and for permanent ground motion, including soil liquefaction.(21) Temporary ground deformation has been found to be limited to ±0.41% or less ground strain. Permanent ground deformation may be larger. The Japanese standards provide two levels of ground motion: Level 1 for soil motion that occurs once or twice during the pipeline lifetime and Level 2 for very strong seismic motion due to inland or trench types of earthquakes likely to occur at a low probability during the lifetime of gas pipelines. Pipe deformation of either ±1% strain or 0.35 times the pipe thickness divided by the diameter as a nominal strain is considered the upper limit of Level 1, for which the pipe should not be severely deformed or require repair. Pipeline deformation of ±3% strain is considered the upper limit of Level 2 and may also apply to liquefaction cases.(22)

2.4.2 High Temperature and Pressure

Pipeline design for high temperature and pressure may involve plastic strain in the hoop direction. The risk of ratcheting failure has been considered for some designs. Ratcheting is a process whereby cyclic and asymmetric loads are applied into the plastic range and the total plastic deformation increases with each cycle until a failure limit is reached. Here, asymmetric means that the maximum and minimum stresses in the cycle are not equal in magnitude but are of opposite sign. Stress-strain diagrams are shown in Figure 2. DNV 2000(1) requires that operating temperature and design pressure shall cause plastic deformation only on the first cycle of operation.

Operation at high temperature relative to the original laying temperature may provide a sufficient source of compressive force that a pipeline laid on the seabed can buckle like a bar in compression. Such a global buckling mode may involve upward motion as in upheaval buckling, downward motion at a free span or lateral motion.

The lateral buckling modes are easier to excite than vertical modes on a flat seabed. Estimates of the axial and bending stresses induced within the buckles suggest that these can be large enough to cause concern for local buckling within the larger global buckle.[(23)] Bucking resistance is a function of the material and pipe configuration, so that flowlines with low diameter-to-thickness (D/t) ratios can be designed to avoid local buckling within such a global buckle.

For buried pipe or pipe with a weight covering, for example, dumped rock or concrete mattresses, the direction of least constraint for buckling will be upward, or downward in a covered free span. Cyclic forces that induce buckling may allow a buried pipeline to move upward through the covering layer. This has been dubbed “upheaval creep”.[(24)]

2.4.3 Offshore Environmental Loading Conditions

Uneven seabed conditions may make it economical to include plastic strain of the pipeline as it conforms to the shape of the seabed.

The seabed shape in near-shore Norway caused a design with approximately 0.5% plastic strain to be considered for the Haltenpipe project.

Free span conditions are not usually assessed for plastic strain, because the assessment for resonant vibration usually controls the allowable span. However, some areas with small current and wave loadings may be able to accept longer pipeline spans based upon a strain-based assessment. Appropriate strains for a spanning assessment will likely be at the lower end of those where strain-based design applies. This will be true because of the wide variability and difficulty of control of some of the parameters used in span assessment, such as axial tension in the pipeline.

The span areas where strain-based design would be applicable would likely be either at small water depths where spans are covered by concrete mattresses or at large water depths where current and wave loadings are small and thus the allowable span length is strain dominated rather than fatigue dominated. Concrete weight coating and the weight of covering mattresses used at small water depths, less than 500 ft, add considerable static load to the pipeline in the vertical direction, while protecting the pipeline from hydrodynamic forces of waves and currents and loads from fishing equipment or anchors.

Seabed motion such as subsidence, mudslides, and seismic activity may also make assessment by strain-based design advisable.

Cases may need to be assessed for both the as-installed pipeline and the operating pipeline, since the pressure and weight of the contents may significantly modify the span lengths and local strains.

2.4.4 Deepwater Offshore Loading Conditions

Pipe laying in deep water requires consideration of the external pressure on the buckling resistance of the pipe.

The provisions for combinations of bending and external overpressure differ in DNV 2000[(1)] and API RP 1111.[(25)] API RP 1111 is more restrictive for combinations of small overpressures and large amounts of bending curvature. API RP 1111 is also more restrictive for combinations of large overpressures and small amounts of bending curvature. However, it is less restrictive for combinations where the pressure is approximately 40 to 70% of the critical overpressure.[(26)] The choice of calculation methods for the critical parameters is the smaller part of the difference. The larger part of the difference is due to the form of the equations combining the curvature and pressure terms. Both documents require that the pressure and curvature terms be combined and compared against a limiting value. DNV 2000 uses the combination of the sum of the pressure term and the 0.8 power of the curvature term. API RP 1111 uses the sum of the two terms, but places an additional limit on the pressure term, effectively defining a two-part curve in pressure-curvature space.

2.4.5 Arctic Onshore Environmental Loading Conditions

Limit state design methods have been applied for subsidence, permafrost thaw subsidence, frost heave, slope instability, combinations of permafrost thaw and slope instability, and seismic loading.

Arctic lines can be separated into lines that increase melting of surrounding soil and lines that increase freezing of surrounding soil.[(27)] Lines that increase melting can be susceptible to strain by subsidence. Lines that increase freezing can be susceptible to frost heave.

Thaw stable soil is sometimes found within the area that would be melted by pipeline operation. Thaw stable soil can greatly limit the subsidence. It is also possible for the soil above the pipeline to form an arch and carry some of the overburden load. A thaw-stable gravel layer underlies much of the coastal area around the oil and gas developments on the Alaskan North Slope.

Modeling of the soil can provide estimates of the pipe loading, although computational limitations do not allow the full soil model and the full steel model to be applied at the same time.

The designers of the Norman Wells pipeline used a limit of 0.0075 (0.75%) longitudinal strain during its design and construction.

The trans-Alaska Pipeline System uses a critical curvature equivalent to a 0.004 (0.4%) axial strain for the main line pipe (48-in. diameter, Grade X-65, 0.462-in. wall thickness).[28]

Areas of discontinuous permafrost are more difficult in design for than areas of permafrost because of the soil interfaces that must be accommodated.

2.4.6 Arctic Offshore Environmental Loading Conditions

Limit state design methods have been applied to subsea pipelines in arctic areas including conditions of seabed ice scouring, subsea permafrost thaw subsidence, strudel scour, and upheaval buckling.

Seabed ice scouring is the gouging of the seabed by the passage of the keels of floating ice. These gouges not only push sea floor material ahead of and to the side of the keel, they also deform the underlying seafloor material. Limiting gouge depths for pipeline locations have been estimated statistically from the 100-year return period event. The bending deformation from the passage of a keel can be estimated by finite-element modeling at the level of the pipe below the original sea floor. One method has the soil displacement during a limiting scour event imposed through spring elements into the pipe model with steel plastic properties and large displacement capabilities.

Permafrost thaw subsidence can occur when the higher temperatures of the pipeline melt the water that was frozen in the soil and cause the overburden load to crush the soil and deform the pipeline. Permafrost is found not only onshore, but also under the near shore regions offshore. While uniform thaw followed by crushing and subsidence would not add bending strain, the risk of plastic bending is considered based on a non-uniform crushing and subsidence.

Strudel scour is a form of erosion of the sea floor that can occur when water is channeled along defects in sea ice connected to the sea floor. The resulting craters may leave the pipeline with an unsupported span, which could be assessed by methods for those spans.

Upheaval buckling is a global buckling behavior of the pipe that is under longitudinal compression loading, but has limited restraint against upward motion. The longitudinal compression may be imposed by temperature difference between the warmer pipe and the colder surrounding soil.

The Northstar pipeline was designed with a maximum expected bending strain of about 1% from seabed ice gouging, and about 1% for subsea permafrost thaw subsidence. The assessment for strudel scour did not use plastic design. Upheaval buckling was prevented by the relatively low D/t ratio of 18 and by the burial depth to avoid ice gouging. The strains from the two types of bending would not be expected to occur at the same location, so they were not added.[29,30]

3.0 Pipeline Resistance to Compressive Axial Strain

The design of pipelines for plastic strain must account both for resistance to tension and to compression along the axial direction of the pipe. In tension, the issues relate to the failure modes of plastic collapse or fracture. In compression, the failure modes relate to several varieties of buckling. The entire length of pipeline segment can buckle like an Euler beam, either vertically or horizontally. Alternatively or in combination with these modes, a pipeline may buckle a local area of the pipe wall.

Local buckling is not, at its initiation, a reasonable limit state to be designed against for pipelines within the standard wall thickness regime. The beginning of a ripple in the pipe wall does not impede the flow of product through the pipeline. Neither does it allow a leak. As the buckle extends and expands, it may reach one of these limit states. On the other hand, it should be recognized that local buckling may be a sign of degraded capacity to resist other types of loadings. Local buckling thus may bring the pipe closer to other limit states.

Upper limits for the change of diameter have been proposed to allow continued flow of product without disruption and also allow passage of pigs through the pipeline, for instance a 5% loss of diameter. A limit that relates to leakage has been proposed as a 10% hoop strain at the buckle peak. CSA Z662-1999[31] uses a 2.5% hoop strain for this limit.

The choice of an appropriate limit state for local buckling must be based upon the loading system and an understanding of its reaction to the change of pipe stiffness during buckling. A completely load-controlled situation at the buckle will cause the pipe to fail when it reaches its maximum moment. A completely displacement-controlled situation at the buckle could achieve much larger strains than those at the maximum moment with continued stability. There are many intermediate cases, such as those recognized by plastic design of restrained structural beams, where the initial region of buckling has a capacity dependent upon the resistance of adjacent areas. The lower stiffness of a buckled area may also attract elastic deformation from adjacent areas of the pipe, allowing those regions to straighten while the curvature of the buckled region increases.

Much of the understanding of local buckling in pipelines has been developed through finite-element modeling or other modeling methods. This chapter will focus instead on the results of testing of steel pipes. This will allow design equations to be checked directly against their intended area of application. It will also allow examination of variables that may not easily be included into model pipes, such as girth weld residual stress, variation in strength across girth welds, materials with yield plateaus, and variation of mechanical properties with position.

The tension side of a girth-welded pipeline in bending also has many complexities. Flaw size and fracture toughness may influence the failure strain if brittle or ductile fracture is the failure mode.

3.1 Critical Strain as an Appropriate Parameter

Critical strain, the compressive strain at the maximum loading that can be reached during buckling, has both strengths and weaknesses as a parameter for defining the limit state in local buckling of pipelines. For load-controlled situations, it obviously corresponds to a limit state, although that limit state can be more directly understood based upon a critical stress or critical moment. For displacement-controlled situations, strains far in excess of the critical strain, as calculated directly from the maximum loading, can be achieved in certain situations. As noted above, the critical strain does represent a strain level that must be exceeded before these failure modes can be accessed.

CSA Z662-99[31] provides both a method of determining the critical strain and an exception where the critical strain-based requirement may be waived. The exception is allowed when secondary loads combined with internal pressure dominate the mechanical behavior, where one example of a secondary load is bending caused by ground movements. Local wrinkle formation, softening of the wrinkle zone and section collapse must be checked, as well as meeting the tensile strain limits in all directions.

For low D/t pipes, such as those with D/t below 30, visible wrinkling or rippling may occur at strains of less than half the critical strain.

3.2 Plain Pipe Data

Data on critical strain capacity for plain pipe or tube is available for steel, austenitic stainless steel, and aluminum alloys. Some additional data has been generated for steel pipe with concrete coating. There has been a tendency to mix the steel and stainless steel results when providing summaries of critical strain capacity data. This may provide optimistic estimates for steel since greater work hardening may increase the plastic strain in stainless steel.

A collection of this plain pipe data[32-42] is shown in Figure 3.

The stainless steel data, as a group, show a much flatter curve with increasing D/t than the data for steel, suggesting the importance of the shape of the stress-strain curve may change at different D/t.

3.3 Girth Weld Effect

Several investigators have tested the capacity of steel pipes with girth welds in loading modes where the pipe wall can buckle adjacent to a weld. Girth welds have been shown to attract the buckle to a nearby region of pipe wall within a region of constant moment loading. Welding residual stresses, differences in material strength across the weld, and misalignment of the pipe wall across the weld are all considered to participate in the attraction between the buckle location and the girth weld.

DNV 2000[1] provides a girth weld factor that reduces the allowable compressive strain under displacement-controlled conditions. This multiplying factor is set to one up to a D/t of 20 and then declines linearly with D/t to 0.6 at D/t of 60. This form is based upon the data of Yoosef-Ghodsi[90] at D/t of 60 and an expectation that the effects of weld-induced imperfections will die away for thick-walled pipe.

Publicly available data can be collected from more recent tests and from earlier tests on fabricated tubes. Figure 4 shows data for pipes without internal pressure.[13,32,42-45] Girth welding reduces the critical strain over the entire range for which data is available. The form of the reduction is similar to that used in DNV 2000.[1]

It should be noted that the form of the reduction is very dependant upon the small amount of critical strain data for tubes with D/t below 30. In this regime, Sherman observed visible wrinkling of girth-welded pipes at strains less than half of the critical strain. If the initiation of visible wrinkling were used as a limit state, the multiplying factor for the girth weld would be between 0.67 and 0.50.

Some part of the difference between plain pipe and girth-welded pipe may be due to the inclusion of stainless steel data in the plain pipe case. Stainless steel pipe tends to provide better critical strain performance because of the small change in slope of the stress-strain curve near the yield point.

Murphey and Langner(39) had suggested a multiplying factor of 0.5 for pipe that is "inhomogeneous, with significant point-to-point variations in either the wall thickness or the yield stress". This suggestion was not taken up by subsequent codes and standards as it relates to girth-welded pipes. Their suggestion appears to be based primarily on data for tubes with D/t greater than 50.

Buckles need not be found exclusively adjacent to girth welds in a welded pipeline. Several examples can be cited of buckling failures in areas of significant ground motion that showed concertina buckling in base metal remote from a weld.(11,46) Indeed Gresnigt(47) reports a full-scale buckling test on API 5L X52 pipe with a girth weld in the constant moment region that buckled remote from the girth weld. The pipe size was 609.6-mm diameter and 6.4-mm-wall thickness.

3.4 Information from Weld Fracture Studies

Bend testing of pipes to determine weld fracture resistance has been done with local loading placed on the compression side to bend the pipe. Many cases(48,49) have been observed where the pipe does not fracture, but rather buckles on the compression side at the location of the localized loading.

The critical value of global compressive strain for buckling has been observed to be lower in these tests than in standard buckling tests. Since the amount of instrumentation to measure compressive strain is usually very limited in these tests, the strain estimates have not been included in the results shown in the previous section. Berge et al.(48) reported buckles at critical global strains from 1.8 to 3.5% on welded pipe with D/t of 18.

The limited discussions of buckling modes suggest that localized loading extended the range where the localized buckling mode dominated over the ovalization mode. The Berge[48] results, for instance, described localized buckling rather than ovalization, even though the D/t of 18 would be well within the range where ovalization would dominate under standard buckling test conditions.

3.5 Effect of Internal Pressure

Internal pressure increases resistance to local buckling because the tensile hoop stress it creates helps the pipe resist the diametrical changes that occur locally at the buckle. The amount of the increase in critical longitudinal strain with pressure has been an object of disagreement between different groups of investigators. The hoop stress due to the internal pressure has been recognized as the primary parameter, but this is normalized by either the elastic modulus or the yield strength in different formulations.

Internal pressure also tends to suppress some shapes of buckle, in particular. The diamond-shaped buckle is suppressed in preference to an outward bulge.

The DNV 2000 standard[1] multiplies the allowable critical strain by a factor of $(1+5\sigma_h/f_y)$ where σ_h is the hoop stress from internal pressure and f_y is the yield strength of the pipe multiplied by a safety factor. The previous edition had used an additive term of $5\sigma_h\alpha_{gw}/E$. Gresnigt suggested adding a term of $3000\,(PD/2tE)^2$ where P is the internal pressure and E is the elastic modulus. This form is used by CSA Z662-99. Zimmerman et al.[16] calculated pressure effects for a variety of stress-strain curve shapes and report a particular one with an additive term of $340\,(120\text{-D/t})(\sigma_h/E)^2$.

If the experimental critical strains from tests of both pipes under internal pressure and pipes with no pressure are available, removing the correction for internal pressure should make them roughly coincide.

A plot of this type for plain pipe[32,42,50] is shown in Figure 5. The DNV 2000[1] method provides reasonable agreement between no pressure and pressure tests with the pressure correction removed, although a group of test results falls below the no pressure band once the pressure correction is removed. The test results in this group tend to be for larger-diameter pipe and for intermediate values of hoop stress-to-yield strength ratio, for instance 0.2 to 0.5.

A plot of this type for steel pipe with girth welds[16,32,42,51] is shown in Figure 6. None of the methods provide good results over all the available data. The behavior of the pressure correction terms is usually more reasonable for D/t<65 than for higher D/t values. DNV 2000,[1] Gresnigt,[47] and Zimmerman[13] all over-predict the effect of pressure, while DNV 1996[14] was conservative in most cases. One case where it is not conservative is discussed below in the section on yield-to-tensile strength (Y/T) ratio.

The existence of cases where the additive methods cause negative critical strains on Figure 6 suggests that the multiplying factor method has advantages. However, a factor with a much smaller effect of pressure is needed. A preliminary model can use a similar form to the DNV 2000[1] factor with a smaller effect of pressure of the form $(1+\sigma_h/\sigma_y)$. Figure 7 shows that this preliminary model brings the no-pressure data and the pressurized data nearly into coincidence.

The effect of this new pressure correction term can be observed in Figure 4 where data for pipes with internal pressure has been corrected using the new term both for plain pipes and girth-welded pipes.

There is a significant difference between plain pipes and pipes with girth welds in terms of their critical compressive strains with applied internal pressure. This difference may relate to the shapes of the buckles that are most affected by the girth weld and by internal pressure. Both tend to make the outward circumferential bulge the preferred shape, while discouraging other buckle shapes.

3.6 Effect of External Pressure

External pressure reduces the resistance to local buckling. It can also create the possibility of a propagating buckle, a local buckle that extends along the pipe leaving a section of collapsed pipe.

The DNV 2000[1] requirement can be rearranged to a similar form to the effect of internal pressure. This leaves the multiplier for external pressure as $(1-ap_e/p_c)^{1.25}$, where a is a safety factor between 1.2 and 1.5, p_e is the external pressure and p_c is the characteristic resistance for external pressure.

API 1111[25] uses a requirement that has the form of a multiplier of $(g-p_e/p_c)$, where g is the correction factor for initial ovality. There is also a restriction on the maximum ratio of p_e/p_c to no more than 0.7 for seamless pipe or ERW pipe and 0.6 for double-submerged arc-welded pipe.

The two-part requirement in API 1111[25] tends to be more conservative for very high external pressure or low external pressure, but less conservative for intermediate cases just below the maximum of p_e/p_c.[26]

Corona and Kyriakides[37] demonstrated a significant difference in buckling resistance based upon the order in which the external pressure and bending loading are applied. Pipe tests where the bending is applied first can achieve higher combinations of pressure and curvature than either cases where the pressure is applied first or where the pressure and bending are applied in alternating steps.

3.7 Y/T Ratio

The Y/T ratio was included as a parameter in the DNV Submarine Pipeline Systems standard in the 2000 edition[1] within the equation for displacement-controlled local buckling strain. This equation was the first to genuinely recognize that material properties in the plastic range can change the performance of the pipe wall in local buckling. Yet a guidance note recommends that only two values of the Y/T ratio be used, 0.90 and 0.92, and these differ by less than 5% in the resulting allowable critical strain.

This is a relatively small effect compared to that predicted by Korol,[33] who used the tangent modulus method and predicted that the critical strain could be reduced by a factor of 4 if the D/t was 33 and the ratio of elastic modulus divided by tangent modulus increased from 2.5 to 100.

Testing experience has indicated to several investigators that the shape of the plastic part of the stress-strain curve is critical to the local buckling performance in the plastic regime. Murphey and Langner[39] proposed a reduction in their predicted design strain of 0.5 to 0.3 D/t to account for pipe materials with flat stress-strain curves. They defined flat curves as those where the slope of the engineering stress/engineering strain curves goes to zero or becomes negative.

Variation in results of tests at the University of Alberta[32] has also been explained by examining differences in the plastic part of the stress-strain curve. The low critical strain of one pipe near D/t of 60 tested with high internal pressure can be noted in Figure 6. This specimen, with diameter of 508 mm and wall thickness of 8.37 mm, was designated L178P80BW-1.

Experience with cold field bending of pipe[18-20] has indicated that different pipes from within the same grade and even the same heat lot may show significantly different buckling characteristics.

The shape of the stress-strain curve at small multiples of the yield strain has been found to be an important parameter in the resistance to ductile fracture. ECAs that include the stress-strain curve information are required by DNV 2000[1] for cases where the accumulated plastic strain is 0.3% or more. Information from this type of testing could also be used to significantly improve the estimate of the local buckling resistance. However, even this information is not the most directly relevant to local buckling, since it is obtained in tension rather than compression.

A parameter that should be more effective at estimating the performance than the Y/T ratio is the work-hardening ratio as defined by Anelli et al.[52], the ratio of the tensile stress at 0.5% strain to the tensile stress at 3.0% strain. This parameter appears to be reasonably repeatable within a heat of pipe. Anelli[52] shows variation of this value for X65 sour service line pipe only between 0.92 and 0.94.

There is sufficient information in the API report of Sherman[45] to estimate the work-hardening ratio for the pipes used. All of Sherman's[45] pipes showed a plateau on the stress-strain curve. Figures 8 and 9 show the effect of work-hardening ratio and steel grade on the critical compressive strain. Higher work-hardening ratio does reduce the critical strain on average. However, the effect is difficult to discern among the scatter.

Suzuki et al.[50] reported the development of pipe with improved buckling resistance, based upon increasing the strain hardening and avoiding a plateau on the stress-strain curve at yielding. The strain hardening of interest was over the range of 1 to 4% strain. The primary testing method used axial compression, but the results were confirmed for bending loading. Results have not been reported for girth-welded pipe that uses base pipe material with improved buckling resistance.

The description of a plateau in the stress-strain curve covers both cases of Lüders yielding directly after a sharp yield point and cases where flat regions of the stress-strain curve occur after some work hardening. As noted earlier, the tangent modulus, the slope of the stress-strain curve at a given point, goes to zero at such plateaus, and this correlates to lower expected buckling resistance.

3.8 Yield Strength as a Separate Parameter

Pipe and pipeline assessments have historically not used the standard minimum yield strength (SMYS) of the pipe material as one of the parameters for assessing critical strain. Similar assessments of structural elements have recommended including either the SMYS or its square root within the assessment for local buckling, such as for plate elements or structural sections.

API RP2A for offshore platform structures uses SMYS as part of the assessment for local buckling strain capacity of circular hollow sections.

Korol[33] used an equation for critical strain that gave critical strain as proportional to the yield strength to a negative power between 0 and -1. He then derived the exponent based upon calculations including the effect of D/t and the ratio of elastic modulus to tangent modulus, λ. He concluded that it was reasonable to use the power of -1 in standards since it was appropriate to materials with stress-strain plateaus and to large values of D/t. He recognized that an exponent nearer -0.5 might be considered for the boundary between plastic design and compact section cases.

Dorey, Murray, and Cheng[32] noted that the data collected at the University of Alberta would support a conclusion that yield strength was an important parameter. Much of that data is for pipes with internal pressure.

The HOTPIPE project models[53] that were used to calculate the allowable level for bending strain in DNV 2000[1] did not include yield strength as a variable. Two values of hardening exponent within the Ramberg-Osgood formulation were used for X65 pipe.

The Suzuki et al.[50] results for plain pipe in axial compression do not show a strong effect of yield strength over a range of strengths from 442 to 579 MPa. The effects of behavior near yield (round-house or plateau) and strain hardening between 1 and 4% strain were much greater than those due to yield strength.

The critical strain data shown above for girth-welded pipes and girth-welded pipes with internal pressure can be plotted to show the effect of yield strength. Figure 9 shows the results using the new internal pressure correction for girth-welded pipes described earlier. The test results indicate an effect of yield strength, although the change is only 50% on critical strain over the entire range of data from 250 to 550 MPa. A greater effect of yield strength is noted for the pressurized pipes than for those without pressure.

The greater effect of yield strength on pressurized girth-welded pipe may come from many causes, including the individual selection of pipes for testing. The change of buckling mode with increased internal pressure toward an outward buckle adjacent to the girth weld may tend to make the pipe more sensitive to the pipe yield strength.

3.9 Summary

The critical strain at the peak compressive stress along the pipe axis has weaknesses in predicting the behavior of pipelines being designed for plastic strain. It remains the primary parameter of comparison because it can provide a conservative bound to all intermediate states between load-controlled situations and displacement-controlled situations.

Local buckling of girth-welded tubes shows critical compressive strains that are lower than for plain pipe by approximately the girth weld factor in DNV 2000.[1] The estimate is very sensitive to the small number of welded pipes reported with low D/t.

Internal pressure has been accounted for by widely differing methods in different recommendations and standards for preventing local buckling of pipelines. The DNV 2000[1] recommendations over-predict the effect of pressure when compared to tests of girth-welded pipes, such as those reported by Dorey, Murray, and Cheng.[32] A simpler model that lessens the effect of pressure can better account for these data.

Measures of the material strain-hardening properties in terms of Y/T ratio provide a very poor estimate of the effect of post-yield behavior on local buckling plastic strain capacity.

Measures of the material strain-hardening properties that account for the behavior near the yield strain can provide better estimates of the effect of post-yield behavior on local buckling plastic strain capacity. One such measure is the ratio of the tensile stress at 0.5% strain to the tensile stress at 3.0% strain.

Yield strength should be recognized as an important parameter for assessment of the risk of local buckling, particularly for materials with a strong change of slope in the stress-strain curve near the yield point. A higher yield strength correlates to a lower critical strain for local buckling.

The effects of higher yield strength on buckling resistance can be minimized or reversed by the choice of material without a yield plateau and with greater work hardening at strains just above yielding. While tests have shown this effect in plain pipe, testing has not yet shown this behavior in girth-welded pipe.

4.0 Factors in Choosing Material Based on Tension Stress-Strain Behavior

When forces and/or displacements are applied that take the pipeline beyond its elastic capacity, it is advantageous to distribute the plastic strain over a large amount of material rather than localize the strain on a small amount of material. That way, a higher overall strain can be reached before any individual area exceeds its strain capacity. Strain hardening of plastically deformed steel will help to distribute the strains over a wider area as the overall plastic strain increases.

Pipeline steel strain hardening capacity has historically been controlled by placing a minimum requirement on the elongation to failure of the pipe material and of the weld material and by requiring a minimum difference between the yield and ultimate strength of the pipe steel. In addition, the weld metal is required to have both minimum yield strength and minimum ultimate strength that match or overmatch the base metal. The difference between the yield and ultimate strength of the base metal is often expressed as a maximum of the ratio of the Y/T.

These four parameters can be set and placed in purchasing requirements relatively early in the design process.

There are occasionally problems later in the material qualification or welding qualification stage when one of the four parameters is not met. This tends to be a problem most when attempting to qualify welding onto base materials that have yield strengths well above the minimum required. This can leave the Y/T ratio of the pipe too high. It is also possible that higher strength base material may leave the weld metal undermatched with respect to the actual yield strength of the base metal.

Localized deformation modes may make it more important to choose material properties that reduce the local accumulation of strain in any one area. For instance, the reeling process may localize bending adjacent to the reel. Here, it may be important to avoid not only lower strength weld metal, but also low yield strength of the pipe on one side of a weld joint where that side of the joint may accumulate local strain without accompanying plastic strain in the weld or in the pipe on the other side.[(1)]

4.1 Choosing Maximum Y/T Ratio

A common specification limit is 0.92 for Y/T. API 5L restricts the Y/T of cold-expanded steel pipe to 0.93.

The EPRG has studied the effect of higher Y/T on strain capacity of base metal with defects. A higher Y/T was seen to reduce the conservatism of the design very slightly under strain-based loadings.

The DNV 2000[(1)] standard provides a recommendation that base metal for use in conditions with accumulated plastic strain >2% meet a lower Y/T value of 0.85. The requirement is that transverse Y/T be 0.92 or lower for SMYS at 415 MPa or greater and 0.90 or lower for SMYS below that value.

The measured value of Y/T is critically dependent upon the direction of testing and the procedures for extracting a tensile specimen. The tensile testing section below gives more information.

4.2 Choosing Elongation-to-Failure Limits for Pipe Material

Standard values for tensile elongation of pipe material are usually considered sufficient, both for stress-controlled applications and strain-controlled applications.

The minimum elongation (e) values for pipe to API 5L[(54)] are given by an equation based on the specified minimum ultimate tensile strength (U) and the cross-sectional area (A) of the tensile test specimen. The minimum elongation in 2 in. is given in percent to the nearest ½%. In the U.S. customary units (in., lb), the equations is $e = 625{,}000\ (A)^{0.2} / (U)^{0.9}$.

DNV 2000[(1)] provides a recommendation that pipe for service at accumulated plastic strain of 2% or more have elongation of 25%. The minimum requirement is 18% for steels with SMYS ≥415 MPa and 20 to 22% for steels of lower strength.

4.3 Choosing Elongation-to-Failure Limits for Weld Material

Standard values for tensile elongation of weld metal are usually considered sufficient.

The minimum elongation values for deposited weld metal are given in the AWS A5 specification for the filler material.

4.4 Choosing Minimum and Maximum Weld Metal Strengths

The minimum weld metal yield strength is usually set with two requirements, one from the weld metal grade chosen and one based on setting the weld metal strength relative to the base metal strength. The weld metal grade chosen will limit minimum weld yield and ultimate strengths and also can implicitly limit the maximum strengths, based on the chemistry and operating characteristics of the electrode.

DNV 2000 says that the weld metal yield strength should exceed the base metal SMYS by an amount within a given range of offsets.(1) For welds without accumulated plastic strain, the offset range is 80 to 250 MPa. For welds with accumulated plastic strain, the offset range is 80 to 200 MPa. This is, of course, for welds in base material that is itself recommended not to exceed SMYS in yield strength by 100 MPa. These are not requirements, as expressed by the use of "should" rather than "shall". The requirement is that the weld metal must have strength, ductility, and toughness meeting the requirements of the base metal. The weld metal qualification notes that the weld metal and base metal yield strengths should not differ by more than 100 MPa.

When the weld metal strength is discussed, it is common to make an exception for the weld root area. This area is often welded with a lower-strength filler material that improves the resistance to the formation of welding defects. Lower-strength filler for the root region is not used for automatic welding offshore.

Variation of weld metal strength may be observed, both between electrodes and between positions on the pipe where those electrodes were used.(55) Lot testing of electrodes may be used to prevent excessive variation of strength of the resulting welds in comparison to the pipe material. Lot testing is discussed further in relation to engineering critical assessment (ECA), since toughness, in addition to strength, can vary from lot to lot within electrodes of the same grade.

Strength can also vary because the welding procedure must change when welding pipe whose axis is horizontal to account for the effect of gravity on the weld pool. In some instances, lower strengths are observed on the lower half of the pipe.(56) Thus, strength and toughness tests are placed at multiple points around the circumference.

4.5 Remedial Measures for High Y/T

When the pipe material is found to have a higher Y/T ratio than expected, some of the safety margin against local failures has essentially been removed. This safety margin may be rebuilt by more extensive analysis of the local failure modes and the types of resistance available to prevent failures by those modes.

One part of this can be ECA, using toughness data and fracture mechanics methods to demonstrate the safety margin in the presence of imperfections.

4.6 Remedial Measures for Undermatched Weld Metal

Undermatched weld metal has the potential to reduce safety margins on allowable strain by concentrating plastic strain in the weld metal. As just noted for Y/T of base metal, the safety margin may be rebuilt with more extensive assessment of local failure modes and the types of resistance available to prevent failure by those modes.

ECA may become both more important and more difficult for undermatched welds. Procedures recommended for mismatched welds tend to account conservatively for the concentrated plastic strain. Thus, the required toughness to resist fracture for a given flaw can increase rapidly with the level of undermatch in yield strength.

Differences in the base metal strength in the hoop and axial direction may affect the determination of undermatch. If a weld appears to be undermatched on a comparison of all-weld metal tensile strength to pipe hoop strength, testing of the pipe in the axial direction may show that the weld is less undermatched or not undermatched compared to that direction.

Buckling tends to be spread much wider than the width of an individual girth weld. So there is less connection between undermatch and buckling than there is between undermatch and the tensile failure modes. Testing has demonstrated that local buckling is not sensitive to weld metal mismatched at 75% of the base metal yield strength.(57)

4.7 Tensile Testing

Several methods are used for defining yield strength from a tensile test record. The 0.5% total strain (often abbreviated in European publications as Rt0.5) criterion is used for pipeline steels. Other criteria, such as the upper yield point or the 0.2% plastic strain offset are widely used, but are not standard for pipeline steels.(58)

There is a noticeable effect of the previous strain history of the pipe and the tensile specimen on the measured yield strength of linepipe materials, particularly those with high tensile strengths. Some standards, API 5L notably among them, allow both the use of round cross-section machined bar specimens and flattened transverse rectangular cross-section bars. The machined round bars do not add a plastic deformation step, but cannot test the entire cross-section. The flattened rectangular bar tends, for all pipes that can meet X70 or greater, to provide lower yield strengths due to the Bauschinger effect on reversed loading.

Longitudinal properties tend to be similar to transverse properties, except that UOE pipe tends to have a lower yield strength in the longitudinal direction.(59) The difference between the longitudinal and hoop direction yield strengths of the pipe material may be crucial to determining the acceptable flaws in the girth weld area, since the girth weld yield strength can best be compared to the pipe longitudinal yield strength when determining the strain expected in the weld area. In rare cases, large strain leading to failure may be induced longitudinally in a pipe when loaded in tension to values expected to be acceptable based upon measured transverse properties only.

The measurement of tensile strength, but not yield strength, is changed based on the testing method. Tensile testing using force control, which is standard at manufacturers, will cover the range between the yield load and the tensile load very quickly. The rapid loading rate, possibly above the allowable standard of ASTM E8,(60) will tend to increase the strain hardening and give a higher tensile strength and greater appearance of strain hardening. Constant displacement tests, which more closely model strain rates in service, will tend to provide a lower ultimate tensile strength because the loading rate in the plastic region will be lower. This effect will be most noticeable for low work-hardening materials, that is, those that may be near the upper allowable limit for Y/T.

This can become important when comparing weld metal qualification tests to manufacturer’s tests on the pipe material, or when comparing longitudinal testing of the pipe material as part of qualification for strain-based service to manufacturer’s tests in the transverse direction on pipe material.

4.7.1 Tensile Testing of Weld Metals

Tensile testing of weld metals can add extra complexity to the choices in tensile testing because of the limited extent of the weld. Strap tensile specimens taken across the weld are the simplest to cut from the pipe, but may give only qualitative information, such as when the specimen fails outside the weld area, about the weld mechanical properties. The strap tensile specimen can be improved from the point of view of determining properties related to the weld by notching at the weld and by removing the additional weld material at the weld root and weld cap.

All-weld metal tensile specimens can be used reliably to give mechanical properties of the weld metal itself. These properties are used for both the longitudinal and transverse directions compared to the axis of the weld.

5.0 Optimizing Pipe Material for Strain-Based Design: Tension and Compression Strain

Pipe material for strain-based design pipelines can be chosen within relatively broad requirements as described above. Higher levels of acceptable strain or other attributes desirable in design, such as a weld metal with easier operation or larger allowable flaw sizes for inspection, can be obtained by optimizing the mechanical properties of the base pipe material. However, not all changes to the base metal mechanical properties that improve one desirable parameter improve the others.

Looking at the base metal longitudinal tensile properties, we can consider the properties described above (yield strength, tensile strength, and elongation to failure) and in addition consider the shape of the tensile stress-strain curve near yield (smooth or plateau), the uniform elongation (elongation at the ultimate tensile strength), and the amount of work-hardening within the first few percent strain.

When designing girth-welded pipelines for high strains, the possibility of failure under both tension and compression must be considered. Table 2[61,62] lists base metal parameters and their effect on compression and tension resistance. Note that the qualitative effects can cancel one another and that magnitudes are not given. It is quite possible to have higher yield strength pipe material with higher resistance to both compressive buckling and to tension failure at the girth weld, by changing other parameters in Table 2 as well.

There may be some advantage to choosing material that has properties skewed to resist the most important failure mode, either tensile or compressive. This principle can also be used to suggest that pipe might be chosen with high strain capacity in the longitudinal direction and high strength in the hoop direction to resist the load-controlled loading from internal pressure.

5.1 Range of Materials

Carbon steels to API 5L, such as X60, X65 and, X70, predominate in the discussion of strain-based design of pipelines because of their widespread use in such applications. However, other materials may be chosen for particular properties, such as resistance to corrosion from internal or external fluids.

Duplex stainless steels have been applied for reeled pipe with notable applications for North Sea fields.(63) Pipes are qualified for reeling both by full-scale tests and by small-scale tests for fracture toughness and microstructure on material subjected to strain cycles. Some examples of buckling problems have been observed on the layship during installation of reeled pipe.

Titanium alloy pipelines have been considered for reeled applications.(64) They have also been applied in riser systems and as end connections for risers systems at tapered stress joints. The titanium alloys used are either Ti-6Al-4V extra-low interstitial (ELI) with ELI or derivative grades that have small additions of palladium or ruthenium for improved corrosion resistance. Titanium, when used in combination with carbon steel, may preferentially attract strain because of the lower elastic modulus of the titanium. Det Norske Veritas (DNV) has proposed a recommended practice for design of titanium risers,(65) which refers to the more general standard for dynamic risers for the displacement-controlled loading provisions.(66)

5.2 Corrosion Protection and Weight Coating

It has been suggested that above 0.5% strain the coating system may need to take account of the pipe strain. This would require a different approach to weight coating to avoid cracking and displacement of the concrete, but also the choice of a pipeline coating that can accept being uncovered. The standard coating placed between pipe steel and weight coat is not designed to be exposed alone without the weight coating.

The effect of plastic strain upon the coating has been used as a reason for providing a maximum allowable strain at local buckles on the intrados of bends.

The anticorrosion measures taken on the pipe may need to be checked for their strain resistance.(67) This would include both the anodes and their connections to the pipeline. Anodes are usually attached after the pipe is straightened when using reeled pipe.

6.0 Prevention of Strain Localization around Girth Welds

Pipes under longitudinal plastic strain can concentrate plastic strain in regions in or adjacent to the girth welds. This concentration can occur in the weld metal, for instance, due to choice of welding materials with lower strength than the base pipe or due to variability of pipe strength compared to the weld metal strength that can leave a small proportion of the girth welds or even part of the girth welds with lower yield strength than adjacent pipe material. It can also occur in the adjacent regions of the heat-affected zone (HAZ), which can soften relative to the base pipe for some materials. This section examines these strain concentrations and the available means to prevent or limit them. Also in this section are short discussions of other local strain concentrations in pipe walls such as those from corrosion, dents, and changes in the external coating.

The representation of the girth weld area by only the elongation and the minimum yield and ultimate strength leaves out much of the complexity of the girth weld region. The strength and strain-hardening properties will vary across the HAZ adjacent to the weld. In addition, the weld metal may not be of uniform strength. The root of the weld, for instance, may be made with lower strength weld metal to reduce the risk of cracking during welding.

Thus, there are many details that come into play as the girth weld must be qualified.

Strain localization will be opposed not only by strain hardening, but also by the restraint of adjacent material that does not deform as much as the local material. Restraint is particularly effective when the local area of strain concentration is small.

Preventing excessive strain localization by restraint requires limiting the size of the low-strength region. This brings in additional parameters for an assessment of the girth weld region, such as the weld width, the width of regions of lower weld metal strength, and the width of the HAZ.

The method of preventing excessive strain localization by restraint sounds directly contrary to the idea described earlier of having as much of the structure as possible take up the plastic strain. Indeed, when plastic strain begins, the low-strength material of limited size does carry all the plastic deformation. That low-strength material can have a rapid increase in plastic strain, a "burst", as loading or displacement increases. That burst of plastic strain can come to a close when the deformation gets large enough that plasticity in the adjacent higher-strength material is required to fit up to the already plastically deformed lower-strength material. After the burst of plastic strain is complete, the structure switches to a more uniform distribution of plastic deformation.

6.1 Strain Concentration at the Girth Weld

Strain may be concentrated at the girth weld by:

- Shape of the cap
- Shape of the root
- Misalignment of the pipe wall centers across the weld
- Differences in thickness across the weld
- Pipe ovality
- Differences in strength in and around the weld.

Ovality and differences in thickness can cause "high-low" across the weld, which is the primary geometrical strain concentrator for local elastic strain at girth welds. High-low is measured as an eccentricity of the mid-thickness position between the two sides of a weld.

Strain concentration may be determined from elastic stress concentrations using the Neuber method. In that method, the product of the plastic stress- and strain-concentration factors is set equal to the square of the elastic stress-concentration factor (SCF). If the stress increase is small, that is, there is little strain hardening, the plastic strain-concentration factor will be the square of the elastic SCF.

DNV 2000[(1)] requires that the pipe material meet additional quality requirements if it is to be used for accumulated plastic strains $\geq$2%. The quality requirements increase pipe inspection and restrict the maximum differences between the pipe end thicknesses and the local wall thickness variation.

These improvements in required quality will help to reduce the misalignment bending stresses at the girth welds.

Buitrago and Zettlemoyer[(68)] note that it is difficult to achieve SCF<1.2 with seamless pipe without special procedures to match the ends. Welded pipe can achieve closer tolerances for ovality and thickness variation, and thus a lower SCF.

The shape of the weld cap and root shape are usually considered to be very important for resistance to high-cycle fatigue. Strict controls have been placed on these configurations for risers. However, for plastic design or low-cycle fatigue, the shape of the weld toe is considered to be less critical, since the stress concentration will be smoothed out by the plastic deformation. H. A. Bratfos[69] recommends that the effect of cap and root shape be included using the Mk method from BS 7910[70] rather than a blanket strain concentration factor through the entire thickness. The Mk method allows for an increase in local stress only in the part of the pipe wall closely adjacent to the surface.

6.2 HAZ Softening

In most carbon steels, the HAZ increases in hardness and strength when welded. However, some combinations of steels and welding heat inputs can cause the HAZ to soften and become a location where strain accumulation can occur.

Studies[71] have concluded that the soft zone does not provide enough loss in strain capacity in pipes to pose a risk to integrity without either defects in the HAZ or cyclic plastic loading. The burst of plastic strain in the lower strength HAZ was also observed to be reduced at lower D/t ratios, so that no burst was observed for D/t below 24. A study on the strain capacity of the HAZs in the trans-Alaska Pipeline System also concluded that there was no apparent reduction in strain capacity compared to the base metal.[28]

Welding at high heat inputs tends to promote HAZ softening. It can also promote a wider HAZ that reduces the constraint from the adjacent weld metal and base metal.

Steels subject to HAZ softening tend to be those with higher strength and with carbide precipitates that are strongly affected in size and distribution by the welding heat in the HAZ. For instance, niobium additions have been noted as providing more stable metal carbides in the HAZ than vanadium carbides, thus preventing or reducing HAZ softening.

Cyclic deformation of material with softened HAZs may cause premature failure when the strain capacity of the HAZ is used up without fully activating the restraint of the adjacent base metal. As the direction of loading is reversed, the Bauschinger effect may lower the yield strength in the plastically deformed material, which will tend to keep the deformation localized in the HAZ.

EWI used finite-element models and aluminum tube specimens to examine the effects of softened HAZs on strain concentration. These examinations are described in Appendix A.

EWI's examinations showed a strong effect of the internal pressure stress on the strain concentration in softened HAZs. These examinations showed that the strain concentrations are much more sensitive to the level of internal overpressure than to variables such as the diameter-to-thickness (D/t) ratio. Common levels of hoop tensile stress during pressurized pipeline operation would be sufficient. EWI examined cases where the hoop stress was 35 and 70% of the base metal yield strength.

The aluminum model tests on two aluminum tubes with partial-penetration girth welds showed much higher strain concentration in the HAZ of the tube with internal pressure. However, the remote strain to failure did not differ by a similar amount.

This work highlights that previous work on samples without internal pressure effects may be unconservative for application to conditions where plastic strains could be applied to pressurized pipe. Methods that use small-scale specimens or curved wide-plate tests to determine strain concentrations may miss the concentrations that have been increased by the internal pressure interaction.

6.3 Wall Loss and Corrosion

Corrosion and other mechanisms that locally reduce the wall thickness may create strain concentrations of their own. Some examinations of the effects of local wall loss in combination with strain-based loading have been completed. These have demonstrated failures from fracture, burst from internal pressure, and wrinkling followed by rupture,[(72)] with loading providing combinations of internal pressure, axial loading, and bending loading.

Strain capacity of the area of reduced wall thickness was noted to be of particular importance, with the strain of interest combining hoop and axial strain. The difference between load control and displacement control on the bending was noted to be of particular importance, because plastification of the thin section from internal pressure allowed much of the applied moment to be relieved at constant displacement.

6.4 Dents and Gouges

Local changes in wall thickness or wall shape, such as dents and gouges induced by installation or operation, concentrate strain and stress. The concentrations in strain may be estimated using the Neuber notch approach from the concentration of stress. This approach may break down for cases where the plastic strain is not restrained by neighboring elastic regions.

Dent size may be estimated by finite-element modeling for a given loading condition. Large deformation, elastic-plastic assessment may be needed in addition to accounting for high strain rate material properties for impact events.

Dents, gouges, and local corrosion areas can act as preferred sites for fatigue cracking under cyclic loading. Areas that appear to be acceptable on a strain-based assessment may need repair to avoid fatigue failure.

6.5 Concrete Weight Coating or Thermal Insulation Coating

Concrete weight coating in offshore pipelines that is used for sea bottom service will not be continued across field weld joints. This may cause bending loads to be concentrated around the field welds as the stiffness of the pipe alone is lower than the weight-coated pipe composite. The span of this stiffness change may need to be considered to change with time if the load is in place more than a few minutes and the corrosion coating between the pipe and the weight coating can creep at the ambient temperature.

Strain concentrations in excess of 1.4 have been observed.(73,74) Strain concentrations are increased by greater weight coat thickness and by higher concrete crushing strength.

It is possible to design the concrete with notches that will prevent the longitudinal compressive loads from being carried in the concrete.

Strain has also been reported to be concentrated by changes in the external anti-corrosion coating in the area of field joints.(75) This only becomes an issue when the tangent modulus of the steel becomes very small, that is when the steel is at its yield plateau. In this regime, the modulus of the corrosion coating may be close to or even exceed that of the underlying steel. In these conditions, a lower modulus of the external coating in the area of a field joint can direct more strain into the steel.

6.6 Misalignment Across Girth Welds

The Northstar project used a maximum-allowable misalignment (high-low) of 3/32 in. (2.4 mm) across girth welds in API X-52 10.75-in. OD × 0.594-in. wall seamless pipe.(76) This is a 16% misalignment based upon the nominal wall thickness. This is very similar to the visual acceptance criteria in DNV 2000 where all misalignment is limited to 15% of the nominal wall thickness with a maximum of 3 mm. Smaller values of misalignment are commonly specified for offshore construction, such as 1/16 in. (1.6 mm) or even smaller.

7.0 Qualification of Pipe

7.1 Qualification of Base Pipe Material

L. Collberg and K. Mørk[4] reported that much of the discussion of DNV 1996 surrounded the requirements for base pipe mechanical properties for accumulated plastic strain. These requirements were changed into recommendations in the 2000 edition. They also warned that enhanced mechanical properties may still be required as pipe of higher strength grades is used for accumulated plastic strain.

DNV 2000[1] requires pipe material that is to be used for displacement-controlled conditions to meet a more stringent requirement ("Level I") for inspection of transverse defects. The Level I requirement adds an ultrasonic inspection of transverse imperfections in the pipe body of seamless pipe and a surface inspection of transverse surface imperfections. Both of these inspections are required for the first 20 pipe sections. If acceptable results are obtained, thereafter random testing of 10% of pipe sections is required.

The surface inspection for transverse imperfection may be done with eddy current, flux leakage, or magnetic particle testing for ferritic pipe. For non-ferritic pipe, eddy current testing or dye-penetrant testing may be used.

No lower limit on the amount of displacement-controlled strain is given for the requirements of Level I. However, if the pipe design can be reconsidered as a load-controlled situation with sufficiently low stress to meet those design requirements, it can be assessed to the lower Level II.

7.2 Qualification of Weld Seam in Pipe

DNV 2000[1] requires the weld seam of welded pipe for displacement-controlled conditions (Level I) to meet an expanded requirement for inspection of transverse imperfections in the weld area. There is an exception given so that no inspection of this type is required for high-frequency-welded (HFW), electron beam-welded (EBW), and laser-welded (LBW) pipe. The application is thus to submerged arc welding (SAW) pipe with longitudinal or spiral seams. The requirement increases from 5% of pipe for load-controlled situations to 100% of pipe for displacement-controlled situations.

7.3 Qualification of Welding Procedures

7.3.1 Batch Testing of Welding Materials for Girth Welds

Batch testing of all welding consumables is required by DNV 2000[1] when ECA is performed or the SMYS ≥ 415 MPa. This requirement applies for lines with accumulated plastic strain >2% since the ECA is required for those lines as described below. The batch tests require specimens from girth welds: an all-weld metal tensile with hardness measurement, a macro with hardness measurement, one set of Charpy V-notch tests from the weld centerline at half-thickness, and fracture toughness testing, if required by the ECA.

CSA Z662[31] requires batch testing of welding consumables when the ECA method in Appendix K is used.

Batch testing is required by these standards so that the fracture toughness values used by ECA, as well as the strength values, are based on data with a smaller variability. Some of the variability in fracture toughness is recognized to come from variations in chemistry and processing variations within the normal range of electrode production. However, similar variations can also occur from other causes, such as differences in welding procedure.

7.3.2 Resistance to Weld Cracking

Risk of cracking during welding has been seen as one of the reasons for placing an upper limit on weld metal yield strength. Higher-strength weld metals have been observed to be more sensitive to cracking mechanisms involving hydrogen. Since weld metal cracking is most likely in the root pass, welding procedures that change strength of the welding consumable after the root or hot pass have been developed. As this indicates, use of proper consumables and procedures can minimize cracking risk.

Standard parts of the qualification (bend testing, metallographic examination, and Charpy V-notch impact testing) are in place for all pipe welds to help catch this cracking at the qualification stage. The risk of this cracking will tend to prevent higher strength consumables from being used.

The tendency will then be to use welding consumables that match the most likely pipe strength with the mostly likely weld metal strength to within a few percent.

7.4 Resistance to Strain Aging

Strain aging is the reduction of ductility and toughness that can occur after plastic deformation has been applied in carbon-manganese steels. Strain aging is particularly noted in steels that exhibit discontinuous yielding with an upper yield point, a lower yield point, and a yield plateau before strain hardening begins. Strain aging may occur at ambient temperatures and may be speeded by mild increases in temperature above ambient.

DNV 2000(1) requires several additional tests to account for strain-aging effects on strength, ductility, and toughness on materials where the accumulated plastic strain will exceed 2%. The material must be tested after tension and compression loading has been applied to reach at least the design accumulated plastic strain and after an artificial age at 250°C for 1 hr.

For the base metal to be qualified it must, after this treatment, meet the normal base metal requirements for hardness, Charpy V-notch impact toughness, and for longitudinal tensile and yield strength. In addition, it must have an elongation not less than 15% and Y/T ratio not to exceed 0.97.

The girth weld areas must also be tested with applied plastic strain and artificial aging. This includes two all-weld metal tensiles, four transverse weld tensiles, one macro with hardness tests, and four sets of three Charpy V-notch impact toughness tests. The all-weld metal tests are not required if t<10 mm and the Charpy tests are not required if t<6 mm. The Charpy tests place the notches of the four sets at four locations: weld metal, fusion line (FL), FL+2 mm, and FL+5 mm.

The strain-aging resistance requirements may also have an effect on the resistance of the pipe to local buckling during bending. Material that is most susceptible to strain aging will also be the material that is most susceptible to local buckling during bending because both are correlated to large yield plateaus after a discontinuous yield point.

Some types of steel will be preferentially eliminated by the strain-aging tests from consideration for high strain applications. Electric arc furnace-melted steels will be those most sensitive to strain aging. Thermomechanical-controlled processing (TMCP) steels may also be sensitive to strain aging because of their high-dislocation density. One project used a guidance of checking for strain-aging effects when the aluminum-to-nitrogen ratio fell below 2.

Strain-aging testing programs should account for elevated temperatures that will occur during either installation or service. Coating installation procedures, both for the main pipe and the girth weld areas should be considered when choosing strain-aging conditions.

7.5 Toughness Requirements

DNV 2000[(1)] references BS 7448,[(77)] but does not require a specific test from among those within that standard. The requirement for ECA of the material for designs with accumulated plastic strain at 0.3% or up is a BS 7910[(70)] Levels 2 or 3 assessments. These levels allow the use of toughness in the forms of KI, crack-tip opening displacement (CTOD), J, and in the form of R curves for both CTOD and J. The commentary notes that Level 2 is considered safe when operational conditions (as opposed to installation) will not lead to fatigue crack growth or unstable fracture.

The commentary to DNV 2000 also specifically allows the use of specimens with shorter notches than those in BS 7448 or equivalent standards for single-edge notch bend (SENB) specimens. The notch must be deeper than any imperfections to be assessed by the ECA. The use of smaller notches may reduce the constraint around the crack tip and allow noticeably higher CTOD values or other measurements of toughness.

DNV 2000 also places some restrictions on the positions of acceptable notches for the fracture testing. The weld metal specimens must be notched in the through thickness direction and in the plane of the weld centerline. FL/HAZ specimens must be notched so that the direction of crack extension crosses the FL from the weld metal side or is parallel to the FL. The position is qualified by post-test metallography to show that the pre-crack tip is within 0.5 mm of the FL and that grain-coarsened (GC) HAZ structure be present within 0.5 mm straight ahead of the tip.

Testing of fracture toughness using tension-loaded specimens is also allowed by DNV 2000. These can more easily model the low crack tip constraint of a shallow crack in a pipe wall. The crack tip constraint must not be smaller than that for the most severe pipeline defect assessed in the subsequent ECA.

8.0 ECA Methods

ECA is primarily used in strain-based design to set the allowable flaw size for inspection or to check that the material toughness is sufficient for a given flaw size. The methods are applied to both girth- and seam-welded areas based on the engineering understanding of brittle and ductile fracture and plastic collapse.

ECA for strain-based design must use a rather high level of complexity. The assessment of flaws in areas of general plasticity was not the original domain of any of the standard assessment techniques and these have been extended to cover it by various modifications.

It is worth noting that the original form of the CTOD design curve in BS PD 6493:1980[(78)] was developed and validated in terms of strain and then converted to stress. Several of the ECA methods described below, as BS 7910 Level 1, and API 1104 Appendix A are derived from this source.

ECA methods are also applicable to fatigue. Fatigue is considered in Section 9.0 on Multiple Loading Cycles.

8.1 BS 7910:1999

BS 7910[(70)] is the most widely used standard for assessing flaws in metallic structures. It includes three primary levels of fracture assessment Level 1 for simplified assessment, Level 2 for normal assessment, and Level 3 for ductile tearing assessment. Within these levels are individual methods that use different amounts of material specific information.

Level 1, for simplified analysis, has explicit guidance for strain-based assessment. The assessment allows the plastic-collapse part of the normal Level 1 assessment to be avoided, while retaining the assessment for fracture. The fracture assessment can be done using the ratio of the maximum strain to the yield strain, rather than the ratio for stresses. The justification that the situation is strain-based requires either that the local strain at the area where the crack is placed can be reliably estimated or that the stresses fall below two limits, that the nominal stress falls below the yield strength and the nominal stress times the stress concentration falls below twice the yield strength. An elastic-plastic assessment is suggested if the crack tip strain exceeds four times the yield strain.

Levels 2 and 3 are the primary levels for fracture assessment, but do not contain explicit guidance on assessment for strain-based loading. The failure assessment diagram (FAD) format was designed based upon the R6 procedure for pressure vessels and thus the plastic-collapse check and the correlation between plastic collapse and fracture assume that load-based procedures are appropriate.

Guidance is provided in Annex I on the significance of weld strength mismatch on the fracture behavior of welded joints, including some comments on the mismatch of HAZs.

The internal surface flaws that are assessed for plastic collapse are checked using the Kastner criteria, which tend to rate larger pipe flaws more severely than other plastic-collapse criteria.

8.2 DNV 2000

The DNV 2000(1) standard adds some comments on the procedure used within BS 7910, since the procedure there is designed for stress-based rather than strain-based assessment.

A material-specific stress-strain curve is required, as noted in the commentary, so only BS 7910 Levels 2B, 3B, and 3C are accepted. For weld regions, conservative determinations require that the upper bound material-specific stress-strain curve from the base metal be used to determine the stress from the applied strain. Then the lower bound material-specific stress-strain curve from the weld metal is used to determine the resistance on the FAD. This can make the calculated fracture resistance differ markedly between under- and overmatched welds.

The maximum value of the limit-load ratio L_r is allowed to increase to the ratio of the uniaxial ultimate strength to the yield strength. For load-controlled cases, this same ratio cannot exceed the flow strength (average of yield and ultimate strength) divided by the yield strength. Also, the material-specific stress-strain curve is used in its true-stress/true-strain form rather than the more common engineering-stress/engineering-strain form.(69) This allows smooth extension of the FAD to the maximum value of the limit-load ratio.

8.3 API 1104 Appendix A

As noted above, API 1104(79) is the fabrication standard connected to design standards that restrict the allowable axial strain. It does not itself restrict the allowable axial strain. However, the method for alternative acceptance of girth weld imperfections provided in Appendix A covers axial strains of not more than 0.5%. These are the applied strains. A residual strain from the welding residual stress of 0.2% was assumed in developing the criteria.

The method within Appendix A is based upon assessment methods from an earlier version of BS 7910, BS PD 6493:1980. The current BS 7910 Level 1 provides similar methods. These methods provide a determination of the resistance to fracture, but do not include the effects of plasticity or allow for a plastic-collapse fracture mode.

Warnings have been given against applying API 1104 Appendix A criteria at greater than 0.5% strain.[80]

8.4 CSA Z662-M1999 Oil and Gas Pipeline System

Z662[31] provides alternative acceptance criteria for girth weld imperfections in Appendix K. These criteria are unusual in that no explicit accounting for residual stress was included when analyzing the base data. The requirements are based upon the level one assessment of BS PD6493 (now superceded by BS 7910) like API 1104 Appendix A. There is also a plastic failure assessment that limits the length of a flaw in a bent pipeline. The form of this requirement limits the ratio of maximum effective applied tensile bending stress to the specified minimum yield strength of the pipe to the range less than 1.03.

8.5 EPRG

The EPRG guidelines on the assessment of defects in transmission pipeline girth welds[81] were published in 1996. The EPRG guidelines for ECA provide a minimum allowable toughness for the pipe and girth weld areas and then provide a plastic-collapse assessment procedure. The plastic-collapse assessment procedure is used to set the allowable flaw size.

This assessment method, although specific to pipeline welds, may be limited in application to strain-based design cases, since the plastic-collapse assessment procedure is dependent upon methods appropriate for load-controlled cases.

8.6 ASME BPV Section XI

The ASME Boiler and Pressure Vessel Code[82] has ECA criteria for nuclear vessels and piping. The situations of primary interest to this industry differ from the energy pipeline industry in several particulars. The materials are more often stainless steels, with much higher work-hardening capacity than common pipeline steels. Also, loadings are more likely to due to pressure than due to external forces.

The screening criteria for flaws separate the ECA cases into three groups: brittle fracture, ductile tearing, and plastic collapse. Cases that reach plastic collapse are those that can reach the metal flow strength on the metal ahead of the crack.

8.7 WES TR2808

The Japan Welding Engineering Society[83] has published a guidance document that accounts for seismic loadings, both by accounting for cyclic loading effects and by accounting for dynamic (high rate) loading events. It focuses on brittle fracture, using the provisions of a previous document on brittle fracture to do the final fracture assessment. Pre-strain from earlier cycles and rate of loading are included in an assessment of the increase in flow strength. The increase in flow strength is then correlated to a temperature shift in the fracture toughness-transition curve.

8.8 Experience with ECA Applied to Strain-Based Design

Berge et al. have recently completed a set of full-scale fracture tests performed as part of the Deepipe project.[48] Remote strains up to 4% were reached in 10 tests.

They observed that conservatism inherent in the model of ductile fracture could not easily be disentangled from the conservatism that comes from the use of small-scale fracture test results with CTOD measured at maximum load.

A small amount of undermatch of weld metal strength was a feature of five of the tests. The strain concentration was not observed to be greater in the undermatched weld metal than it was in the weld metal with overmatch. This may have been limited by the width of the weld, approximately 1/3 of the pipe thickness.

These investigators found that local strain measurements for nominally identical situations varied significantly. These differences point to the variability of base and weld metal strength properties within a given weld or joint of pipe. Indeed, they reference a comment from a pipe manufacturer that X65 pipe may vary by 50 MPa in yield strength from end to end.

Pisarski et al.[84] reported an analysis of high-strain loading and reverse loading in bending. Hoo Fatt and Wang further analyzed these results and compared the original results from a

CTOD tearing assessment with their own J-R tearing assessment. The experiments and models did show some stable growth by tearing of initial flaws on both the tension side for the original bend and the tension side for the reverse bend.

8.9 Safety Factors for ECA

Safety factors are used as part of the assessment of the acceptability of imperfections for two primary purposes. First, the failure mechanism being assessed must be assessed conservatively, so that, rather than the risk of failure by that mechanism being 50 or 10%, it becomes very small. Second, effects not considered directly during the design assessment are covered by the safety factors.

Designation of safety factors for ECA is complicated by the differing effects of these factors if they are placed on different parameters, such as stress, strain, toughness, and flaw size. Safety factors may be applied on any one term individually or as partial safety factors on each of the terms to account for their individual variability.

Safety factors applied on fracture mechanics calculations for strain-based design have not been widely discussed or published, while those for stress-based design have been the subject of extensive analysis and development of reliability-based procedures.

The safety factor used for the ECA of the Northstar pipeline(30) can be used as an example for those cases where very high safety levels are required for strain-based design. There a safety factor of 3 on strain was applied, somewhat higher than the safety factor on buckling from the compression side of the pipe in bending.

Cases where the safety levels are normal or low, such as for installation without internal pressure, can be assessed with smaller safety factors on strain. However, these levels have been based on engineering judgment in individual cases and have not been collected or standardized. One example of a standardized safety factor for ECA comes from CSA Z662:1999(31) which uses a safety factor of 1.5 on axial stresses, but not on longitudinal stresses (in the same direction) caused by pipe bending or other causes.

8.10 Peak Strains

Design choices for pipelines may rest on the peak strains that can occur locally in the pipe material or weld area. The peak local strain that can occur without failure will be a function of both the material properties and the configuration of the applied strain.

Stewart et al.[85] have shown that, for common steel pipe materials, the hoop strain at burst is close to half the tensile elongation at the ultimate strength in a uniaxial test. The D/t ratio does not have a strong effect on this result. The results are dependent upon the shape of the work-hardening portion of the stress-strain curve and on any load-controlled loading in the axial direction.

Similar results were obtained by Smith and Popelar,[28] who used 0.08 (8%) as an upper limit on strain for corroded sections of linepipe based on 69% of a burst strain of 0.12 (12%) associated by Hohl and Vogt[81] with Y/T no higher than 0.9.

WES TR2808[83] for cyclic and dynamic strain resistance to fracture is described as usable to an upper limit of 10% local strain, but also able to account for 10% skeleton strain from previous cycles. The skeleton strain method is described in Section 9.2 below.

9.0 Multiple Loading Cycles

Cycles of loading that include plastic deformation in both tension and compression may require special handling. This is particularly true when any loading direction has significant load-controlled loading during the cycles, as discussed in the ratcheting section below.

Wrinkled pipe from compression buckling has been demonstrated to have similar pressure capacity to smooth pipe. Wrinkled pipe has also been shown to have resistance to cracking under additional compression in the same direction. However, the cyclic strain resistance may have been compromised.[86]

Das et al.[86] have performed a series of tests on wrinkle behavior under cyclic loading and demonstrated that small numbers of cycles, 4 to 10, can induce cracking at the peaks of the wrinkle.

Klever et al.[87] have examined design conditions for high-temperature pipelines. They explain requirements for limiting operational plastic strain to the first cycle of temperature and pressure, based on plastic ratcheting causing diameter expansion with each start-up and shut-down cycle that includes plastic deformation. They also calculate a less stringent limit on allowable thermal strain that would limit the hoop strain per cycle to less than 0.01%.

The ABS Guide[88] has provisions for assessing fatigue on a strain basis. The guidance provides a two-part design line for total strain range and number of cycles, as follows

$$\Delta\varepsilon = 0.055\ N^{-0.40} \text{ for } \Delta\varepsilon > 0.002 \quad (1)$$

$$\Delta\varepsilon = 0.016\ N^{-0.25} \text{ for } \Delta\varepsilon \leq 0.002 \quad (2)$$

The strains can be interpreted based on the area near the weld, but not including the shape effects of the adjacent weld edge.

The ABS curves are derived from the X Curve in 1970s editions of the AWS Structural Welding Code – Steel, which was described by Marshall.(89) Marshall originally defined the X Curve to fit local hot spot strains adjacent to weld joints in tubular structures for the Gulf of Mexico. The conditions of interest were predominantly local bending loading, support from surrounding regions to prevent buckling, and fatigue environmental loadings with plastic deformation likely on the highest strain cycles. These conditions avoid buckling and ratcheting.

Nielsen et al.(91) reported cyclic bend testing of a pipe section removed after undergoing an upheaval buckle. This 8.625-in. pipe with 14.33-mm wall of X52 steel was estimated to have cycled 20 to 25 times to 3.0 to 3.5% strain during service. Additional cycles were applied in the testing laboratory, first 50 cycles of 1% strain and then 6 cycles of 3.5% strain that resulted in failure. These estimates give a range of 7.0 to 10.8 times the lifetime predicted by the ABS curve as described above.

Seto et al.(92) performed low-cycle fatigue tests on flawed butt welds in materials relevant to gas pipelines. They compared these tests to the “earthquake-resistant design guide for gas pipelines” that included a requirement that pipelines have design strain amplitudes of 0.5% or smaller for 50 design cycles over 100 yr. They drew a design curve through this single point with an equation of approximately

$$\Delta\varepsilon = 0.056\ N^{-0.44} \quad (3)$$

At 50 cycles, this equation gives a 13% lower strain than does the ABS Guide. The reasoning behind the 50 cycles in the Japanese standard is to take an earthquake effect that might occur once or twice during a 100-yr lifetime of the pipeline and then assume that it occurs three times with 15 cycles and an additional 5 cycles to round up to 50.

Seto et al.’s(92) fatigue tests showed lifetimes with a variety of defect types that all exceeded their design line under alternating (R=-1) loading under displacement control. The material tested was API 5L X65. Welds with gas tungsten arc welding (GTAW) roots and SAW fill passes were tested both with reinforcement allowed to remain and with the reinforcement removed. The avoided issues of buckling by using a flat plate specimen with stiff supports.

Kyuba et al.[93] performed displacement-controlled uniaxial fatigue tests on transverse butt welds in plates with differing degrees of undermatching. The roots and caps were ground off, but some specimens had an added 2-mm-diameter hole to simulate a welding defect. Yield strengths were measured as 550 MPa for the base metal, with a yield plateau, and 420, 480, and 530 MPa for the three weld metals. Results for the two higher yielding weld metals were very similar, with both directing failures to the base metal on the specimens without holes. All of the data significantly exceeded the ABS design curves.

Pereira et al.[94] performed cyclic testing on butt welds from X 80 pipe. The strip specimens showed concentrated strain in the softened HAZs, but still significantly exceeded the Japanese standard (50 cycles at ±0.5% strain). All 12 specimens failed after between 900 and 1250 cycles of nominal strain range of 0.9 to 1.1%.

9.1 Methods of Accumulating Strain in Cycles

When multiple plastic cycles are applied, several methods can be considered to sum the strains from each cycle to get an accumulated peak strain for assessment.

One method, mentioned above, is the accumulated plastic strain approach. This approach, used in DNV 2000,[1] defines the accumulated plastic strain as the sum of the plastic strain increments, irrespective of sign and direction.

Another method, just described, is the strain-life fatigue method, where the plastic strain increments are combined not into an accumulated plastic strain, but into an estimate of the number of cycles that can be allowed.

A third method, not yet described, is used in WES TR2808[83] and called skeleton strain. Skeleton strain is defined based on a curve made by piece-wise connection of the stress/strain curves both as tension increases and as compression increases, as shown in Figure 10. The skeleton strain is the maximum magnitude of strain reached on this curve in either the tensile or compressive direction. The piece-wise connection process works by taking sections of the stress/strain curve from the point where stress magnitude of that sign (tension or compression) exceeds that on any previous cycle to the point where that cycle reached its maximum magnitude of strain. The section is then added to the piece-wise curve by connecting it to the previous piece at its final stress. This has the effect of shifting the strains to higher magnitudes when the curves are connected.

Skeleton strain was designed to be effective at assessing seismic loading tests for building connections. These tests use one or several cycles of a given strain and then increase the strain level and repeat the cycling until failure. Skeleton strain approaches have not been demonstrated on examples where the cycles get smaller in magnitude of stress. Thus, they may not be effective at providing models of reeling where the first strain half-cycle onto the reel will be larger than the straightening cycles or the subsequent pipe-laying cycles.

Skeleton strain is less conservative than accumulated plastic strain because it does not add the compressive and tensile plastic strains. It also does not add the entire plastic strain increment on each half-cycle. Instead, it adds only that part of the plastic strain increment that has stress magnitude exceeding that on previous cycles.

9.2 Safety Factors on Strain-Based Fatigue

Safety factors for fatigue are commonly applied at several stages of the assessment and on the final lifetime from the assessment. The two primary types of assessment, comparison to collected lifetime data and fatigue crack growth assessment, use different safety factors. When comparing to collected lifetime data, the design lifetime is chosen based upon the minus two standard deviation line of the group of data. When using a fatigue crack growth assessment, the crack growth rate is usually chosen as the mean plus two standard deviations. The factor applied on the final lifetime is used to account for the errors in lifetime assessment that can occur when checking a variable cycle history against design methods that are primarily based on single amplitude cycles. A variable cycle history can obviously place the cycles in different orders and it is known that the order does affect the lifetime.

Strain-based assessments of fatigue could include cases where both types of assessment would be used. Relevant data may be difficult to obtain for crack growth under cycles with plastic strain, since the data becomes dependent upon the degree of constraint around the crack tip. There is thus a tendency to rely more upon comparisons to collected lifetime data, as reflected in the collected literature data described above.

The safety factor on the final assessed lifetime should be chosen in part based upon the application and partly upon the methods of assessment and the amount of conservatism already included in the assessment. Applications for variable amplitude loading where the designer wishes a high level of safety can use a safety factor on fatigue lifetime of as high as 10, as is done for the highest safety level in the DNV guidance of dynamic risers.(66)

9.3 Ratcheting

When cyclic loading with plasticity is combined with a load-controlled loading in any direction, the result can be ratcheting, the cycle-by-cycle increase of plastic strain. The increase in plastic strain is prominent in the direction of the load-controlled loading.

A completely displacement-controlled cycle that causes tension and compression plastic strain in the longitudinal direction of the pipe can cause ratcheting when it is combined with internal or external pressure. Here, the ratcheting will be on the circumferential strain, tending to expand the pipe under internal pressure and tending to shrink it under external pressure. Increasing the longitudinal strain range or the pressure difference will make ratcheting strains larger.(95)

Ratcheting need not only occur in the circumferential direction. The axial direction can undergo ratcheting extension or contraction when all or a significant fraction of the longitudinal loading is load-controlled as tested by Hassan and Kyriakides(96) and Xia and Ellyin,(97) for example.

Another means of accumulating cycle-by-cycle strain during cyclic plasticity is for the tension plasticity to combine with wrinkling or buckling during the compression portion of the cycles. The wrinkling or buckling adds both stress concentrations to the subsequent longitudinal stresses and locally varying hoop direction strains.

Critical locations for ratcheting analysis tend to be at locations of localized support such as the ends of free spans, artificial supports, and adjacent to subsiding soil or seabed.

Assessment methods for ratcheting that rely on otherwise acceptable finite-element programs for plastic deformation may fail to model the material behaviors associated with ratcheting.

Coiled tubing tests can act as scale models of pipelines. Extensive testing and experience is available for coiled tubing. The two most common grades of coiled tubing have yield strengths of 70 and 80 ksi, similar to common pipe steel materials. The tubes are repeatedly cycled in bending as they move over the reel and the arch before straightening. Cyclic bending with a mean tensile axial stress has been demonstrated to cause extension of the tubes, while cyclic bending with internal pressure has been demonstrated to increase the maximum diameter. The maximum diameter increase is expected in the plane of the bending, although the minor axis of the ovalized pipe is often found to also increase, partly due to rotation of the tube.

10.0 Probabilistic Methods

Probabilistic methods have not been widely used for strain resistance, although they can be as appropriate to strain-based design as they are to stress-based design. Some probabilistic analysis has been completed based on collections of finite-element model results, such as those used to develop the compression resistance equations in DNV 2000.[1]

Zhou et al.,[98] as part of a slope hazard assessment model, defined the tensile and compressive strain limits as random variables, in addition to the soil strength. The random variables were all normally distributed and defined by the mean and standard deviation, denoted as N (mean, standard deviation). The tensile strain limit depended upon the pipe grade using the distribution N (0.010, 0.0039) for Grade 448 and 483 (X65 and X70) and N (0.026,0.009) for all other grades both higher and lower in strength. The compressive strain limit distribution was set based on the expectation of significant compressive strain beyond the critical buckling strain ε_c, as calculated by standard formulae. The distribution was set up as $N(\varepsilon_c+0.025,0.012)$. These distributions are dependent somewhat upon the situation being modeled. The tension strain distributions relate to construction practices in Alberta for natural gas pipelines, while the compressive strain limit is dependent upon the assumption of displacement-controlled loadings on unstable slopes.

As more data become available on parameters relevant to strain-based design, a greater application of probabilistic methods can be expected as well.

11.0 Criteria for Full-Scale Testing

Full-scale tests have particular value when the previous experience and smaller-scale testing results are insufficient to provide confidence in the expected behavior of the pipeline under axial strain conditions.

Full-scale tests, because of their increased expense over smaller-scale tests, will usually be done in small numbers. This testing should be completed so that it provides relevant information on resistance to at least one failure mode. Comparisons between different failure modes (buckling versus ovalization or wrinkling versus tensile fracture) have rarely been a feature of full-scale test programs.

DNV 2000[1] requires that the characteristic strain capacity from ECA be “validated by realistic testing of girth welded pipe, e.g., by full-scale bend testing.” This requirement is applied only for installation methods introducing plastic strains for cases where accumulated plastic strain is applied >2%. Note that full-scale bend testing is only one of the examples of the class of "realistic testing of girth welded pipe." It then notes that the extent of testing and the details of the test procedure are subject to agreement. The purpose of the testing is to demonstrate that possible weld defects will not result in fracture during pipe laying, and will not extend by stable growth to a size that will be unacceptable from a fatigue or fracture point of view during operation.

Those who choose to do full-scale testing must then choose whether all the parts of the environmental loading need to be included: the pressure differential, the longitudinal loading, and the transverse bending moments. Adding longitudinal tensile loading to the combination of internal pressure and transverse bending moment can increase the longitudinal tensile strain before local buckling on the compression side and thus test a greater range of local tensile strain.[(16)]

Also, as noted above and in Appendix A, the internal overpressure can have a significant effect on the development of plastic strain when there are regions of lower yield strength. Thus, for cases where the plastic strain will be developed during pressurized service, the testing could valuably include internal pressure.

Testing for a study on cold-field bending found that buckling occurred at the same strain for axial loading that created a full-circumferential buckle and for moment loading that created a part-circumferential buckle on the compression side.

Full-scale test results of failures of girth weld imperfections in tension have been collected as part of the validation of ECA methods for pipelines. Tests have been conducted both under bending alone and under combinations of bending and internal pressure.

Higher failure strains have been achieved in greater thickness pipe that reaches ductile failure on the tension side.[(99)] This suggests that full-scale testing may provide additional advantage in demonstrating safety in ductile failure conditions.

Much of the ductile fracture testing done to validate ECA methods has been done on wide-plate specimens. The curved wide-plate specimens have been understood to be conservative compared to the full-scale bend test results. The effect of internal pressure has not been considered in this assessment.

Some full-scale tests have been done comparing similar pipe in bend test and wide-plate tests.[100]

A set of tests on reeling with artificial pipe flaws[84] did show stable growth of flaws originally 3.2-mm deep × 50.4-mm long × 0.3 mm during a simulation of reeling with 2.4% strain. The pipe material met API 5L X52 with 16-in. OD and 1-in. wall thickness. Similar-size artificial weld flaws did not grow during the simulated reeling test.

A very small number of tests have combined buckling during bending with fatigue induced by moment loading. These indicate that moderate buckles can take large number of fatigue cycles that simulate the pressure variations in natural gas pipelines.

Full-scale testing need not be done where well-known behavior would be repeated in the testing. This tends to be particularly true for compression failure modes such as local buckling. The combinations of factors that apply to failure modes in tension, as well as the factors of safety included in the assessment methods tend to make full-scale testing more valuable for the tension failure modes.

12.0 Current Research and Development

Several organizations have current research projects that will be released to the public domain after their completion in areas that directly or indirectly impact strain-based design of pipelines. This section provides a partial list of programs that EWI has been made aware of.

DNV has a group-sponsored program to provide guidelines on applying fitness-for-service methods to reeled pipe. This program includes efforts by TWI and SINTEF. The program is nearing completion with the results to be published in a DNV-recommended practice. This project sets out to define realistic flaw acceptance criteria and material property requirements to ensure that steel pipe and girth welds can be reeled and operated with minimum risk of failure. Experimental studies have been conducted on representative pipe materials to measure changes in material properties and assess flaw stability as a result of cyclic plastic strains caused by reeling. This will be complimented by the development of specific analysis procedures for reeled pipe, which will help define acceptance criteria.

TWI has a group-sponsored program on acceptance criteria for pipe girth welds inspected using automated ultrasonic testing (AUT). The project also aims to reduce the difficulty of qualification of AUT inspection procedures, partly by reducing the requirements for individual inspection qualification. The project uses three levels of strain in service: elastic, small plastic strain such as during S-laying operations, and large plastic strain as during reeling operations. The primary output is to be correlated combinations of minimum required material properties and AUT acceptance criteria.

Boreas Consultants is leading a group-sponsored project on on-bottom lateral buckling pipeline design called SAFEBUCK. The project will develop guidelines for the strain-based design of on-bottom, high-pressure/high-temperature subsea flowlines. Thermal expansion in long HP/HT flowlines must be accommodated in the system design. The high cost of trenching and burying and/or expansion spools means that an on-bottom approach, which avoids these features, is preferable. The project will develop predictive models for the performance of on-bottom flowline systems and assess, by means of full-scale tests, the integrity of the design under cyclic plastic strain. The project will develop technologies for the economic development of long tie-ins where thermal expansion is an issue and provide guidelines for their implementation. SAFEBUCK is using four primary design cases, two from the North Sea and two from the Gulf of Mexico, with one of each being a pipe-in-pipe case.

Boreas Consultants has launched a project on the re-use of subsea steel flowlines. Flowline re-use is an increasingly attractive prospect for offshore fields where remaining reserves are becoming more marginal, and cost reduction is the key to the viability of the development. Where a flowline is to be removed, the case for re-use is strengthened. The financial and technical feasibility of the re-use of steel flowlines will be assessed and the project will assess the integrity of used flowlines during the relocation operation, and during the second service period. Pre-recovery pipe inspection requirements will be established and a study of the safety implications of the relocation operation will be undertaken.

Engineering Mechanics Corporation of Columbus has a project from the Pipeline Research Council International studying strain-based design using finite-element modeling on flawed welds under high strains.

13.0 Recommendations

1. The current use of strain-based design has many project-specific components. This limits the ability of a "cookbook" approach where each step can be laid out as part of common design sequence to apply to all areas of pipe strain-based design. This situation would indicate that taking the current state-of-the-art methods and creating a code or standard would be ineffective at covering the range of needs for future pipeline designs. Yet, because there are many choices that are part of a particular pipeline strain-based design, the availability of guidance and recommended practices can help simplify the design and

qualification process for many pipelines. Going forward with this approach, the guidance provided in this report could profitably be taken forward by the industry into, for instance, an API-recommended practice.

2. The primary areas where strain-based design will be used are in design of reeled laying of offshore pipelines, in thermal design of arctic pipelines, in design of types of offshore pipelay systems, in design and assessment of pipelines in areas with significant expected ground movement, and in HT/HP pipeline designs.

3. Some pipelines may also have some applications of strain-based design where cyclic loadings cause occasional peak stresses above the pipe yield strength. Here, the cyclic lifetime assessment is improved by using strain ranges for the cycles, instead of stress ranges.

4. Past design practices have asked designers to determine whether a particular loading was load-controlled or displacement-controlled without any other possible choices. Designers today need to recognize that there are a range of intermediate cases between full-load control and full-displacement control. The behavior of the pipe, particularly its buckling resistance, can change significantly depending upon the designer's choice of the appropriate intermediate case for design.

5. Guidance on local buckling compression resistance of pipelines appears to be well founded when using the critical strain. The additional strains that can be achieved under partly or fully displacement-controlled loading should be more thoroughly studied to allow more specific guidance.

6. The methods for assessing tensile failure resistance of pipelines by ECA become fewer when the plastic strain exceeds 0.005 (0.5%) and fewer still as the strain increases to 0.02 (2%) or more. More validations trials are needed in the open literature to support the use of the few existing methods up to high axial strains.

7. Further study is needed on the effect of pressure, internal or external, on the tensile failure resistance of girth welds in pipelines. Models and experiments done for this project have indicated an important effect of strain concentration around welds with mismatched areas.

8. Further study is needed on the effects of prior strain history on the resistance of pipeline materials, particularly weld materials, to different failure modes. Current research is

focusing on the effects of reeling cycles on the material properties, both for subsequent single strain events and for cyclic loadings.

9. Methods of assessing cycles of loading that include plastic strain are available. But the limited number of tests on which they are based may mean that these methods are conservative for many pipeline design situations to which they might be applied. Additional testing and analysis of cyclic behavior of pipelines are needed to improve the methods currently available.

10. Design of pipelines to resist ratcheting has become more important recently because of thermal cycle effects on high-temperature pipelines and flowlines. As for other types of cyclic loading, the current design methods are relatively conservative, but have been shifting to allow more cycles of plastic strain. Additional testing and assessment is needed in this area to improve the current methods.

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Table 1. Examples of Pipelines that have Used Strain-Based Design

Pipelines Built with Strain-Based Designs	
Northstar for BP	Shallow subsea in Alaskan arctic
Haltenpipe for Statoil	Design strain limits near 0.5%, mostly for spanning on uneven seabed
Norman Wells for Enbridge	On-shore pipeline across permafrost, strain-based acceptance of on-slope design
Badami for BP	River crossings in Alaskan arctic
Nova Gas Transmission Line in Alberta	Strain-based acceptance for discontinuous permafrost
TAPS fuel gas pipeline	Strain-based acceptance of upheaval buckling in permafrost
Ekofisk II pipelines for ConocoPhillips	Limit state design over subsiding seabed
Malampaya for Shell	Limit state design for seismic events and seabed movement
Erskine replacement line for Texaco	Limit state design for HP/HT pipe-in-pipe replacement
Elgin/Franklin flowlines and gas export line	Limit state design for pipeline bundles
Mallard in North Sea	Limit state design for pipe-in-pipe
Pipelines Considered or in Process with Strain-Based Designs	
Sakhalin Island for ExxonMobil	On-shore pipelines in seismic area
Liberty in offshore Alaska for BP	Shallow water Arctic pipeline
Thunder Horse for BP	Limit state design for HP/HT flowlines

Table 2. Effects of Pipe Mechanical Properties on Axial Strain to Failure

Parameter Change	Commonly Specified	Compression Failure Resistance	Tension Failure Resistance
Increase yield strength	Yes	Reduced	Reduced
Increase tensile strength	Yes	Increased	Increased
Increase elongation to failure	Yes	Reduced	Increased
Smooth yield region (versus plateau)	No	Increased	Reduced
Increase uniform elongation	No	Reduced	Increased
Increase work hardening near yield	No	Increased	Reduced

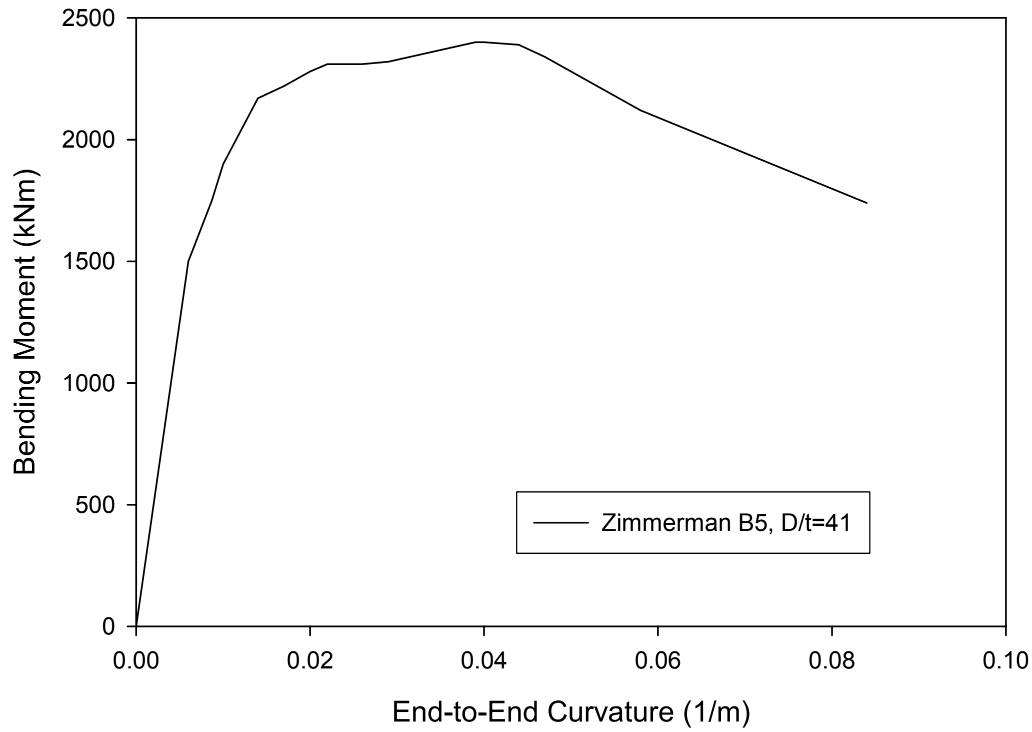

Figure 1. Example of Moment Curvature Curve Determined under Displacement Control[40]

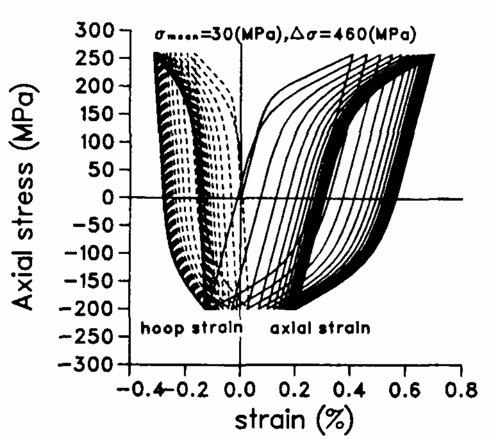

Figure 2. Ratcheting Effect of Cycles with Plastic Strain and Asymmetric Stress[94]

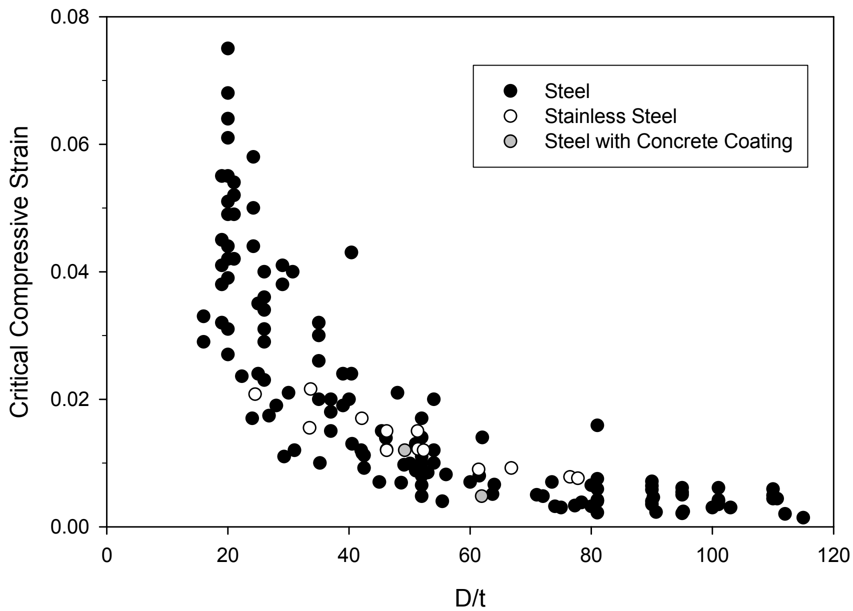

Figure 3. Critical Buckling Strain for Plain Pipe in Bending

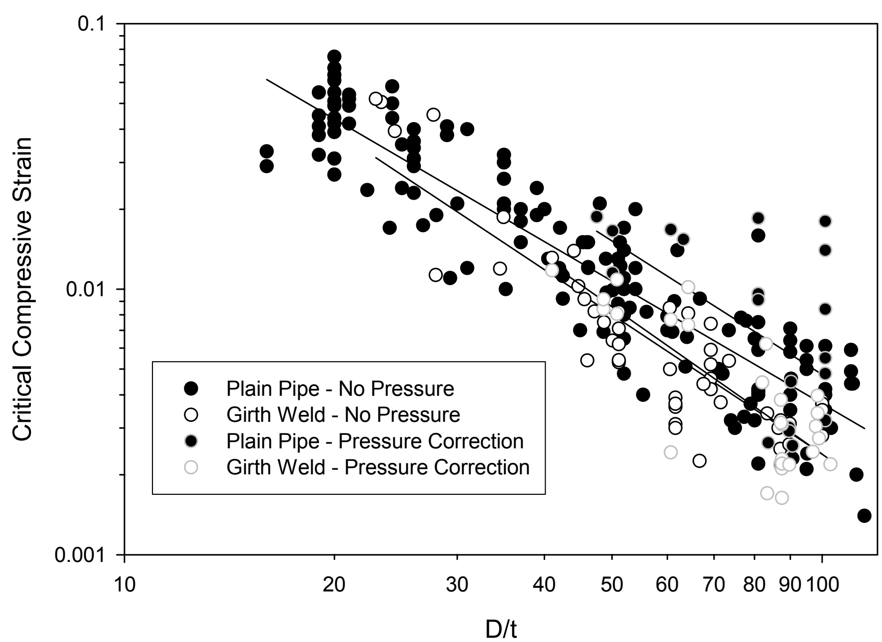

Figure 4. Critical Buckling Strain for Plain and Girth-Welded Pipe

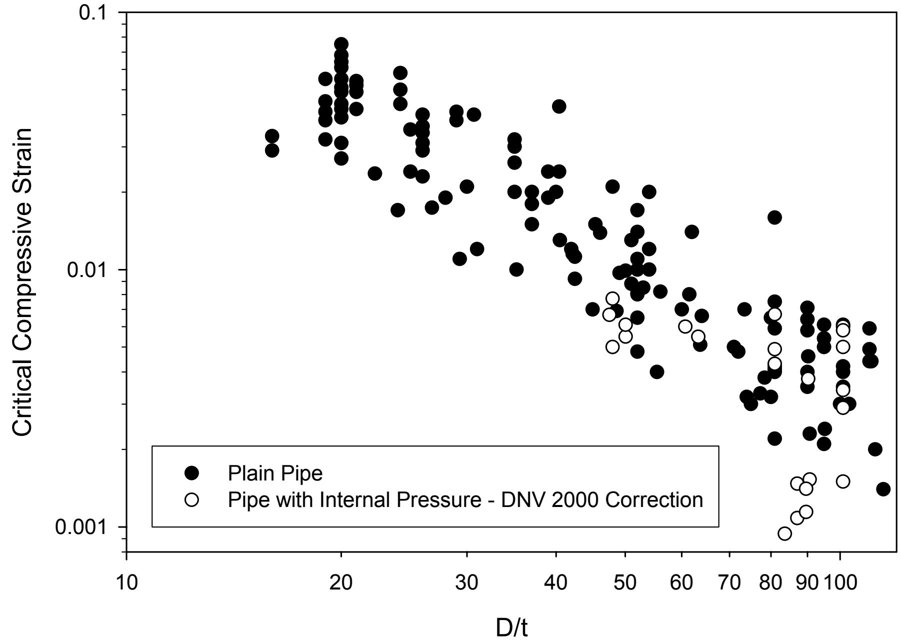

Figure 5. Critical Buckling Strain for Pressurized Plain Pipe

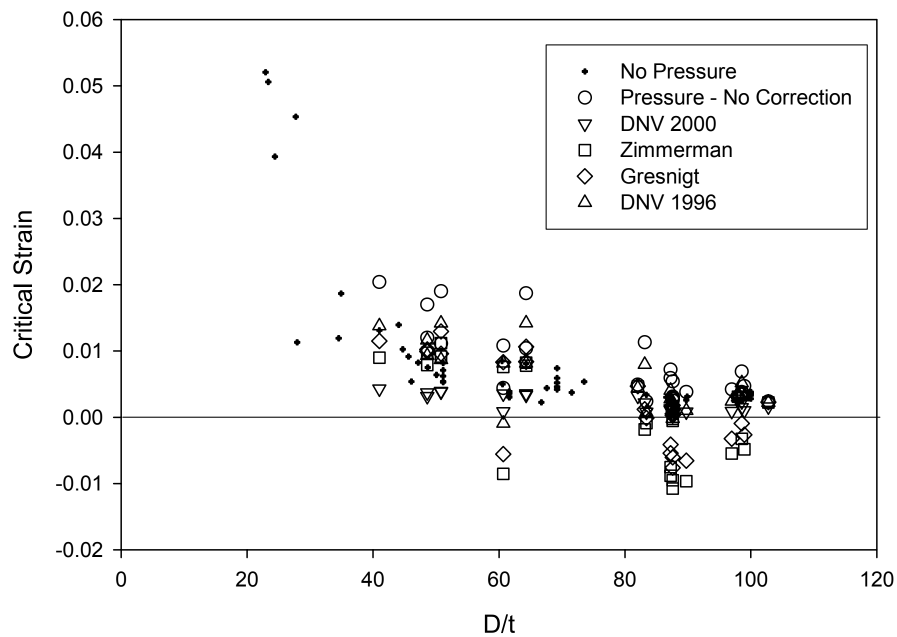

Figure 6. Critical Buckling Strain for Pressurized Girth-Welded Pipe

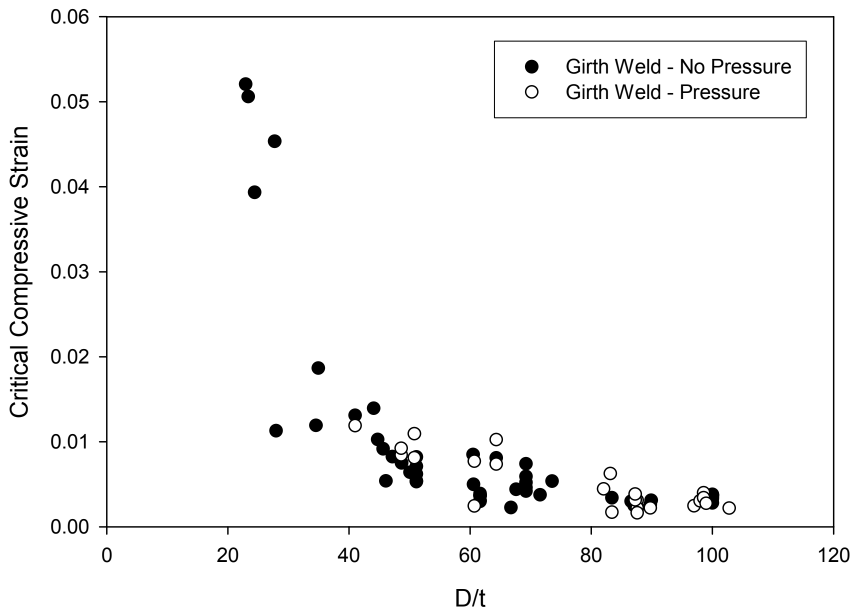

Figure 7. Critical Buckling Strain for Pressurized Girth-Welded Pipe with New Pressure Correction

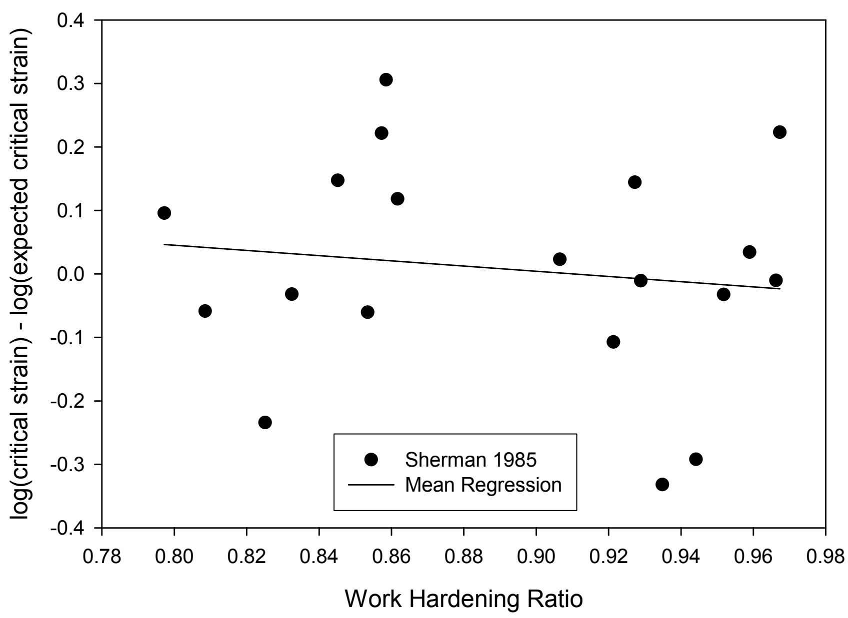

Figure 8. Effect of Work-Hardening Ratio on Critical Buckling Strain[43]

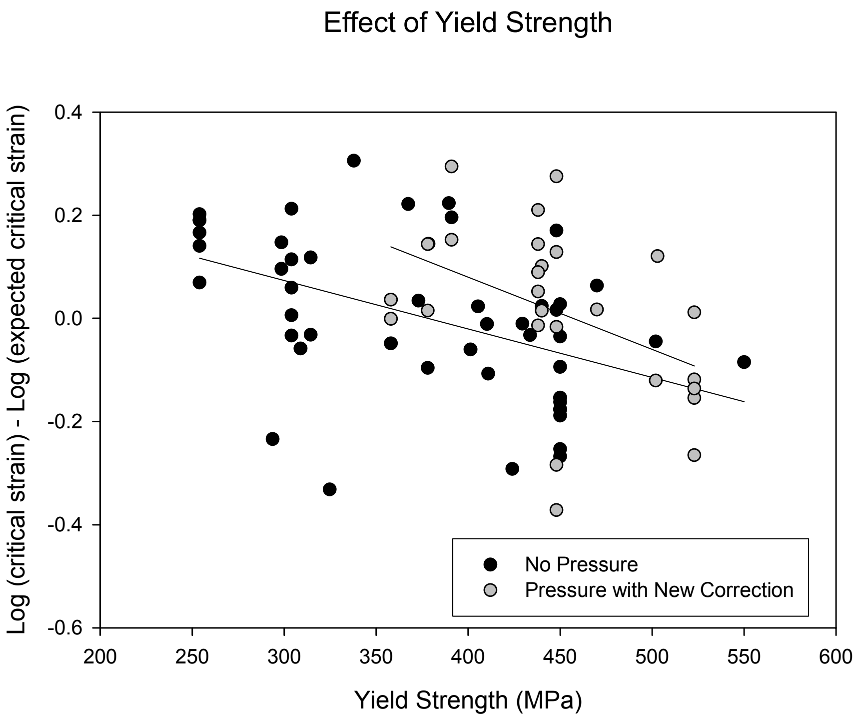

Figure 9. Effect of Yield Strength on Critical Buckling Strain

[redacted]

Figure 10. Definition of Skeleton Strain[(83)]

Appendix A

Finite-Element Models and Tests for Strain-Based Design with Low-Strength Regions Near Welds

Finite-Element Models and Tests for Strain-Based Design with Low-Strength Regions Near Welds

As part of the larger program on strain-based design, a concentrated effort was made to examine the effects of welds on local strain distribution when the strains exceed the yield strength of some part of the weld. Finite-element models were created that allowed either the weld or heat-affected zone (HAZ) to be the low-strength region. Specimen tests were also performed to confirm some aspects of the model results.

The effort described here relates to the case where plastic strain is applied in tension along the pipe axis direction. Compression along the pipe axis direction was not considered here.

Finite-Element Models

Finite-element models have been built to examine the effect of strength variations in regions of a girth weld on strain accumulation. Hoop stress generated by internal or external overpressure was also considered. The weld was meshed with three regions shown in different colors on Figure A-1, assuming cylindrical symmetry. This allowed the three regions to be given different mechanical properties. Models were analyzed using the general-purpose finite-element program ABAQUS.

The models were loaded with global axial tension strain to take advantage of the additional symmetry that allows the use of two-dimensional model with cylindrical symmetry. Mirror symmetry at the weld centerline was also included.

The mechanical properties of the base metal were chosen to represent an X-65 pipeline steel with smooth yield behavior. To create regions of different strength, the yield strength was adjusted without changing the shape of the stress-strain curves. These stress-strain curves are shown in Figure A-2. A small number of check cases used a base metal with a strain plateau at the yield strength where the strain hardening was delayed until 1% elastic strain was reached.

The strain concentrations were checked at several values of pressure loading in the hoop direction. The pressure loading is applied first as a load-controlled loading and the axial strain is then added. Hoop stress of these magnitudes can be generated by external pressure for compressive hoop stress and by internal pressure for tensile hoop stress.

The results described below are arranged to begin with the case of no difference in strength among the weld, HAZ, and base metal. This follows with a small number of cases with the weld region undermatched and then a more extensive examination of the case where the weld metal is overmatched compared to the base metal, but an intermediate region of HAZ and root is undermatched.

Results for No Difference in Strength

In the case where no difference in material properties is specified between the three regions, the only strain concentrations arise at the change in thickness due to the weld cap.

Figure A-3 shows the strain distribution in the model pipe with diameter-to-thickness ratio (D/t) of 20 for axial stress alone. The maximum strain is observed adjacent to the corner of the weld cap.

Figure A-4 shows the strain concentration as a function of remote strain. Strain concentration is the ratio of the maximum strain to the remote strain. The strain-concentration effect of hoop stress is also shown on that figure for three other values of the ratio of hoop stress to the yield strength of the base material: 35% of yield in compression, 35% of yield in tension, and 70% of yield in tension.

Results for Low-Strength Weld Metal

The inclusion of differing material properties for plastic deformation into the model causes the strain-concentration results to change once the axial strain is large enough to cause yielding. In the case of an undermatched weld metal, the strain will be concentrated in the weld metal after it begins to yield.

The case of the girth butt weld with a 10% undermatched yield strength and the HAZ and root with a 10% overmatched yield strength was examined to learn the extent of the strain concentration. The material properties were chosen to represent an X65 pipe material with a smooth yield behavior with the yield strength value adjusted to describe regions of overmatch and undermatch. The stress-strain curve is shown in Figure A-2. The pipe D/t was 20.

Figure A-5 shows the peak strain concentrations in the weld metal as a function of the remote strain. Again, several different values of the ratio of hoop stress to yield strength were imposed before axial strain to examine the effects of internal pressure. Without internal pressure, the strain concentration does not exceed 1.8 times the remote strain. The addition of compressive hoop stress to 35% of yield reduces that to less than 1.3 times. On the other hand, the addition of tensile hoop stress increases the concentration of stress reaching a concentration factor of more than 8 when the hoop stress reaches 70% of the yield strength of the base pipe. The strain distribution for one example is shown in Figure A-6.

The use of weld metal with significantly lower yield strength than the base metal is very rare in pipeline construction for strain-based design, since the additional strain concentration at the low-strength weld is recognized to have a much higher demand for toughness to resist the growth or fracture of weld flaws.

Results for Low-Strength HAZ and Root Areas

As just noted, designers of pipelines for strain-based applications are unlikely to choose weld metal that is undermatched compared to the base metal. Material and welding process choices that lead to low-strength regions of the girth weld can still occur, even when the weld metal is overmatched. The root pass is often manually welded with an undermatched consumable to reduce the risk of hydrogen cracking and promote better tie-ins of the root bead. The HAZ can also be of lower strength than either the primary weld metal of the base material, particularly when the welding heat input is high and the base metal is sensitive to heat-induced reductions in strength.

Models were examined where the smooth yielding base metal with X65 properties was combined with a higher strength weld metal, either 5 or 10% higher in yield strength above the base metal yield. The root area and HAZ, the green area in Figure A-1, had a corresponding lower yield strength 5 or 10% below the strength of the base metal.

These models show a strain concentration at the most severe location of approximately 2 times for the 10% undermatch in the root and HAZ and approximately 1.5 times for the 5% undermatch. The increase in local strain was essentially proportional to the far-field strain with a higher proportionality constant than one once past the yield strain. The results are shown in Figure A-7, where the effect of different D/t is also shown. The strain-concentration factor is the ratio of the peak strain in the root and HAZ material compared to the remote strain in the base pipe material. The effect of the D/t is much smaller than the effect of the fraction of undermatch over the range of D/t from 20 to 200 and of undermatch up to 10%.

Figure A-8 shows that changing the hoop stress from zero to 35% of yield in compression slightly reduces the axial plastic strain concentration in the root and HAZ. However, for combinations with tensile hoop stress, the axial strain concentration is very significantly increased when under remote plastic strain. Cases with both 35 and 70% of the yield strength in tension as the hoop stress were examined. The localization of the strain can be observed in Figures A-9 and A-10, which allow comparison of the effect of internal pressure.

Significant effects of internal pressure on the strain capacity of welded pipelines have not been expected by design engineers or metallurgists. Welded pipes have been routinely tested for strain capacity with no added internal pressure, even when the service conditions would require internal pressure between the 35 and 70% of pipe yield strength values used above. Strain capacity of welds has also been routinely tested with wide-plate sections of pipe that are loaded solely in the pipe axis direction.

Two yielding criteria, the von Mises and the Tresca criteria, are widely used by engineers to test the likelihood of yielding. Both use the three principal stresses, with Tresca using the largest difference between the principal stresses and von Mises using the square root of the sum of the differences between each of the principal stresses. If an example is taken of a pipe under axial stress near yield only and compared to an example where both the hoop and axial stress are at the same value near yield, both criteria would suggest that the material is equally close to yielding in both cases. This, of course, assumes that the radial direction stress is essentially zero and acts as the minimum principal stress. Seeing that there is no major difference relative to the onset of yielding predicted by either of these criteria, most engineers expect that even once past yielding in the plastic regime for axial strain there would be little effect of internal pressure.

Thus, when the finite-element model results were put before engineers from the pipeline industry, they looked for possible reasons that the model results could be in error, such as:

- An overly wide HAZ
- Lack of welding residual stresses
- Transition effects at the sharp transitions between the three different materials
- Problems with the hardening characteristics chosen.

EWI performed additional modeling to attempt to address these concerns. A model with a narrower HAZ as shown in Figure A-11 was used in combination with a temperature distribution in Figure A-12 that caused secondary stresses similar to those that would be expected in an as-welded joint, as shown in Figure A-13. Once again, the large magnitude of the strain concentration for combinations of axial strain and internal pressure was observed, as shown in Figure A-14.

Comparisons using differing plasticity models, deformation plasticity and von Mises plasticity, did not show any important effect on the concentration of strain at the weld. The Poisson's ratio was also varied to check whether that parameter had any direct effect on this result. No important effect was observed.

EWI Tension Plus Pressure Testing

As noted above, engineering practice for pipeline design and testing has not accounted for the effect of hoop stress on the axial strain capacity of welded joints. This suggested that more evidence beyond the finite-element models would be needed to demonstrate a large effect of internal pressure on the strain capacity of welds with low-strength regions.

EWI chose to perform a small test program using Al Alloy 6061 rather than steel. The Al alloy was chosen because the HAZs can reliably be expected to be the lowest strength area of the component. The lower strength of the Al alloy also made a larger specimen possible with a given machine capacity.

The specimen design is shown in Figure A-15. It is essentially a tube with end caps that screw into a fixture to apply tension load. The two pieces of Al Alloy 6061 T651 bar were machined and then welded with Al Alloy 5356 to make a single girth weld at the mid-length of the specimen. The internal pressure could be introduced through the diagonal hole at one end.

The girth welds were partial penetration welds with approximately 2 mm lack of penetration at the root.

Two specimens were tested: one with no internal pressure and one with internal pressure of 500 psi. Strain-gage rosettes on the external surface of the tube were used to measure the axial plastic strain at the weld, HAZ, and base metal away from the weld. A servohydraulic test machine was used to provide the loading to achieve axial tension strain.

The strain-gage traces for the axial direction are shown in Figure A-16 for the specimen without internal pressure. Also recorded during the test were the load versus time and load versus crosshead displacement, as shown in Figures A-17 and A-18.

For the specimen with internal pressure, the strain-gage traces for the axial direction are shown in Figure A-19. Also recorded during the test were the load versus time and load versus crosshead displacement, as shown in Figures A-20 and A-21. The small rosette strain gages used during the test did not have the capacity to measure beyond 10% strain. There was a significant amount of remote strain increase after the gages on and adjacent to the weld had reached their saturation level before a through-thickness crack was observed at the weld.

Both specimens eventually failed with a crack through the weld metal from the root lack of penetration. The through crack occurred at a slightly higher remote strain of 1.7% without pressure, compared to 1.6% with pressure.

The results show that the strain concentration in the HAZ, while obviously strongly increased by the internal pressure, did not proportionally change the remote strain to failure. This may be partly a consequence of the root lack of penetration, which significantly reduced the load-carrying area at the weld.

The strain-concentration factor results for the Al tube tests are shown in Figure A-22. The points are somewhat scattered at small values of remote strain because the strain concentration is the ratio of two values which are both small compared to their variability. This plot can be compared to those shown for the models of the steel pipe, as in Figure A-8. Although two different material types are being considered, the theme of higher strain concentration when internal pressure is present is visible in both cases.

Conclusions

An undermatched girth weld or undermatched HAZ can significantly concentrate the axial strain in a welded steel pipeline. The amount of strain concentration is strongly dependent on the relative strengths of the regions and the shapes of the stress-strain curves.

Pressure was observed to have an effect on the strain concentration due to axial strains. External pressure was observed to reduce the concentration of strains from what was observed with no pressure. Internal pressure was observed to increase the concentration of strains from what was observed with no pressure.

Specimen tests on girth welds in Al tubes confirmed that internal pressure can concentrate the strain into low-strength HAZs.

Additional work is needed to determine the structural significance of local strain elevation.

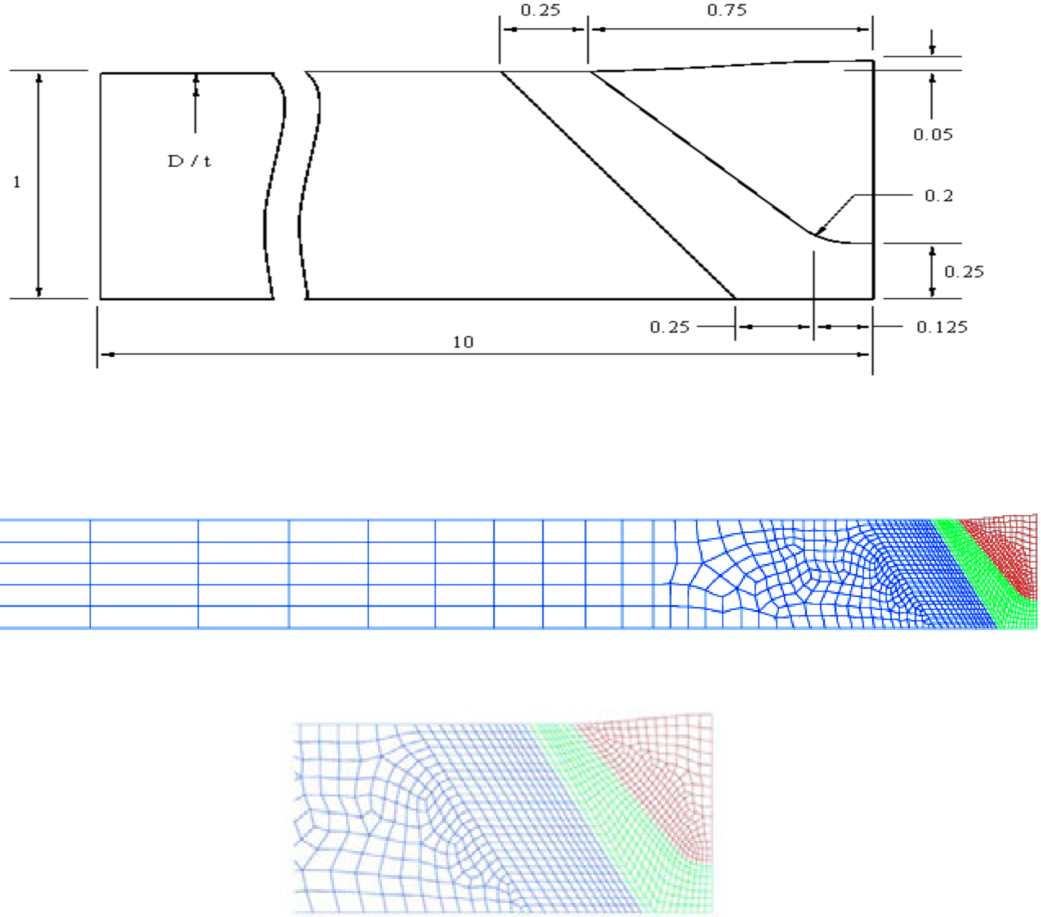

Figure A-1. Base Finite-Element Model

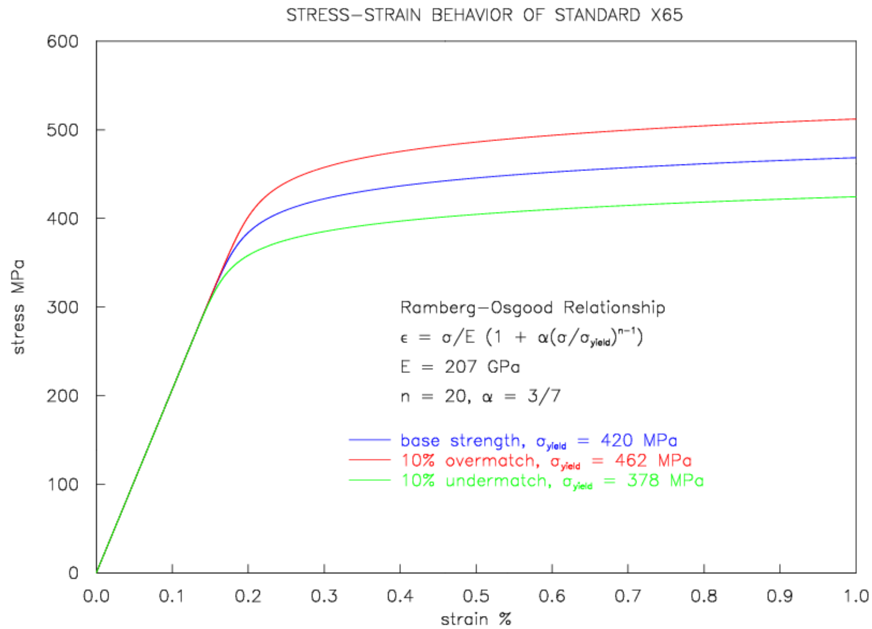

Figure A-2. Smooth Yielding Stress-Strain Curves

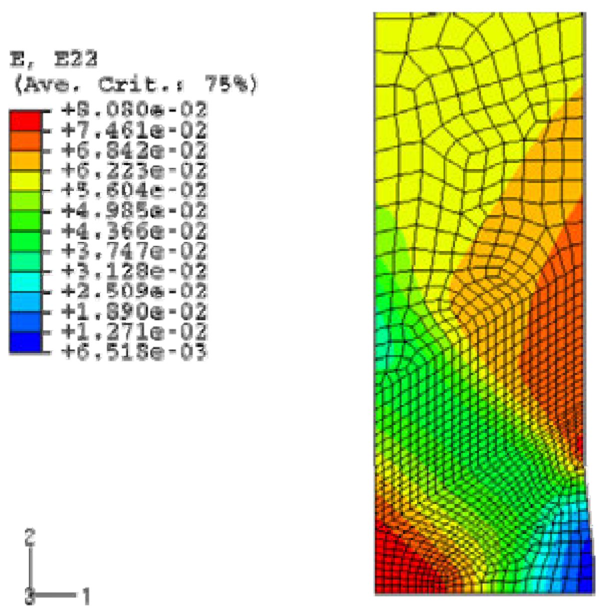

Figure A-3. Strain Distribution for Girth Weld with No Variation in Strength (including 70% hoop stress/yield stress)

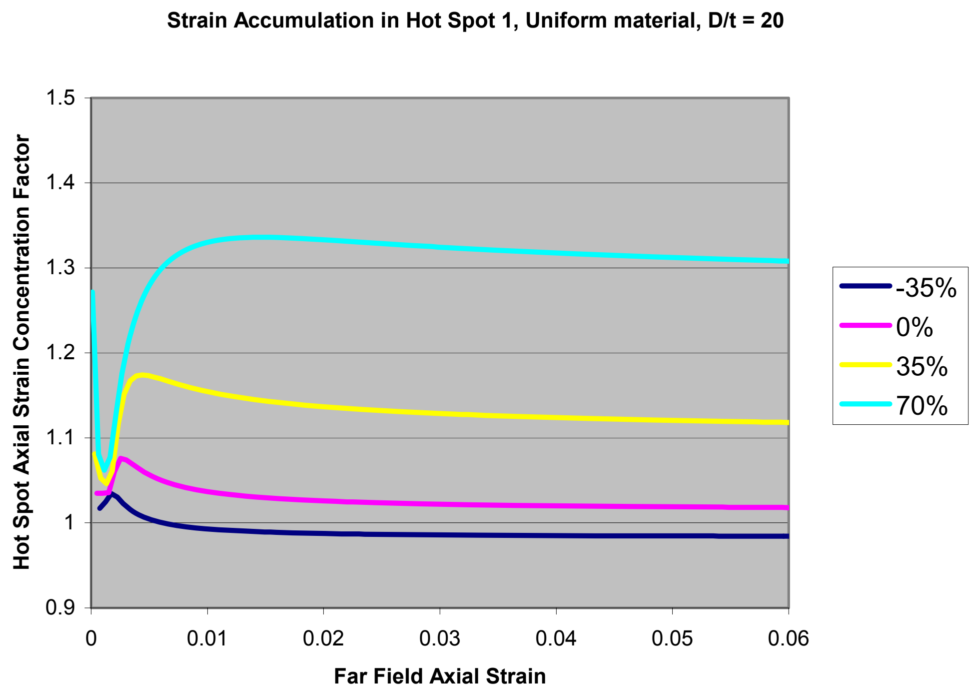

Figure A-4. Strain Concentration with Uniform Material Properties Across Weld

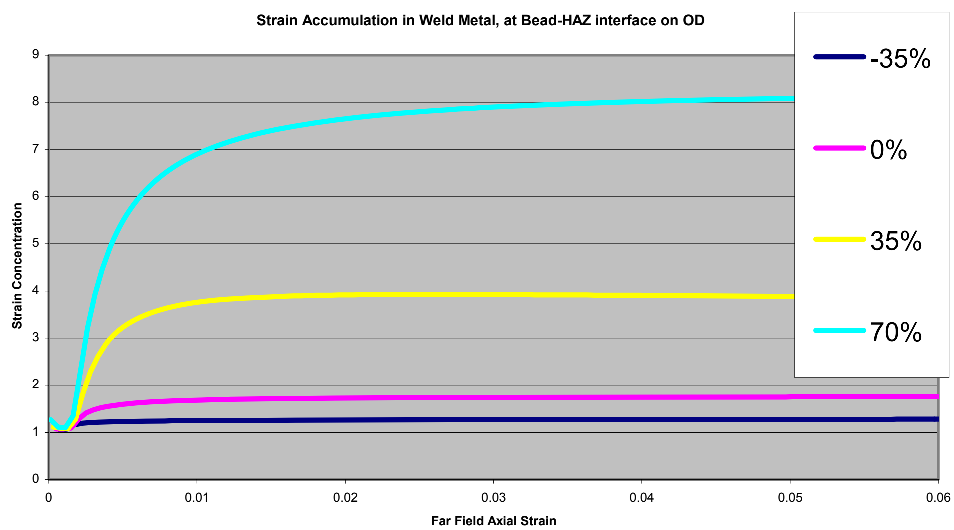

Figure A-5. Strain Accumulation at Weld HAZ Interface for Lower Strength Weld Metal

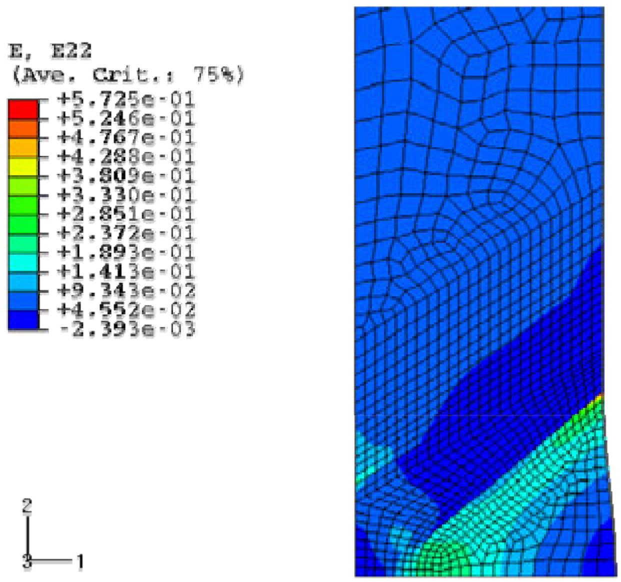

Figure A-6. Strain Distribution in Butt Weld with Lower Strength (including 70% hoop stress/yield stress)

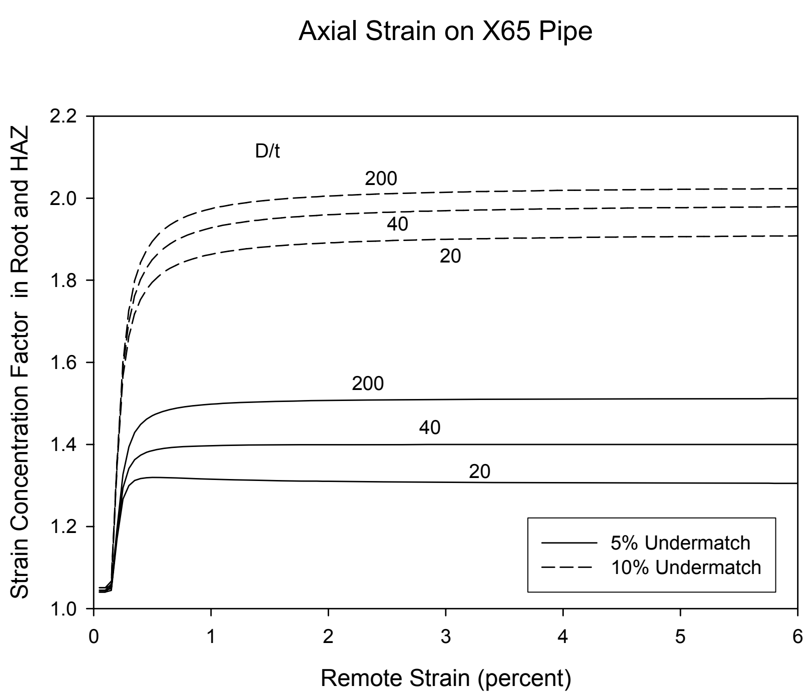

Figure A-7. HAZ Strain Concentration as a Function of HAZ Undermatch and Diameter

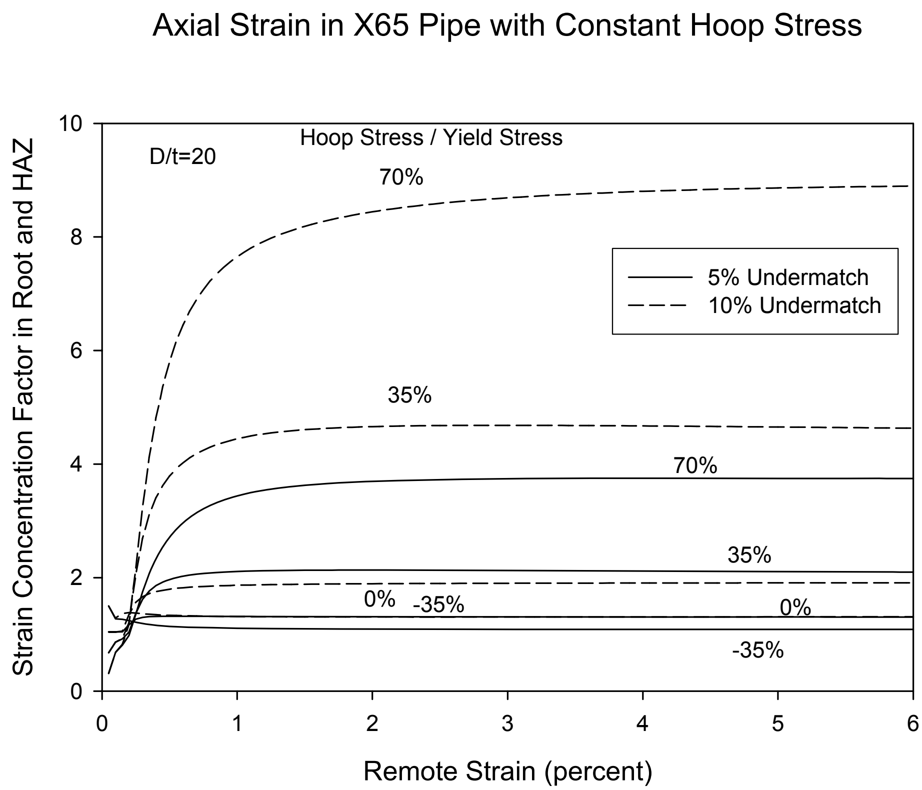

Figure A-8. HAZ Strain-Concentration Factor as a Function of Hoop Stress

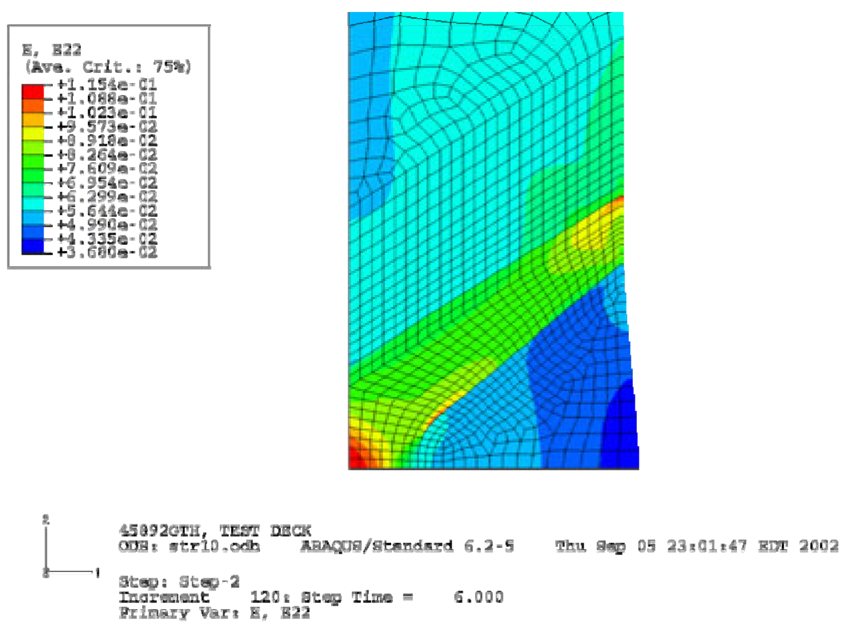

Figure A-9. Axial Strain Distribution for Overall Strain of 6% without Internal Pressure

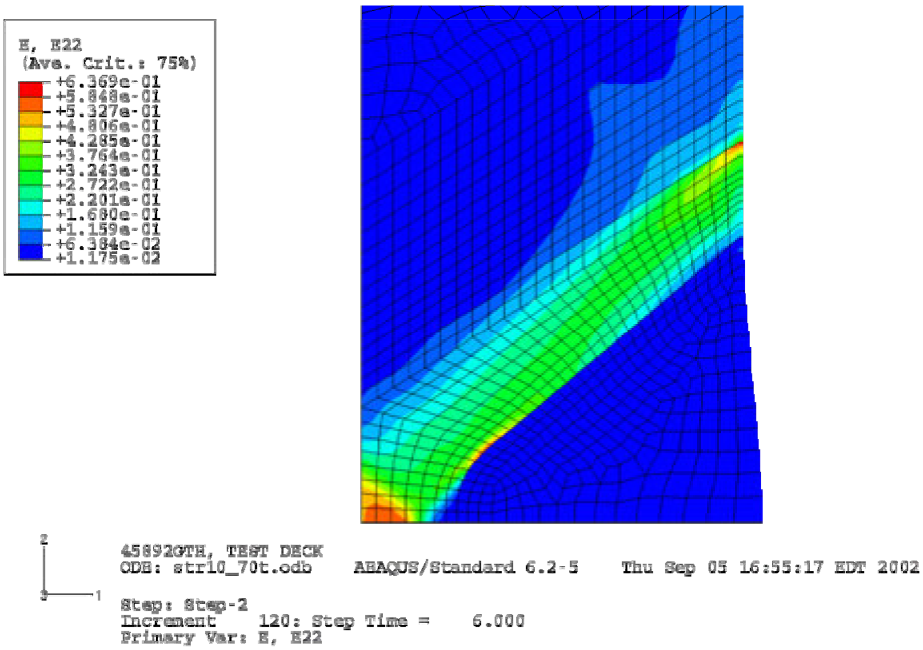

Figure A-10. Axial Strain Distribution for 6% Overall Strain with Internal Pressure Stress 75% of Yield

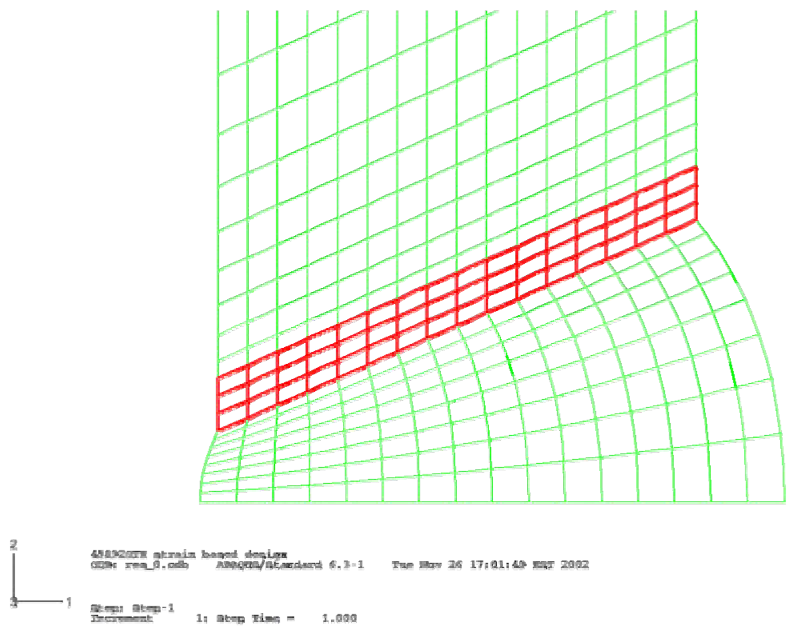

Figure A-11. Finite-Element Model with Narrow HAZ

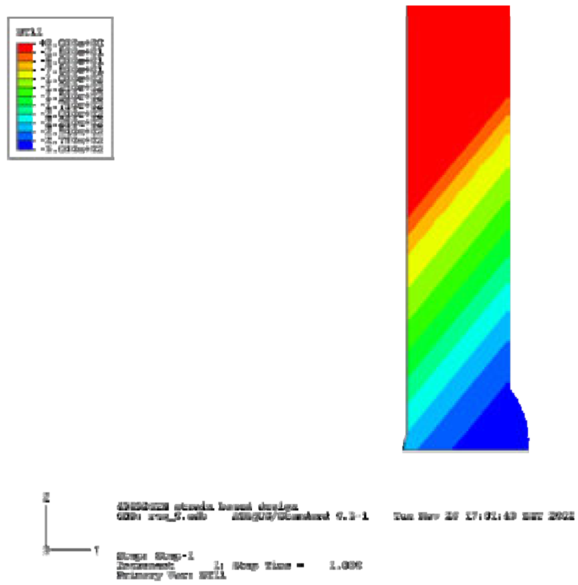

Figure A-12. Temperature Distribution Used to Cause Secondary Stresses

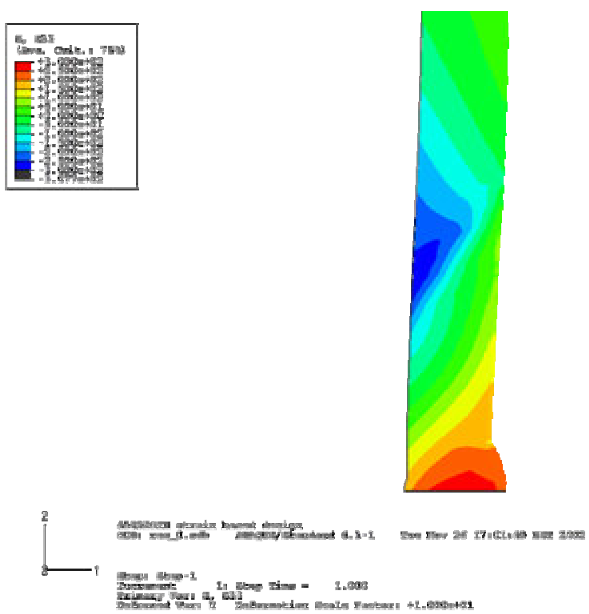

Figure A-13. Secondary Stress Distribution Parallel to Girth Weld

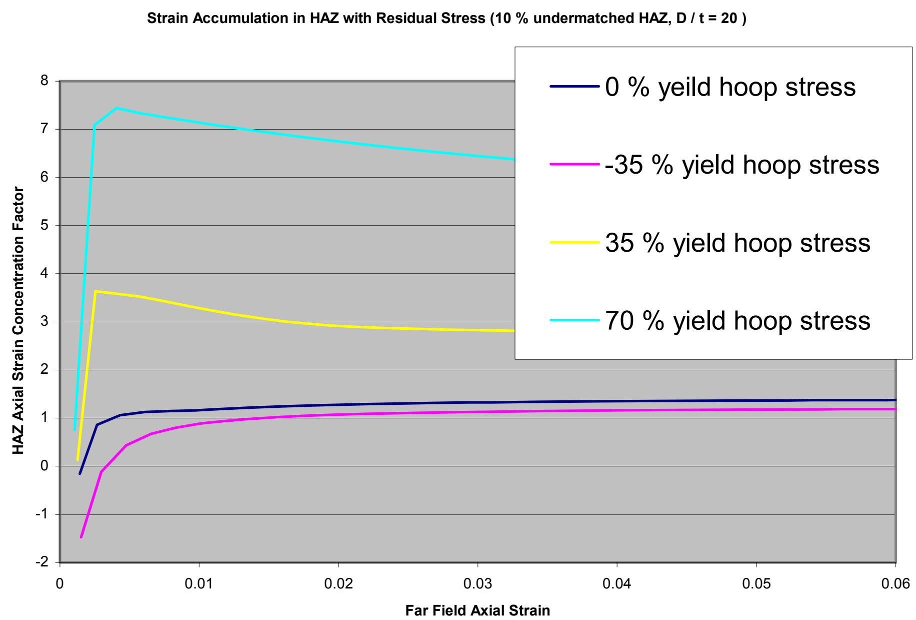

Figure A-14. Concentration of Strain with Narrow HAZ and Secondary Stress

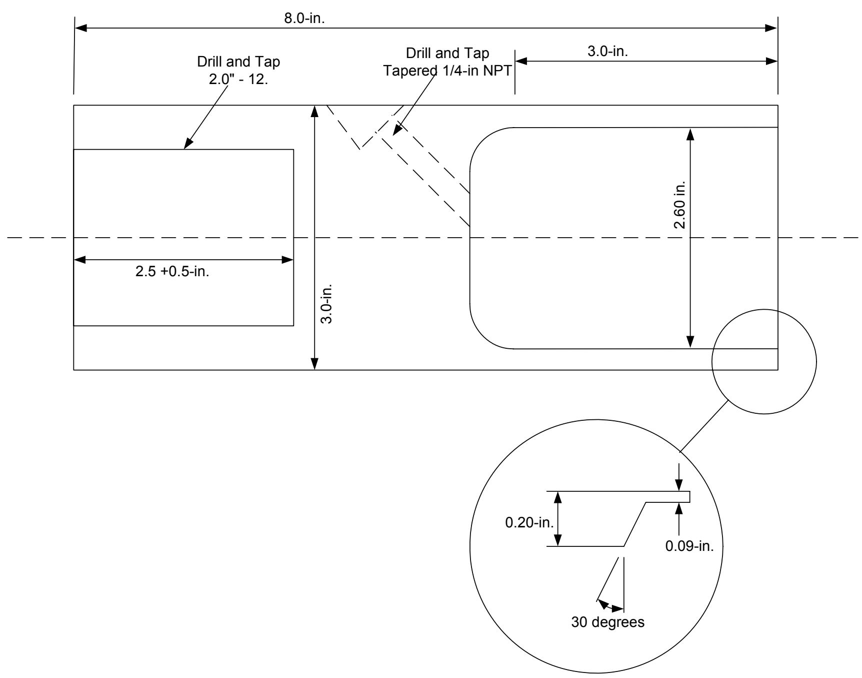

Figure A-15. Half of Al Tube Specimen

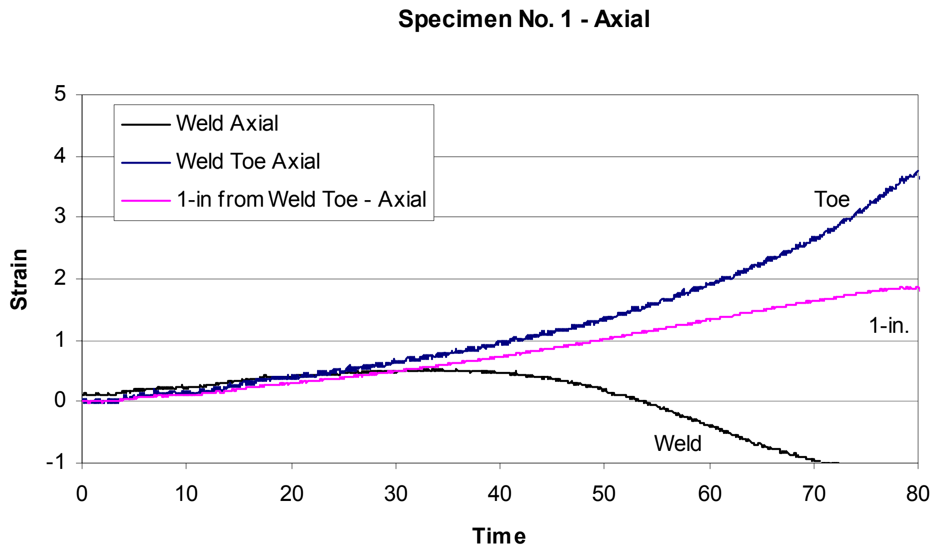

Figure A-16. Strain Versus Time for Al Tube without Pressure

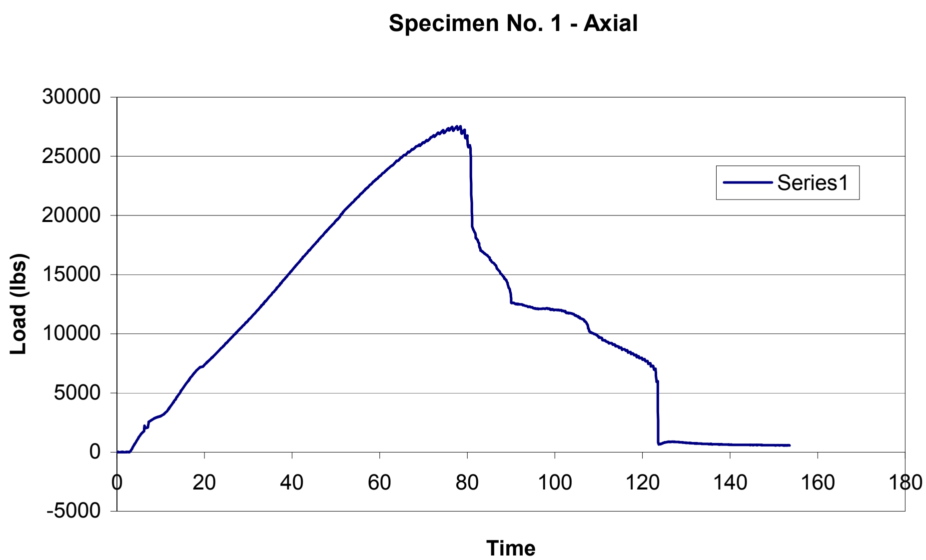

Figure A-17. Load Versus Time for Al Tube without Pressure

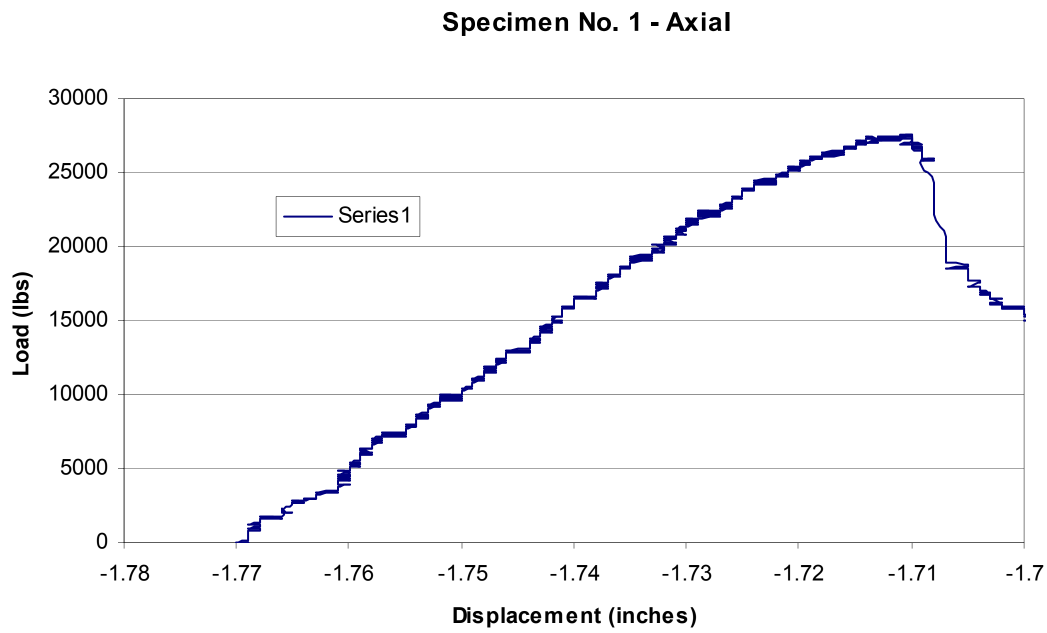

Figure A-18. Load Displacement Results for Al Tube without Pressure

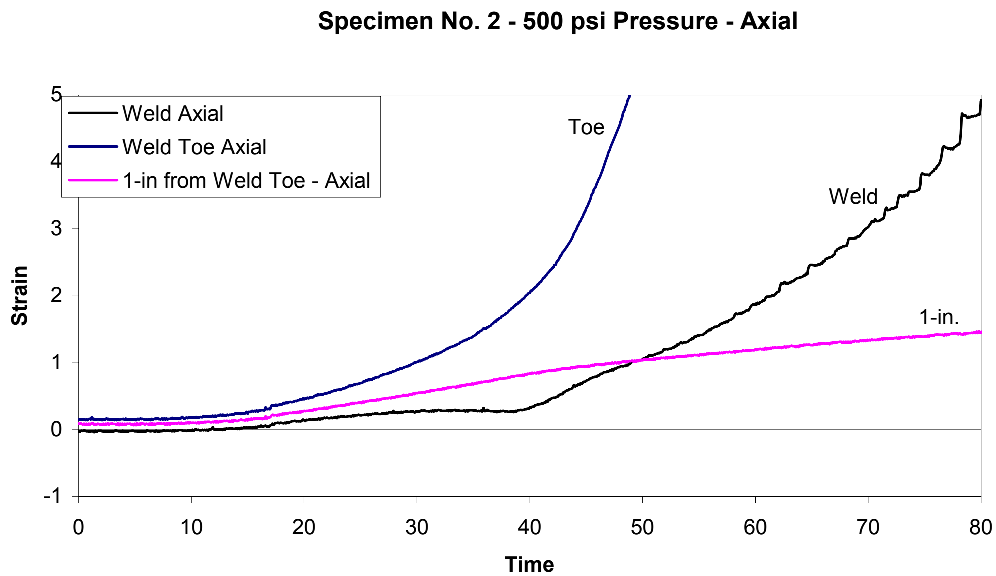

Figure A-19. Strain Versus Time for Al Tube with Internal Pressure

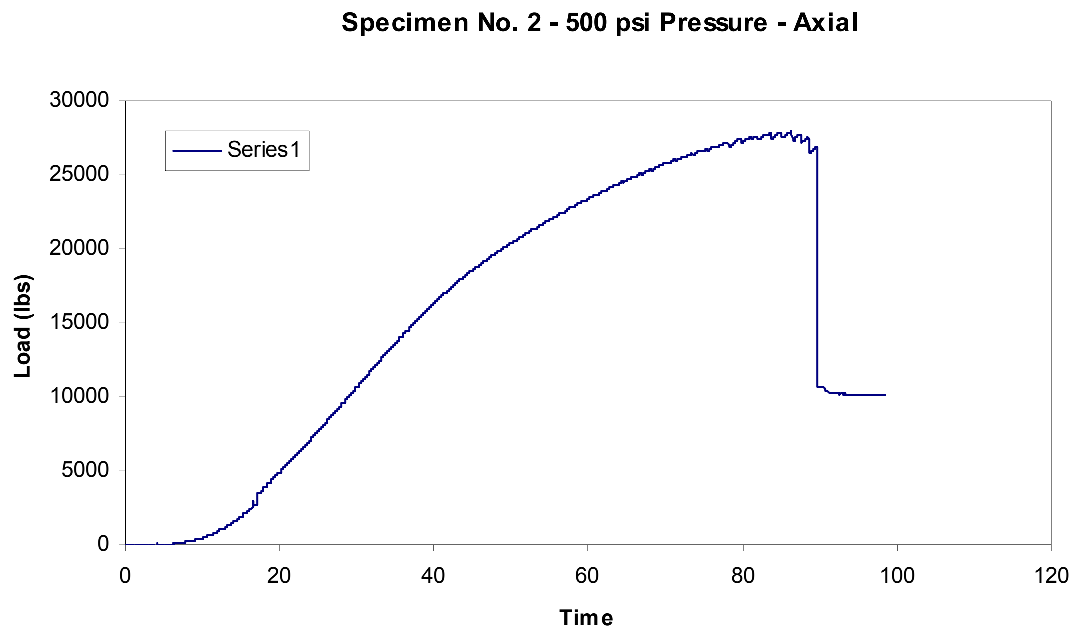

Figure A-20. Load Versus Time for Al Tube with Internal Pressure

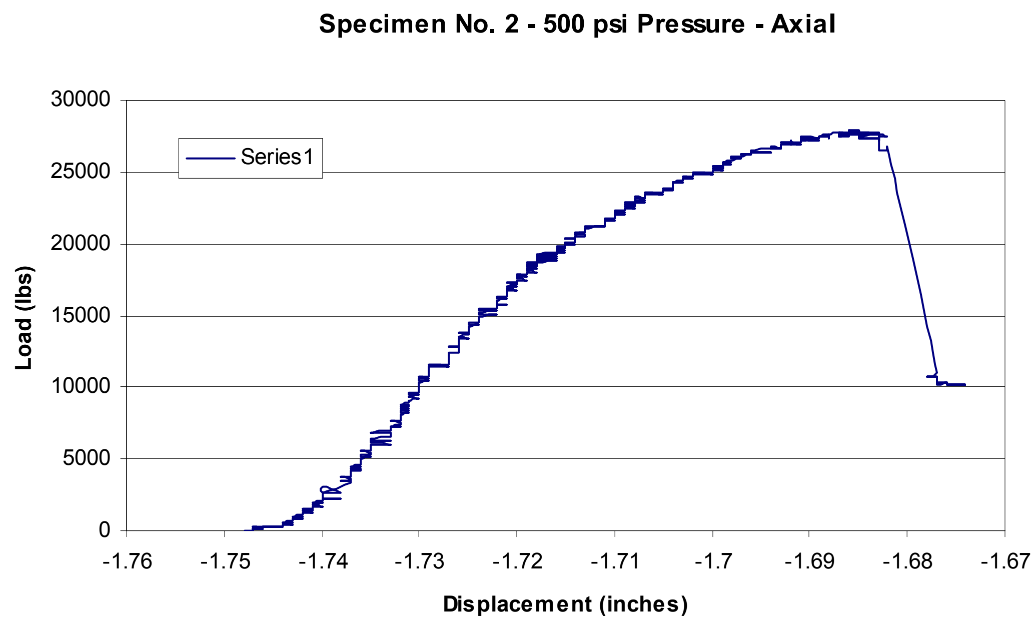

Figure A-21. Load Versus Displacement for Al Tube with Internal Pressure

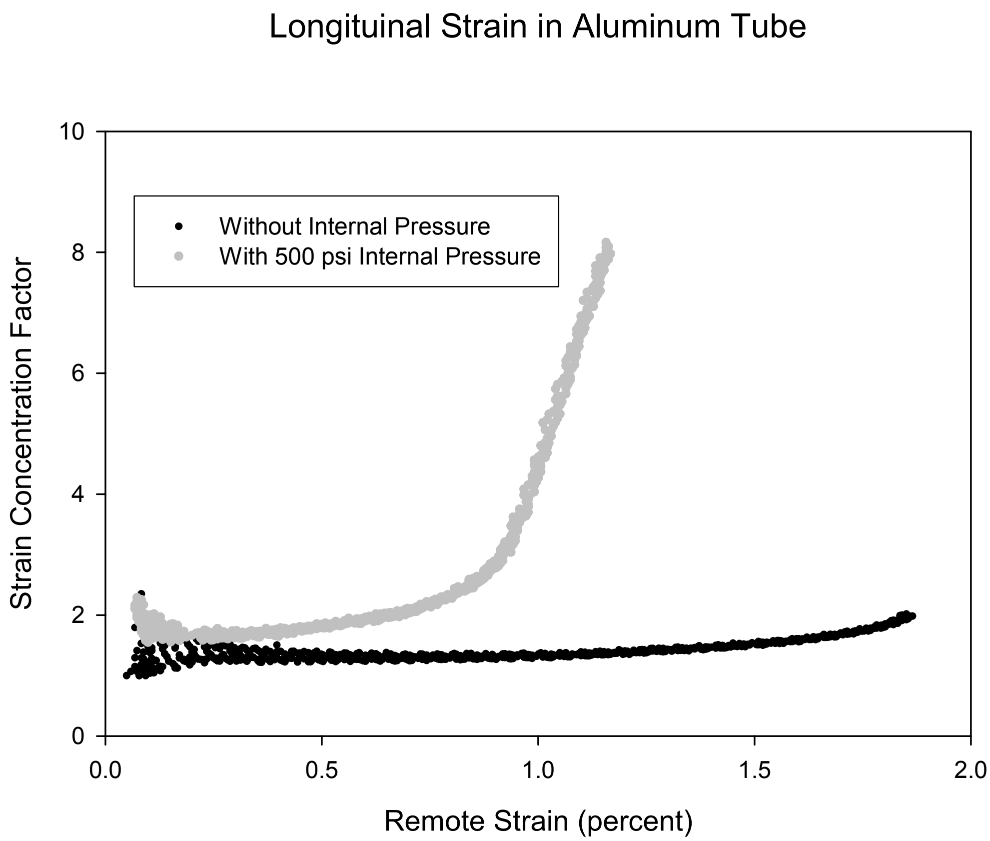

Figure A-22. Strain-Concentration Factor Results from HAZ

Appendix B

Data for Analysis of Critical Strain for Pipes in Compression

Data for Analysis of Critical Strain for Pipes in Compression

EWI collected data on the compressive buckling resistance of pipe to compare with available equations for the critical strain. The four tables, designated B-1 to B-4, that follow contain the specific data found and used for the analysis. These tables give the results, respectively, for plain pipe, plain pipe with internal pressure, girth-welded pipe, and girth-welded pipe with internal pressure. In some cases, data was obtained from review papers containing results from several sources. These cases are noted with the group designation from the review paper.

All data is given with the diameter-to-thickness ratio (D/t) and the strain at the maximum compressive stress, the critical strain. For the cases with internal pressure, the ratio of the hoop tensile stress due to pressure to the yield strength is given. Also given are two calculations designated DNV 2000 and Mohr. These are the experimental critical strain results multiplied by a factor that depends only on the ratio of hoop stress to yield strength A. The DNV 2000 column uses the factor 1/(1-5A). The Mohr column uses the factor 1/(1-A).

The references for the individual papers described in the tables are given below.

References

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12. Zimmerman, T.J.E., Stephens, M. J., DeGeer, D. D., and Chen, Q., "Compressive Strain Limits for Buried Pipelines," 1995 Offshore Mechanics and Arctic Engineering Conference, Vol. V, Pipeline Technology, pp. 365-378 (1995).

13. Sherman, D. R., "Flexural Tests of Fabricated Pipe Beams," Third International Colloquium Stability of Metal Structures, Toronto, Canada (May 1983).

14. Prion, H.G.L. and Birkemoe, P. C., "Beam-Column Behavior of Fabricated Steel Tubular Members," *Journal of Structural Engineering*, Vol. 118, No. 5, pp. 1213-1232 (May 1992).

15. Sherman, D. R., "Bending Capacity of Fabricated Pipe with Fixed Ends," American Petroleum Institute Report API 84-54 (Dec. 1985).

Table B-1. Plain Pipe without Girth Weld

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Dorey et al. (2000)	50.08	0.0099	378	
Dorey et al. (2000)	90.71	0.0023	472	
Dorey et al. (2000)	90.24	0.0046	483	
Rosenfeld and Roytman (1996)	52	0.008		Group A
Rosenfeld and Roytman (1996)	28	0.019		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	30	0.021		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	31	0.012		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	40	0.02		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	40.5	0.013		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	42	0.012		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	45	0.007		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	48	0.021		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	51	0.013		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	52	0.01		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	53	0.0085		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	54	0.01		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	60	0.007		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	62	0.014		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	71	0.005		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	72	0.0048		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	73.5	0.007		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	74	0.0032		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	75	0.003		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	95	0.0021		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	100	0.003		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	103	0.003		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	112	0.002		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	115	0.0014		Group B (Battelle 1970)
Rosenfeld and Roytman (1996)	81	0.0041		Group D (Van Douwen)
Rosenfeld and Roytman (1996)	81	0.0042		Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0042		Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0035		Group D (Van Douwen)
Rosenfeld and Roytman (1996)	19	0.055		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	19	0.045		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	19	0.041		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	19	0.038		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	19	0.032		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.075		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.068		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.064		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.061		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.055		Group E (Murphey and Langner)

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Rosenfeld and Roytman (1996)	20	0.051		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.049		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.044		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.042		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.039		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.031		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	20	0.027		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	21	0.049		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	21	0.042		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	26	0.04		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	26	0.036		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	26	0.034		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	26	0.031		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	26	0.029		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	29	0.041		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	29	0.038		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	35	0.032		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	35	0.03		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	35	0.026		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	35	0.02		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	37	0.02		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	37	0.018		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	37	0.015		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	39	0.024		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	39	0.019		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.017		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.014		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.011		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.0081		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.0065		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	52	0.0048		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	54	0.02		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	54	0.012		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	81	0.0075		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	81	0.004		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	81	0.0022		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	90	0.0071		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	90	0.0064		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	90	0.0058		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	90	0.004		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	90	0.0035		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	95	0.0061		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	95	0.0054		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	95	0.005		Group E (Murphey and Langner)

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Rosenfeld and Roytman (1996)	110	0.0059		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	110	0.0049		Group E (Murphey and Langner)
Rosenfeld and Roytman (1996)	110	0.0044		Group E (Murphey and Langner)
Gresnigt (1986)	81	0.0159		
Gresnigt (1986)	81	0.0059		
Gresnigt (1986)	95.2	0.0024		
Gresnigt (1986)	101	0.004		
Gresnigt (1986)	101	0.0061		
Sherman (1976)	48.6	0.0069	404	Group G
Sherman (1976)	55.4	0.004	421	Group G
Sherman (1976)	77.3	0.0033	288	Group G
Sherman (1976)	110.7	0.0044	310	Group G
Rosenfeld and Roytman (1996)	30.7	0.04	345	Group J
Rosenfeld and Roytman (1996)	46.1	0.0139	400	Group J
Rosenfeld and Roytman (1996)	61.5	0.008	352	Group J
Rosenfeld and Roytman (1996)	78.4	0.0038	386	Group J
Korol (1979)	28.9		309	
Korol (1979)	42.5	0.0092	305	
Korol (1979)	35.2	0.01	369	
Korol (1979)	80	0.0032	375	
Korol (1979)	49.1	0.0097	306	
Korol (1979)	51	0.0088	376	
Korol (1979)	56	0.0082	298	
Korol (1979)	64	0.0066	309	
Korol (1979)	80	0.0065	361	
Gresnigt and van Foeken (2001)	45.4	0.015	479	
Gresnigt and van Foeken (2001)	29.3	0.011	459	
Gresnigt and van Foeken (2001)	26.8	0.0174	474	
Gresnigt and van Foeken (2001)	22.3	0.0236	450	
Gresnigt and van Foeken (2001)	24	0.017		Group from Fowler
Gresnigt and van Foeken (2001)	25	0.024		Group from Fowler
Gresnigt and van Foeken (2001)	26	0.023		Group from Fowler
Gresnigt and van Foeken (2001)	16	0.029		Group designated Oman
Gresnigt and van Foeken (2001)	16	0.033		Group designated Oman
Gresnigt and van Foeken (2001)	25	0.035		Group designated TNO
Steinmann and Vojta (1989)	42.5	0.0112	333	
Steinmann and Vojta (1989)	63.7	0.0051	285	
Steinmann and Vojta (1989)	42.2	0.0115	387	
Estefan et al. (1995)	24.2	0.044	258.16	
Estefan et al. (1995)	24.2	0.05	258.16	
Estefan et al. (1995)	24.2	0.058	258.16	
Estefan et al. (1995)	21	0.052	288.6	
Estefan et al. (1995)	21	0.054	288.6	
Suzuki et al. (2001)	40.4	0.024	451	

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Suzuki et al. (2001)	40.4	0.043	557	
Rosenfeld and Roytman (1996)	42.1	0.017	850	Stainless (Group F)
Reddy (1979)	46.2	0.015	760	Stainless
Reddy (1979)	46.2	0.0121	760	Stainless
Reddy (1979)	46.2	0.012	760	Stainless
Reddy (1979)	51.3	0.015	810	Stainless
Reddy (1979)	51.4	0.0122	810	Stainless
Reddy (1979)	61.4	0.009	810	Stainless
Reddy (1979)	66.8	0.0092	750	Stainless
Reddy (1979)	76.5	0.0078	775	Stainless
Reddy (1979)	77.8	0.0076	775	Stainless
Nomoto et al. (1986)	52.3	0.012	207.1	Stainless
Nomoto et al. (1986)	33.5	0.0155	236.7	Stainless
Corona and Kyriakides (1988)	33.65	0.0216	259	Stainless
Corona and Kyriakides (1988)	24.5	0.0208	357	Stainless
Rosenfeld and Roytman (1996)	49.2	0.012	337.9	Concrete coated (Group J)
Rosenfeld and Roytman (1996)	61.9	0.0048	334	Concrete coated (Group J)

Table B-2. Plain Pipe without Girth Weld with Internal Pressure

Source	D/t	Critical Strain	Hoop Stress/ Yield Strength	DNV 2000	Mohr	Comments
Dorey et al. (2000)	50.08	0.0158	0.376	0.005486	0.011483	
Dorey et al. (2000)	50.08	0.029	0.751	0.006099	0.016562	
Dorey et al. (2000)	63.29	0.0281	0.826	0.005478	0.015389	
Dorey et al. (2000)	90.71	0.0031	0.206	0.001527	0.00257	
Dorey et al. (2000)	87.09	0.0025	0.14	0.001471	0.002193	
Dorey et al. (2000)	87.09	0.0029	0.336	0.001082	0.002171	
Dorey et al. (2000)	89.65	0.0051	0.693	0.001142	0.003012	
Dorey et al. (2000)	89.65	0.004	0.369	0.001406	0.002922	
Dorey et al. (2000)	47.54	0.0342	0.826	0.006667	0.018729	
Dorey et al. (2000)	90.24	0.0047	0.05	0.00376	0.004476	
Dorey et al. (2000)	60.69	0.0304	0.814	0.005996	0.016759	
Dorey et al. (2000)	83.69	0.0048	0.82	0.000941	0.002637	
Rosenfeld and Roytman (1996)	52	0.02				Group A
Rosenfeld and Roytman (1996)	81	0.011				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	81	0.03				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.035				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.025				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.013				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.005				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0039				Group D (Van Douwen)
Rosenfeld and Roytman (1996)	81	0.0126	0.31	0.0049	0.0096	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	81	0.0128	0.4	0.0043	0.0091	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	81	0.0333	0.8	0.0067	0.0185	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0058	0.2	0.0029	0.0048	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0045	0.4	0.0015	0.0032	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0135	0.6	0.0034	0.0084	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0252	0.8	0.005	0.014	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.036	1	0.006	0.018	Group D (Van Douwen)
Rosenfeld and Roytman (1996)	101	0.0054	-0.014	0.0058	0.0055	Group D (Van Douwen)
Suzuki et al. (2001)	48	0.015	0.4	0.005	0.011	
Suzuki et al. (2001)	48	0.023	0.4	0.0077	0.016	

Table B-3. Girth-Welded Pipes (no internal pressure)

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Dorey et al. (2000)	50.08	0.0064	378	
Dorey et al. (2000)	64.3	0.0081	391	
Dorey et al. (2000)	87.09	0.0025	550	
Dorey et al. (2000)	48.68	0.0075	358	
Dorey et al. (2000)	89.75	0.0026	502	
Dorey et al. (2000)	60.48	0.0085	448	
Dorey et al. (2000)	83.42	0.0034	448	
Zimmerman et al. (1995)	87.26	0.0032	440	
Zimmerman et al. (1995)	41.01	0.0131	470	
Prion and Birkemoe (1992)	69.23	0.0046	304	
Prion and Birkemoe (1992)	69.23	0.0042	304	
Prion and Birkemoe (1992)	100	0.0028	254	
Prion and Birkemoe (1992)	100	0.0038	254	
Prion and Birkemoe (1992)	61.64	0.0031	450	
Prion and Birkemoe (1992)	69.23	0.0074	304	
Prion and Birkemoe (1992)	69.23	0.0059	304	
Prion and Birkemoe (1992)	69.23	0.0052	304	
Prion and Birkemoe (1992)	100	0.0037	254	
Prion and Birkemoe (1992)	100	0.0033	254	
Prion and Birkemoe (1992)	100	0.0037	254	
Prion and Birkemoe (1992)	100	0.0035	254	
Prion and Birkemoe (1992)	61.64	0.003	450	
Prion and Birkemoe (1992)	61.64	0.0037	450	
Prion and Birkemoe (1992)	51.13	0.0071	450	
Prion and Birkemoe (1992)	51.13	0.0062	450	
Prion and Birkemoe (1992)	51.13	0.0082	450	
Prion and Birkemoe (1992)	61.64	0.0039	450	
Prion and Birkemoe (1992)	61.64	0.0036	450	
Prion and Birkemoe (1992)	51.13	0.0053	450	
Prion and Birkemoe (1992)	51.13	0.0054	450	
Prion and Birkemoe (1992)	61.64	0.0037	450	
Sherman (1983)	17.16873		279.2475	
Sherman (1983)	24.40977	0.039331	298.5535	
Sherman (1983)	27.72657	0.04533	337.855	
Sherman (1983)	34.94186	0.018667	298.5535	
Sherman (1983)	46.08696	0.005384	293.727	
Sherman (1983)	66.74074	0.002253	324.7545	
Sherman (1983)	73.52459	0.00536	314.412	
Sherman (1983)	71.55378	0.003743	308.896	
Sherman (1983)	47.17092	0.008241	314.412	
Sherman (1983)	89.88764	0.003112	373.0195	
Sherman (1983)	17.98		374.3985	

Source	D/t	Critical Strain	Yield Strength (N/mm)	Comments
Sherman (1983)	23.35492	0.050592	389.5675	
Sherman (1983)	22.92839	0.052058	367.5035	
Sherman (1983)	27.93798	0.011293	424.0425	
Sherman (1983)	34.54023	0.011931	410.942	
Sherman (1983)	45.64557	0.009156	410.2525	
Sherman (1983)	67.603	0.004389	433.6955	
Sherman (1983)	44.72998	0.01026	405.426	
Sherman (1983)	44.06998	0.013921	378.5355	
Sherman (1983)	86.5704	0.002998	429.5585	
Sherman (1983)	60.55696	0.004987	401.289	

Table B-4. Girth-Welded Pipes with Internal Pressure

Source	D/t	Critical Strain	Hoop Stress/ Yield Strength	Yield Strength (MPa)	DNV 2000	Mohr	Comments
Dorey et al. (2000)	50.8	0.0111	0.376	378	0.003823	0.00811	
Dorey et al. (2000)	50.8	0.019	0.751	378	0.003921	0.010943	
Dorey et al. (2000)	64.3	0.0104	0.419	391	0.003347	0.007363	
Dorey et al. (2000)	64.3	0.0187	0.839	391	0.003544	0.010241	
Dorey et al. (2000)	87.58	0.0025	0.185	523	0.001285	0.002113	
Dorey et al. (2000)	87.58	0.0031	0.354	523	0.001137	0.002296	
Dorey et al. (2000)	87.58	0.0054	0.747	523	0.001186	0.003106	
Dorey et al. (2000)	87.58	0.003	0.364	523	0.001048	0.002206	
Dorey et al. (2000)	87.58	0.0028	0.713	523	0.000603	0.001642	
Dorey et al. (2000)	48.6	0.012	0.429	358	0.003722	0.00845	
Dorey et al. (2000)	48.6	0.017	0.858	358	0.003134	0.009237	
Dorey et al. (2000)	89.75	0.0038	0.74	502	0.000801	0.002194	
Dorey et al. (2000)	60.69	0.0044	0.814	448	0.000856	0.002444	
Dorey et al. (2000)	60.69	0.0108	0.407	448	0.003541	0.007713	
Dorey et al. (2000)	83.14	0.0113	0.819	448	0.002174	0.006246	
Dorey et al. (2000)	83.41	0.0024	0.409	448	0.000781	0.001709	
Zimmerman et al. (1985)	87.26	0.0059	0.883	440	0.001087	0.00315	
Zimmerman et al. (1985)	87.26	0.0072	0.883	440	0.001285	0.003844	
Zimmerman et al. (1985)	41.01	0.0204	0.733	470	0.004293	0.011894	
Bouwkamp and Stephen (1974)	82.05	0.0049	0.101	503	0.00322	0.004455	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	96.97	0.0042	0.719	438	0.000901	0.002454	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	97.96	0.0031	0.019	438	0.002771	0.003043	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	98.56	0.0069	0.737	438	0.001485	0.00399	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	98.56	0.0038	0.116	438	0.002376	0.003409	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	98.97	0.0047	0.714	438	0.00099	0.002754	Rosenfeld and Roytman (Group C)
Bouwkamp and Stephen (1974)	102.78	0.0024	0.095	448	0.001584	0.002194	Rosenfeld and Roytman (Group C)

Appendix C

Guidance Document on Strain-Based Design

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C1.0 Introduction

C1.1 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.

Note: This guidance has been developed before the implementation of standards or recommended practices covering many aspects of strain-based design. Designers are cautioned that the onus to insure integrity of designs beyond yield remains on them. The information here, while it can provide limited guidance, should be supplemented by a good fundamental understanding of the physical phenomena involved and the application to the particular pipeline situation.

Commentary: Design codes and specifications for pipelines either provide limited coverage of cases where strain in the pipe is the appropriate design parameter (for instance, in API 1104) or integrate the coverage of these cases into a larger framework document (as in DNV 2000 or CSA Z662). This document is designed to provide guidance specific to pipeline design where strain is the appropriate design parameter.

Commentary: For designs where some plastic yielding of the pipeline material is expected, a strain-based design method may have major advantages. When strain and stress are not proportional, stress-based methods become very sensitive to details of the material stress-strain behavior and to any safety factors. Strain-based design avoids these problems.

Commentary: Strain-based design has proven applicability to offshore pipe laying, pipelines operating at high temperatures, pipelines in areas of soil movement, and arctic pipelines.

Commentary: For cases where the loading mode is load controlled, where a change in pipe shape will not change the loading, strain-based design is not usually applicable. For cases where the loading mode is displacement controlled, where the pipe could change shape to cause the loading to go to zero, strain-based design is applicable. There are intermediate cases where part of the loading is load controlled and part is displacement controlled, so that a change in pipe shape can change the loading, but not take it to zero. A simple model of the latter case is a vertical hanging pipe that stretches due to a weight placed at the bottom end and then is stretched additionally when the weight is bolted to a floor.

C1.2 Principles

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

Basics are designed to provide the framework for pipeline strain-based design and to apply to all cases. Basics describe the underpinnings 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 “should” is used in provisions, “should” is used in notes, and “may” is used in the commentary.

C1.3 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.

C2.0 Causes of Strain

C2.1 Pressure

Pressure should be assessed based upon the difference between the external and internal pressure. The sign of this difference may be important, that is, whether external pressure is higher, the external overpressure case, or internal pressure is higher, the internal overpressure case. Pressure loadings should be assumed to be load controlled, rather than displacement controlled, in the hoop direction.

C2.2 Soil Movement

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

C2.3 Restrained Thermal Expansion

Thermal expansion will induce longitudinal mechanical compression strain in the pipe wall when the pipe ends is restrained. The mechanical compression strain due to restrained thermal expansion should be assumed to be displacement controlled, rather than load controlled.

Commentary: The description of restrained thermal expansion covers the situations that arise because the stress-free length of a pipe changes with its temperature. A temperature-compensated strain gage will measure strain in a pipe when the ends are restrained and the pipe is heated.

C2.4 Bending to Conform to a Curved Surface

Bending strains in pipe against a curved surface should 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 and displacement controlled.

C2.5 Spanning

Pipeline areas that are not supported by the soil or other surrounding solid material must carry their own weight and the weight of any additional material on the pipe to a supported area. Transverse loads such as from wind, waves, or currents must also be carried to the supported points. All of these are normally described as primary loadings and are thus load controlled. Transverse loads can also excite resonant behavior (vortex induced vibration, etc.), which is controlled neither by load or displacement alone, but by the energy of vibration.

C2.6 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. Another example is fatigue cycles that exceed the yield strength of the pipe material, for which strain range is a better measure of the damage incurred by a fatigue cycle than is stress range.

C3.0 Design Limits

C3.1 Maximum Strain

C3.1.1 Tension

Commentary: Designs would not be expected to attempt to use strains in excess of half the tensile elongation from a tensile test on the base pipe material.

Commentary: The maximum strain limit may be set to a value near 10% (0.1) for many pipeline steels. Lower or higher values have been observed to be appropriate based upon the plastic properties of the material. Strain localization will usually increase the local maximum strain limit at the same time that it increases local strain.

C3.1.2 Compression

Commentary: Compressive strains well in excess of the yield value would only be expected in combination with other deformation mechanisms such as plastic shear and buckling. Limits on maximum compressive strains may be most appropriately defined in relation to the deformation mechanism, although limits on maximum strain may be used to achieve this goal.

C3.2 Global Compressive Strain

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

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

Note: 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.

Commentary: Global in this section describes a loading situation that relates to the entire pipe cross section and extends over several pipe diameters in length.

C3.2.1 Lateral

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

C3.2.2 Upward

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

C3.3 Local Compressive Strain

Pipe sections subjected to axial compressive strain should 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 equations available in standards, such as the following available in DNV 2000 and appropriate to D/t≤45:

$$\varepsilon_c = 0.78\left[\left(\frac{t_2}{D} - 0.01\right)\left(1 + 5\frac{\sigma_h}{f_y}\right)\alpha_h^{-1.5}\,\alpha_{gw}\right] \quad (1)$$

where:

ε_c	is the ultimate longitudinal critical strain
t_2	is the wall thickness, allowing for any service corrosion
D	is the nominal outside diameter
σ_h	is the design hoop stress from internal overpressure
f_y	is the yield strength to be used in design
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)].

Equations are also available in DNV 2000 for the case of longitudinal compressive strain combined with external overpressure.

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 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 strain factor, such as those described in the factors of safety section.

Commentary: The equations for design compressive strain in DNV 2000 are limited to D/t of 45, as in Eq. (1) above. Some comparisons have been made where the same equation forms are applied to higher D/t. The general forms appear to be appropriate up to D/t of above 90, but the effect of hoop stress from internal overpressure is significantly overestimated, as shown by test results collected by Dorey et al. 2000. Mohr has proposed that a better fit can be obtained if the $1+5\left(\sigma_h/F_y\right)$ term were replaced by one of the form $1+\left(\sigma_h/F_y\right)$.

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 based on tests and models of common pipeline steels. Values determined in tests can be used to shift this expectation, but should be based upon an appropriate ratio of primary to secondary loading for the service conditions of interest.

C3.3.1 Elastic Local Buckling

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

C3.3.2 Elastic-Plastic Local Buckling

Note: Methods for assessment of buckling should account for all buckling modes, as has been done by techniques in current standards, such as DNV 2000 and API 1111.

Commentary: Several modes of buckling have been observed in pipes under test conditions. Assessments for local wrinkle formation may need to 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 may need be checked.

C3.4 Plastic Ovalization

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

Note: Ovalization deformation should be limited so that the minimum diameter does not shrink to the extent that the passage of internal inspection devices is hindered. A simple limit may be a minimum diameter with a reduction of 3% from the design inner diameter.

Commentary: Combinations of cyclic bending loading and internal pressure can result in ovalization deformation with an increase in average diameter. These conditions may allow greater ovalization deformation while still allowing 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%) measured as the difference between the maximum and minimum diameters divided by the average of these diameters. Simple estimates can also be made comparing the diameter difference to the original diameter.

C3.5 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 no more than half the material's uniaxial tensile elongation to failure in a tensile test.

Commentary: Global in the context of axial tension strain can describe cases where only part of the pipe cross section is in tension. It may be appropriate to average the tension strain over a length equivalent to two pipe diameters.

C3.6 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 no more than the material's uniaxial tensile elongation to failure in a tensile test.

Commentary: Under appropriate conditions of constraint, such as around crack tips, local tensile strains have been observed to considerably exceed the uniaxial tensile elongation to failure. Such areas can be considered in design using engineering critical assessment (ECA) methods.

Commentary: Local in the context of tension strain may normally be interpreted based on length dimensions from 0.5 to 5 mm. This size range is chosen to be smaller than individual weld passes, but significantly larger than the individual grains that make up the materials. High strains at sharp stress concentrations or cracks may be better interpreted within the context of an ECA.

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 ECA should be completed.

C3.7 Ratcheting

Note: Pipe sections subjected to multiple cycles of plastic deformation should be designed to avoid a ratcheting failure. The pipe section should 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. Pipe sections with plastic strain histories including both tensile and compressive plastic strain and hoop stress due to internal or external pressure may be susceptible to ratcheting failure when the strain accumulates in the hoop direction, causing ovalization deformation or diameter change.

Commentary: Resistance to ratcheting may be partly determined by changes to the material-stress-strain behavior during cyclic loading. Steels with a yield plateau tend to lose this plateau and have lower yield strength during cyclic loading, provided the cycles are applied rapidly enough. Stainless steels, including 13% Cr materials, tend to exhibit cyclic hardening.

Commentary: Ratcheting may also occur due to cyclic deformation of the pipe in combination with accumulating changes to the material supporting the pipe. Upheaval creep has been observed in North Sea buried pipelines where the soil supporting the pipe fills in underneath the pipe during periods when the pipe has an upward deflection cycle.

C3.8 Fatigue under a Load Spectrum

Commentary: Fatigue loading spectra can include stress ranges where the maximum stress of the cycle exceeds the tensile yield strength of the material. Fatigue for these cycles may be assessed based upon the strain range rather than the stress range.

Commentary: The number of strain cycles to failure may be assessed according to a two-part curve from ABS 2001. These curves are derived from the original X curve from AWS D1.1:1972 as described by Marshall (1992) and written below with N as the number of strain cycles and $\Delta\varepsilon$ as the range of cyclic strains:

$$\Delta\varepsilon = 0.055N^{-0.4} \quad for\ \Delta\varepsilon \geq 0.002$$

and (2)

$$\Delta\varepsilon = 0.016N^{-0.25} \quad for\ \Delta\varepsilon < 0.002$$

Commentary: The above two-part curve is based on strain ranges adjacent to the weld that include geometrical concentrations of strain, but do not include concentrations of strain due to the weld cap or root profile or welding imperfections.

Commentary: Local strain concentrations due to buckling would need to be included in the $\Delta\varepsilon$ to account for cases where buckling occurs on the compression part of the cycle. Strain concentrations from buckling may be expected to be large enough to severely reduce the allowable number of fatigue cycles.

Commentary: Fatigue cycles may act in combination with other loads, such as pressure, to cause increasing ovalization.

C3.9 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.

Commentary: Plastic strain may also be concentrated by differences in strength between the base and weld metal.

Commentary: Strain may be locally concentrated by the shape of the weld itself, as at the edge of the cap or root surface. Such concentrations act over a small fraction of the pipe wall thickness and are not normally assessed using strain concentration factors across the full wall thickness. Instead, weld magnification factors are used to assess imperfections that are within the area of the stress concentration, such as weld toe surface flaws, during fracture assessment. Weld magnification factors may be found in BS 7910.

Commentary: Plastic strain may be further concentrated when loading is present in other directions. For instance, hoop stress from internal overpressure may allow further concentration of strains in low-strength girth welds or weld heat-affected zones (HAZs).

C3.10 Accumulated Plastic Strain

Note: 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. 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.

Commentary: Accumulated plastic strain is a relatively severe combination of strain that will not be appropriate to all types of cycles.

C4.0 Factors of Safety

Commentary: Factors of safety may be chosen based upon the uncertainty of the design information, the likelihood of the strain event, and the consequences of failure by the mode contemplated. Strain events with annual probabilities below 1 in 10,000 over the pipeline service lifetime may appropriately be assessed with lower safety factors.

Commentary: Safety factors on strain for buckling failure modes may be applied based upon a table from DNV 2000 and provided in a simplified version below.

Resistance Strain Factor	Safety Class		
	Low	Normal	High
Supplementary requirement U	2.0	2.5	3.3
No supplementary requirement	2.1	2.6	3.5

This table uses safety classes as defined in the following sections. The reduction in safety factors for supplementary requirement U are based upon testing indicating that the pipes used exceed the standard minimum yield strength (SMYS) in the transverse direction by at least 3%.

Commentary: Safety factors on strain, parameters within the ECA, and flaw size for tension failure modes may be coordinated so that overall resistance to these modes is maintained. Where the safety factor is applied on strain alone, the value of this factor may be compared to those in the table below and the safety classes defined in the following sections.

Tension Strain Safety Factor	Safety Class		
	Low	Normal	High
Factor on strain	1.5	2	3

The safety factors are based on those used in engineering practice, for example the factor of 3 used on tensile strain for the Northstar pipeline, and the 1.5 factor used in a somewhat different context by the Appendix K of CSA Z662:1999.

Commentary: A safety factor on longitudinal strain related to pipe rotation, where this can be interpreted as a failure mode, may be applied. This may be appropriate during offshore S-lay of a pipeline with T-joints or other orientation-critical equipment. The safety factor on longitudinal strain may be chosen as 1.3.

Commentary: Safety factors on lifetime for fatigue assessment may be chosen based upon the table below and the safety classes defined in the following sections.

Fatigue Safety Factor	Safety Class		
	Low	Normal	High
Factor on lifetime	3	5	10

This safety factor accounts for the order in which cycles are applied and may be used in conjunction with other safety factors, such as those incorporated in the design S-N (stress range – cycles) or strain-range to cycles curves or in the crack growth rate. Crack growth rates may be assessed based on the mean plus two standard deviation growth rate for the material of interest or for a class of materials to which the material of interest belongs.

Commentary: Fatigue assessments may be preferred that use one fatigue safety factor for all of the cycles. That safety factor may be chosen based on the safety class applicable to the time the final stress range is applied.

C4.1 Installation

Commentary: Installation may normally fall within safety class low. Exceptions may be needed to account for cases such as pressurized installation, installation within sensitive areas, or installation with high stored mechanical or potential energy.

Commentary: Designers may not normally wish to allow buckling strains in excess of the critical strain during the installation phase. Buckling and wrinkling during installation may reduce the margin of safety against several modes of failure during operation below levels expected in design.

C4.2 Operation

Commentary: Operation conditions may fall into each of the safety classes depending upon the pipe contents. Pipes carrying water-based non-flammable fluids and non-toxic non-flammable gases in areas more than 500 m from offshore platforms and areas of frequent human activity may normally be placed in safety class low. Pipes carrying other materials may fall into safety class normal in these same regions. Adjacent to areas of frequent human activity or platforms, the pipes carrying water-based non-flammable fluids and non-toxic non-flammable gases may normally be placed in safety class normal. Pipes carrying other materials in these areas may normally be placed into safety class high.

C5.0 Pipe Material Selection

C5.1 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.

Commentary: Tight tolerances on pipe sections and measures to limit wall misalignment across girth welds may be applied to other conditions where limiting the stress concentration at girth welds is important, such as for risers under environmental fatigue loading.

C5.2 Mechanical Properties

Note: Steel pipe sections with accumulated plastic strain in excess of 2% in design should have tensile properties of representative pipe material meet three criteria recommended by DNV 2000:

1. Measured yield strength minus SMYS of no more than 100 MPa
2. Measured yield strength to tensile strength ratio of no more than 0.85
3. Elongation equal to or exceeding 25%.

Commentary: All three of these recommendations may pose difficulties for pipe manufacturers, particularly for pipe grades above API 5L X65. It may be reasonable to choose values of these parameters appropriate to the steel grade being used. However, these values were chosen, within the small group of parameters commonly recorded, as ones appropriate to pipeline steels for which experience was available in reeled pipe, including API 5L X70.

Commentary: Strain-based design is able to use most effectively materials that have much plastic strain hardening as the strain increases past the yield strain. This stress-strain behavior is characteristic of the most common austenitic stainless steels. Carbon steels with lower yield strength, lower yield-tensile ratio, and higher elongation to failure are more likely to show this behavior. Alternatively, smoothly increasing stress-strain curves up to a given high strain level could be specified in agreement with the producer of the steel pipe.

C5.3 Mechanical Properties after Strain-Aging Treatment

Note: Steel 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, as required by DNV 2000. 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 250°C for 1 hr before additional mechanical testing. The mechanical test results should meet the requirements for the base pipe with the following exceptions:

1. Measured yield strength to tensile strength ratio of no more than 0.97
2. 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.

C5.4 Strength Variability

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

C6.0 Girth Weld Material Selection

C6.1 Mechanical Properties

Note: Weld metal should meet the minimum mechanical property requirements of the pipe base metal.

Commentary: There may be cases where weld metal that meets the base metal requirements cannot be used, such as when corrosion problems may occur at welds or when filler materials of that strength will give unacceptable risk of welding flaws. Under these conditions, strain concentrations at the weld area may cause locally large tensile plastic strains under the design conditions. Compensating increases in weld area toughness, decreases in allowable flaw size, or decreases in strain concentrations from other causes may be needed to reach the high strains without failure.

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 HAZ, 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. Weld metal that is higher than the base metal in strength can also increase allowable flaw sizes within the weld metal in an ECA.

C6.2 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.

C6.3 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. This approach is common for manual procedures, but is not usually used for automatic welds.

C6.4 Strength Variability

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

C7.0 Fabrication and Installation

C7.1 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.

Commentary: Many applications may use tighter requirements on “high-low” to reduce the geometrical stress concentration around the girth weld area.

C7.2 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.

C7.3 Pipeline External Coating

Note: Pipeline external coating should be designed to provide sufficient strain capacity so that the purposes of the applied coating are not compromised by the action of the design strains.

Commentary: Pipeline external coating systems may perform or combine functions of corrosion protection, thermal insulation, and mechanical protection. External coating systems may be designed to have linepipe coating and coating adjacent to pipe girth welds use different materials and layers. Consideration may be given to the strain capacity of the linepipe coating, the coating adjacent to girth welds, and the area where these two types of coating overlap. Coating applied for thermal insulation and the ends of such coating may be particular areas for examination.

Commentary: Tests of pipeline external coating for strain capacity may be completed on plate specimens.

C7.4 Weight Coating

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

Commentary: Weight coating, for instance with concrete, may be used to prevent buoyant rising of a pipe under external overpressure. Removal of long sections of weight coating may allow buoyancy forces to unacceptably change the configuration of the pipeline.

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.

C7.5 Cathodic Protection Devices

Note: Cathodic protection devices should be designed so that connections to the pipeline provide sufficient strain capacity so that the cathodic protection system is not compromised by the action of the design strains.

Commentary: Cathodic protection devices need both the mechanical support of the pipeline and an electrical connection to the pipe steel.

Commentary: Cathodic protection potentials higher than normally used may charge hydrogen into the steel. This hydrogen may have the effect of embrittling the steel, particularly in regions that experience plastic strain.

C7.6 Prevention of Pipe Rotation

Note: Pipe that has been bent with plastic deformation may have a tendency to rotate around its axis under subsequent bending 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 is 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.

C7.7 Dents and Gouges

Commentary: Dents and gouges should only be left in place under rare circumstances; doing so, in general, is associated with a risk of fatigue or other subsequent failures. Dents and gouges from installation or during operation may be assessed using strain concentration factors. Strain concentrations may be assessed both at the deepest point and at the edge of the dent or gouge. Reduction of dent depth due to internal pressure may be considered.

C8.0 Inspection

C8.1 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. Exceptions may require materials and design with unusually high resistance to failure under plastic tension strain.

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

Commentary: Radiographic inspection may supplement the information from other inspection techniques. However, since it has limited measurement capability in the pipe wall through-thickness direction, it is not usually directly connected to an ECA of girth-welded pipelines.

C8.2 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 ECA.

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 and 0.02 (0.5 and 2%) may be determined based upon an ECA, or based upon a generic ECA of a more severe case.

Commentary: The acceptance criteria may need to be reduced from those determined by the ECA to account for the variability of sizing with the inspection technique and procedures.

Commentary: Inspection may not be effective when the allowable flaw size is below that where the inspection technique can detect flaws more than 95% of the time. Change of the inspection method or procedures may be needed to achieve the desired detection capability. Alternatively, inputs to the ECA may be changed so that the resulting allowable flaw size can be reliably detected by the inspection method.

C9.0 ECA

C9.1 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.

C9.2 Intermediate Strain Methods

ECA 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 crack-tip opening displacement (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 BS 7910.

C9.3 Accumulated High Strain Methods

Commentary: ECA methods for accumulated plastic strain in excess of 0.02 (2%) have not been widely validated. An example reported by Hoo Fatt and Wang can be compared to testing reported by Pisarski et al. for a single cycle. 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, and similarly for the compression part.

C9.4 Pressure Effects

Commentary: Internal pressure may reduce the allowable flaw size from an ECA of a girth weld even though the primary stresses from pressure are parallel to the weld and the planar imperfection. The internal pressure stresses increase constraint around the girth weld imperfection, and this higher constraint can have an important effect for longitudinal strains in excess of 0.005 (0.5%). The need to account for pressure-induced constraint may be avoided by testing for fracture toughness with a specimen that exceeds the maximum constraint to be observed in service.

C9.5 Temperature Effects

Commentary: ECA may be completed using the minimum design temperature and the maximum strain history. It may be more appropriate to partition the strains into different temperature groups and assess based on several minimum temperatures.

C10.0 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.

C11.0 References

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