

STRAIN BASED DESIGN FOR LAND HIGH GRADE PIPELINES IN HARSH ENVIRONMENTS

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ABSTRACT

The use of Strain Based Design (SNBD) in pipeline technology has been widely discussed during the last decade, particularly for offshore applications. In fact there have been many instances where the offshore pipeline engineer had to adopt SNBD in order to avoid onerous measures necessary to meet the traditional Stress Based Design (STBD) criteria, advocated by international codes at the time in force. SNBD was first introduced to make allowance for crossing bottom roughness and harsh environments, recently for HP/HT applications. SNBD is currently under investigation for land pipelines, crossing regions affected by geohazards as seismic activity such as land slides, active faults, soil lateral spreading due to soil liquefaction etc.. Conditions for which SNBD are applicable, as well as permissible deformations in relation to line pipe material and safe operation of the pipeline in the long run, are currently of major concern in a series of strategic project developments in North America and East Siberia.

In this paper, an engineering guideline for the implementation of SNBD on land pipelines is discussed. Different aspects to be considered in the definition of permissible strains, are introduced.

KEYWORDS

Land pipeline, design criteria, failure mode, limit state, strain based design, reliability methods, load and resistance factor design.

INTRODUCTION

World energy consumption is expected to continue growing in a scenario where the share of natural gas in primary energy consumption, steadily increases. The demand is growing especially for power generation, in relation to the substitution of pollutant fuels (according to the Kyoto Protocol and subsequent), and increased efficiency in the use of gas by power generating equipment (/1/). Over the next decade, the major markets for gas will be likely improved in traditional areas as per the Northern America, Europe and Northern Asia. New remarkable gas markets are expected to be developed in other regions, namely in the Middle East, the Indian Subcontinent, China and the Far East. In addition to the main traditional gas suppliers (Russia, Iran, Algeria, Norway, etc.), new producing countries (Kazakhstan, Turkmenistan, Qatar, Central and Eastern Siberia) are planning the development of their resources so as to finance their growing-up economy.

It is generally recognised that the pipeline is the most economic and safest technology for land transportation of large quantities of natural gas. For the supply of specific coastal regions (Japan, South China, South Korea, Taiwan, Europe), the transport of gas by LNG chain will be increased.

The transport of gas by pipeline will maintain the prevailing role in the trans-national gas trade particularly from mid-continental producing regions (/2/ and /3/).

The rationalization of design criteria is a keyword for future development programs for such pipelines crossing harsh environments (/4/ and /5/). In many circumstances, the areas crossed by new pipelines are operated by significant seismic risk. Damage to buried pipelines has been observed and documented by many individuals during post-earthquake reconnaissance. For buried pipelines, seismic hazards are generally classified either as wave propagation hazards (WPH) or as permanent ground deformation (PGD) hazards. Since the late 70's it has been successfully shown that the limit state and partial safety factor approach is a rational way to achieve this target. Stress-based design criteria are almost universally used in the assessment of the structural integrity of a pipeline. Applications of these formats is straightforward since only simple linear elastic analysis is required to calculate the load effects in the specified conditions. Load effects are subsequently compared with allowable states of stress. Unfortunately, this may also result in unsatisfactory designs, both from economic and safety points of view. Strain Based Design is therefore advocated!

The advent of new materials and modern welding and NDT technology has definitely removed the hazard of failure modes associated with brittle material behaviour. As a consequence, deformation failure modes and associated limit states involving large plastic strains (e.g. pipe curvatures causing wrinkle patterns in the pipe sector in compression or opening of a crack in the girth weld) or significant geometric distortions of the section (e.g. obstructing the passage of a pigging device) can be utilized. These necessitate non-linear analytical approaches for the direct evaluation of each of the envisaged limit states/failure modes. For this reason it becomes necessary to include the mathematical modelling of both large displacement and non linear material relationships to predict the non-linear response of the pipeline up to the failure condition identified for such limit states.

Achieving a rational assessment of the safety of both ageing transmission system and new challenging projects requires a comprehensive analysis, where the reliability assessment is only one of the major aspects. This will be the primary concern for future efforts, aiming at developing modern design guidelines which rationally and quantitatively account for project-site specific safety targets.

The scope of this paper is the following:

- Discuss the failure modes relevant for on land pipelines in relation to the envisaged loading conditions;
- Present technological issues related to strain based design of pipes subject to large level of deformation under extreme loading conditions due to seismic excitation and arctic environment;
- Present advanced analysis tools used to assess the deformation capacity of land pipelines under operating conditions.

1. RELIABILITY BASED LIMIT STATES DESIGN

In the second half of the '90 ies a series of R & D initiatives addressed to the review of design guidelines for cross country pipelines, with the aim to introduce the limit states design with partial safety factors, purpose calibrated by using structural reliability methods (/7/). Partial safety factors allow to account for pre-established safety targets, which in general reflect a safety philosophy and are based on hydrocarbon industry practice, modern (from the second half of the '70 ies) pipelines

failure statistics and inherent safety of traditional codes (/6/ and /7/). These initiatives received strength from the general consensus that the pipeline industry, after a series of public debates, expressed on the findings of a similar initiative undertaken in the first half of the '90 ies and addressed to offshore pipelines (/8/, /9/ and /10/).

The issue of the LRFD (Load Resistance Factor Design) Code DNV '96 (/11/) was the starting point for the initiatives that have followed. Among these is noteworthy that reliability based limit state design principles are indicated as a design option in the ISO Code DIS 13623 Pipeline Transportation System for the Petroleum and Natural Gas Industry (/12/); therefore an ISO working group was established to prepare a standard on Reliability Based Limit State Methods (ISO 16708, /13/). Unfortunately, such efforts do not explicitly cover the effect of high (greater than 0.85) yield to tensile strength ratio (Y/T) on pipeline integrity. This topic is crucial as:

- most design guidelines are applicable to line pipe steel characterized by Y/T less than 0.85;
- Y/T provides a measure of the strain hardening capacity of the pipeline, which in turn is a guarantee against local effects controlled by loads;
- high grade steels hardly meet Y/T less than 0.85.

As a consequence allowable working factors for high grade steels (X100 and X120) are expected to be less than those allowable for traditional API 5L X65-X70, so that a simplistic proportional reduction of wall thickness for X100 steels with respect to traditional ones is not applicable. As an example, the use of the design format proposed by DNV (/11/) for minimum wall thickness requirements for pressure containment would mean:

- for Y/T less than 0.87, the minimum wall thickness, complying with the established safety target, is calculated using as characteristic strength Y and introducing a certain working (usage) factor with respect to Y;
- for Y/T larger than 0.87 and the same established safety target, using as characteristic strength T and introducing a certain working (usage) factor with respect to T.

A limit state is achieved when the response of the pipeline to loading is unacceptable. A distinction can be made between Ultimate Limit State and Serviceability Limit State. Ultimate limit states for a pipeline entail structural damages which will give rise to the release of the transported fluid into the external environment or the flooding of the line, both in the short and long term i.e. the pipeline is not performing its function e.g. due to leakage or burst. A serviceability limit state is when basic requirements are not met (thereby giving severe state of stress and strain) which means the pipe is not available for traditional operations or is more vulnerable to unexpected conditions.

The structural performance of the pipeline is based on a set of limit states or failure functions covering all relevant failure modes. Each limit state divides the structure into two states, i.e. the safe state and the failed state. The following four categories of limit states are considered in structural design of land pipelines:

- Serviceability Limit State (SLS) beyond which the pipeline will not meet its functional requirements, e.g.
 - Global buckling, i.e. upheaval buckling or lateral buckling,
 - Maximum ovalization i.e. for internal inspection reasons;
- Ultimate Limit State (ULS) beyond which the pipeline may experience loss of structural integrity, e.g.
 - Bursting,
 - Local buckling i.e. ovalisation or bulging under bending dominated condition,

- Unstable fracture/plastic collapse;
- Fatigue Limit State (FLS). An ULS condition covering fatigue damage due to cyclic lifetime loading;
- Accidental Limit State (ALS). An ULS condition due to abnormal action typically with high return periods.

Failure modes may develop in the presence of longitudinal defects which cause the reduction of strength capacity for the containment of internal pressure. On the other hand circumferential failure modes are associated with excessive longitudinal stresses and strains caused by external loads.

In general longitudinal failure modes triggered by internal pressure are negligibly influenced by the longitudinal state of stress, Stewart et al. (/14/) and Gresnigt (/15/), while circumferential failure may be influenced by longitudinal stresses (Bruschi et al., /16/; Zimmermann et al., /17/).

Circumferential failures are relevant in the above mentioned harsh environments, and bending effects are of major concern. In general, the development of excessive longitudinal stresses causes the circumferential failure of a pipe as follows:

- *At a girth weld*, initially starting from a partial wall defect accepted or undetected during inspection, triggered by a single overstress condition or by a sequence of cycles of tensile stress, developing up to the full wall thickness, giving rise to a condition of leak and, at worst, unstable propagation across the circumference leading to full bore rupture (Willoughby, /18/; Wilkowski, /19/).
- *In the pipe body*, usually in the proximity of a girth weld where stiffness discontinuity and material inhomogeneity might be relevant, triggered by compressive over stresses causing excessive strains often accompanied by inward kinking or external bulging, up to wall thinning and bursting in the presence of internal pressure (Denys and Glover, /20/).
- *In the pipe body*, usually in the proximity of a girth weld and associated strain concentration, triggered by overbending in concomitance with internal over-pressure (operation at high pressures), developing through wrinkling and bulging of the pipe sector in compression (Bruschi et al., /21/).

In general the occurrence of a failure mode is linked to the localisation of deformation in one pipe section and strictly depends on the achievable state of equilibrium between the external loads and the internal actions as well as on the boundaries which restrain or allow the development of deformations.

The most critical condition for the localisation of deformation is associated with the development of bending strains, which may be either unbounded or limited by external boundaries. Therefore, it is necessary to differentiate the achievable state of equilibrium for a pipe as follows:

- For a pipe bounded by the surrounding medium such as to prevent it from developing additional bending, other than that imposed by the boundaries, additional strains are fully controlled by the fixed geometry of external boundaries. This condition is usually classified as strain or displacement controlled (DC) and is characterised, for example, by buried pipelines covered by a stable and resistant backfill.
- For a pipe free to bend under the action of external loads, the development of bending depends strictly on the capacity of internal stresses to balance the external loads and is controlled for internal actions within the elastic domain of the material behaviour. External loads causing internal bending actions exceeding the elastic limit might cause unbounded deformations and the uncontrollable and non-localised achievement of failure conditions. This condition is usually classified as stress or Load Controlled (LC) and is characterised, for example, by free spanning pipelines which are resting on the rocky peaks of an uneven seabed.

On this basis, SNBD is applicable only when the pipeline cannot develop unbounded bending. In on land pipeline technology, particularly during these last years, LC versus DC conditions are often mentioned and referred to typical loading condition which the pipeline encounters along the route and during its lifetime.

2. COMPRESSIVE STRAINS, LOCAL BUCKLING FAILURE MODE

The buckling mechanisms are generally subdivided as follows, see Figure 1:

- *Ovalisation Buckling* triggered by the component of bending stress perpendicular to the neutral axis in the sectional plane of the pipe. This increases for increasing curvatures and works to “flatten” the sector in tension and to “kink” the sector in compression, thereby globally ovalising the pipe section. The presence of external pressure contributes to enhance such ovalisation up to collapse into a “dog bone” shape thereby, causing the pipe to loose strength.
- *Wrinkling or Outward Bulging* triggered by excessive compressive stresses: local bending instability starts either with wrinkles that may develop into inward kinks or outward bulges, or with “diamond shaped” yielding loci.

Wrinkling failure mechanisms depend on diameter to thickness ratio, steel material (Y/T and shape), geometric imperfections and ratio between axial and bending stresses (Bruschi et al., /16/). Hoop stresses help to counteract the ovalization effects by activating positive circumferential strains in the plastic field, which cause an increase in length in the circumferential direction and thus an outward expansion (Gresnigt, /15/ and /22/).

Such a limit state might be relevant during operation of land pipelines when subject to permanent ground displacement due to landslides, active faults, etc.. In these circumstances, the axial compression and/or bending moment developed by the permanent ground displacements are responsible for achievable compressive strains. Major concern relates to localisation of strains due to material inhomogeneities as well as to the actual strain-strain curve whether smooth and strain hardening or showing a flat plateau up to the considered strain (Gresnigt et al., /23/). Both imply additional failure paths associated to high compressive strains in the presence of internal over-pressure (Boyle, /25/). Ratcheting, i.e. cumulation of hoop strains under cyclic axial loads and low cycle - high strain fatigue, e.g. caused by fluctuation of in service conditions, both become relevant (Xia and Ellyin, /26/; Tomkins, /27/).

Limit compressive strains related to any possible instability/failure mode have not received attention comparable to that given to ovalization buckling, especially in relation to the effects of internal over-pressure.

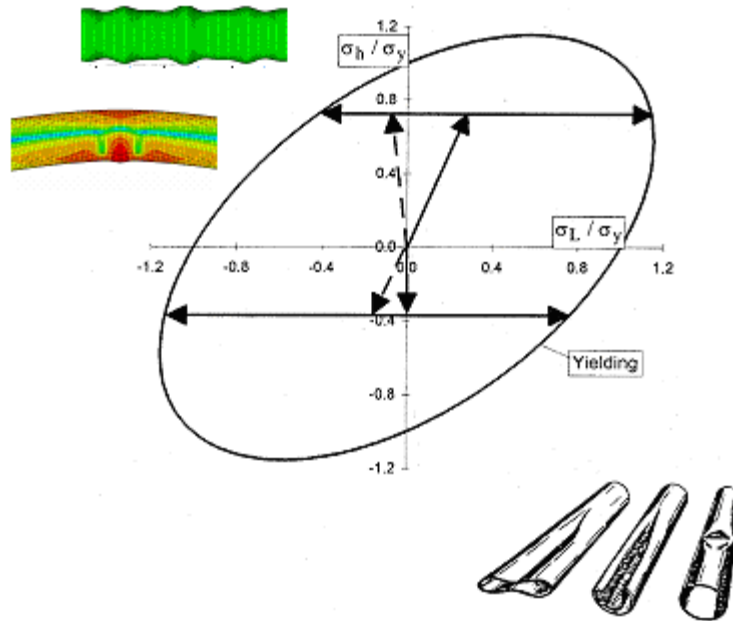


Figure 1 - Local buckling mechanism as a function of differential pressure shown on the Von Mises ellipse.

In the late seventies and early eighties, a few experimental tests were carried out to investigate the buckling mechanisms of thin walled pipes subject to internal pressure, axial force and increasing bending moment, see e.g. Bouwkamp and Stephen (/28/), Sherman (/29/) and Gresnigt (/30/). These experiments focused on the effect of the outer diameter to wall thickness ratio, stress strain relation, axial load and internal pressure load.

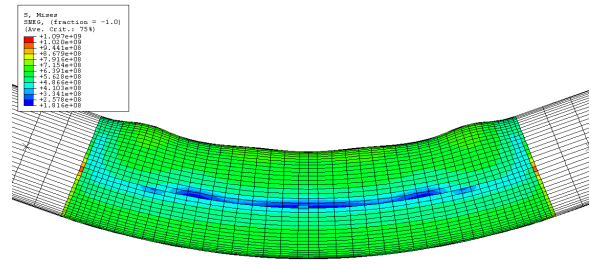
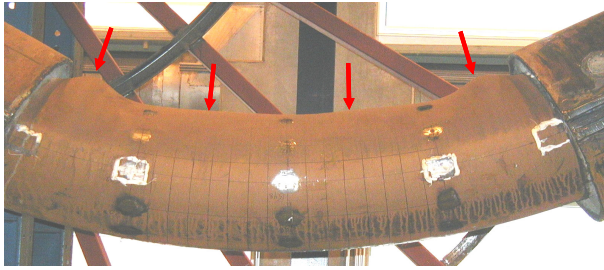
In the early nineties, experimental tests on full-scale pipes in laboratory have been carried out, see for example Mohareb et al. (/31/), Yoosef-Ghodsi et al. (/32/) and Zimmerman et al. (/17/).

Several studies have been performed with standard finite element-based structural computer programs such as ABAQUS, ANSYS, ADINA, etc., see for example Vitali et al. (/33/ and /34/). These studies showed that FE analyses can give reliable results when compared with experimental test results, in particular the shape of the buckling mode and bending moment vs. curvature relations can be reproduced by FE analyses, see Figure 2.

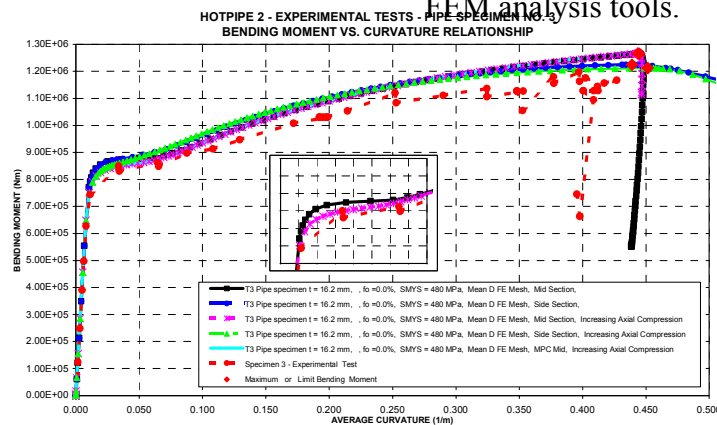
The outcomes of these experimental tests and theoretical studies have been used to calibrate new design equations aiming to calculate the ultimate bending and strain capacity in presence of internal pressure and axial load, see for example the new formula recently implemented in DNV OS-F101 (/11/).

As regards local buckling of pipeline subject to steel axial compression dominated conditions, several studies have been carried out in the last ten years. In particular:

- *Elastic and plastic buckling solutions* using the deformation plasticity theory have been developed; see for example /35/, /36/, /37/, /38/ and /39/. These formulations give the critical values of the compressive stress/strains at the onset of buckling for uniformly compressed pipes in the axial direction. Critical strains/stresses depend on the outer diameter to thickness ratio, inner pressure and stress-strain curve shape, see Figure 3.
- *Experimental tests* have been carried out to better understand the buckling and post-buckling behaviour of pipes subject to compressive loads under monotonic and cyclic loads, see for example /40/, /41/, /42/ and /43/.
- *Standard FEM-based codes* have been validated and extensively used to assess the strength and deformation capacity of pressurised pipes under steel axial compression, see Figure 4.



a) Wrinkling mechanism as evidenced during laboratory testing. b) Wrinkling mechanism as predicted using FEM analysis tools.



c) Bending moment – curvature relationship. Comparison between experimental tests and FEM results.

Figure 2 - Local buckling failure modes – Experimental tests vs. FEM results (/34/).

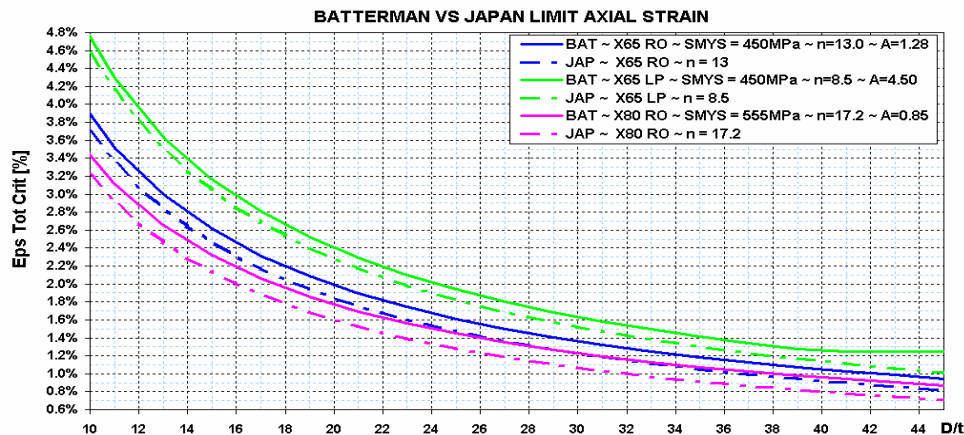


Figure 3 - Limit compressive strain as a function of the outer diameter to thickness ratio for different steel materials according to different formulations (/36/ and /40/).

Experimental tests and FEM analyses carried out evidence that the main parameters affecting deformation capacity of steel pipes are the outer diameter to thickness ratio, inner pressure, pipe geometry imperfections (shape and thickness), shape of the stress-strain curve i.e. with and without the Lüder's plateau and uniform elongation. As an example Figure 5 plots the bending moment - strain relationships for different load combinations (with and without inner pressure) and stress-strain curve shape (with and without Lüder's plateau). In particular:

- The strength and deformation capacity is not affected significantly by the presence of the Lüder's plateau. This is due to the fact that limit moment is reached at level of deformation outside the Lüder's plateau, see Figure 5.

- The bending moment capacity decreases from 0 up to 10% with respect to the Ramberg-Osgood type relationship. The reduction depends on applied loads i.e. inner pressure and steel axial force, but mainly on the extension of the Lüder's plateau. An extension of the Lüder's plateau up to 2% associated with steel axial compression loads gives the highest reduction, see Figure 5.
- The deformation capacity varies slightly with respect to the Ramberg-Osgood type relationship. However, an extension of the Lüder's plateau to 2% strain combined with steel axial compressive loads gives a variation of the limit compressive axial strain of about 10%, see Figure 5.

In the pipeline rules (/11/ and /12/), steel materials of the line pipe are generally specified in terms of requirements on minimum yield stress, minimum ultimate strength and maximum Y/T ratio. In relation to the applicability of strain based criteria, the most relevant parameter is the deformability of the line pipe. This can be qualified during production qualification measuring the uniform elongation (UE) i.e. the strain at ultimate strength. Uniform elongation should be as large as possible. This requirement applies also to weld material and it might be more relevant than minimum toughness requirements needed to sustain high strains in both defected longitudinal and girth welds.

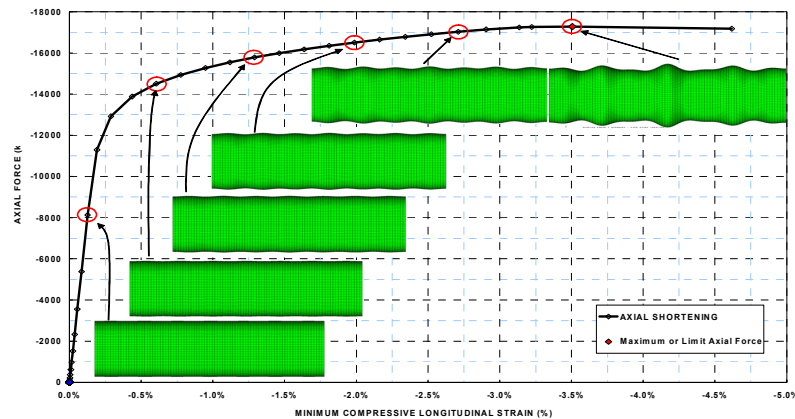
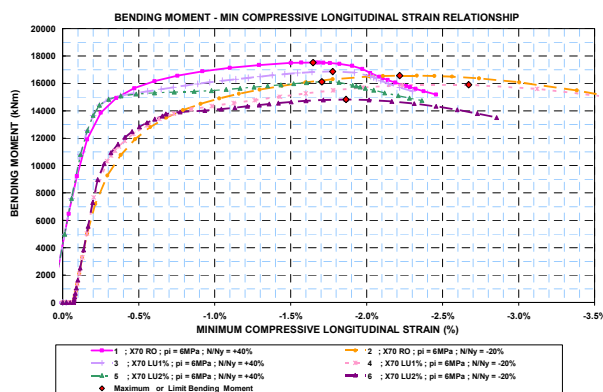
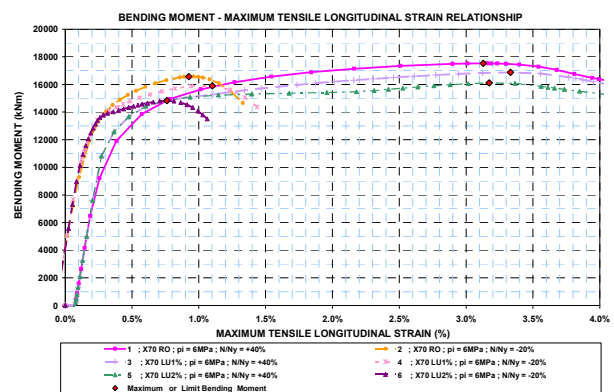


Figure 4 - Local buckling failure modes – Experimental tests vs. FEM results.



a) Bending Moment vs. Minimum (Compressive) Axial (Longitudinal) Strain.



b) Bending Moment vs. Maximum (Tensile) Axial (Longitudinal) Strain.

Figure 5 - Local buckling failure modes – FEM sensitivity analyses on shape of the stress-strain curve (48" pipe; OD/t=48.2, X70 steel material with 1.0%, 2.0% Lüder's plateau extension and Ramberg-Osgood, inner pressure equal to 0 and 6 MPa).

3. TENSILE STRAINS, FRACTURE / PLASTIC COLLAPSE / DUCTILE TEARING AT A DEFECTED GIRTH WELD

Strain-based design criteria means girth welds subject to plastic strains greater than 0.3%, see for example DNV OS-F101 (/11/), practically in the range of 0.5% to 1.0% total strain as anticipated at design stage for a few pipelines in service. Higher strains, in the order of 2.0%, have been considered and experienced in design for installation-reeling for offshore pipelines, but rarely proposed for operation, except endured and temporary acceptance after unexpected developments or incidents. Nonetheless new frontier projects are increasingly demanding in terms of strains the pipeline and girth welds shall safely withstand, e.g. up to 4% in severe seismic and/or arctic environments.

In these circumstances the pipelines are expected to be subject to a load condition that may cause a global response with considerable plastic deformation at certain pipe sections, however predictable as limited because in displacement controlled condition (/11/). The wall thickness and line pipe material are selected to resist such conditions without developing local buckling. In the proximity of/at the girth weld, where global plastic deformation of an adjacent pipe section may develop significant longitudinal internal stresses, an unbounded local deformation or strain localization may occur, e.g. because of soft material in the heat affected zone (HAZ) or presence of a significant circumferential defect, which may lead to the propagation through the thickness or, at worst, rupture due to unstable fracture or ductile tearing.

Strain based ECA guidance for girth welds of offshore pipelines are not of common use (or project purpose developed) or even available, except for DNV OS-F101 as discussed in detail by Braftos (/11/). The proposed approach follows the main lines of BS 7910 (/44/), and the main original contribution towards high strain acceptance is the definition of a new cut-off in the FAD for the plastic collapse failure mode, referred to the relevant material ultimate tensile strength in place of flow stress. So the restriction to plastic collapse failure mode is less severe, and this definitely helps to get allowance for very high strains of tough welds with reasonable defect size e.g. good WMS standard guaranteed by AUT.

The ECA proposed by Braftos (/11/) actually targets strain up to 2.0-3.0% (reeling), which can be qualified from moderate to high strain. Unfortunately the effect of internal pressure is not included, and the approach proposed would be straightforward but it requires further validation. As a comment:

- The strain based ECA is embodied in the most comprehensive strain based design guidance for pipelines, a unique case where there is an explicit link between design formats for installation and operation and material's requirements. These include line pipe from fabrication technology and relevant properties, and welds preparation and NDT.
- Actually the proposed methodology follows the development framework of BS 7910, which remains stress based and for load controlled conditions, possibly applicable in moderate plasticity conditions.
- For very high strains, the ECA approach should be other than the current FAD methodology. Ductile tearing coupled with R-J curve has been recently introduced to open the FAD application to high strains. It would mean to accept a stable propagation of a defect through the thickness (/45/). A new guidance particularly addressed to the pipe reeling has been issued jointly by TWI-DNV-SINTEF. It includes additional requirements for parent pipe and weld material qualification (/46/).

But the use of an old framework with new significant modifications may be confusing or misleading, and competent people are always needed. Referring to the traditional FAD method, there is consensus on that it allows putting together the contribution to failure from poor toughness and from poor strength capacity of weld material. The variables are four:

- The toughness available in the region of the apex of the crack, whether weld material or fusion line or HAZ. This is commonly measured by performing dedicated tests on a limited number of standard specimens.
- The stress-strain curve of the parent pipe and weld material (for the HAZ usually a weighted interpolation is adopted), and relevant parameters as yield and ultimate tensile strength, as well as the deformation at ultimate tensile strength.
- The working point in the FAD plane is defined by calculating the state of stress in the proximity of the defect, as well as the driving force able to open the crack as per MODE I. When load condition is a global deformation the pipeline is subject to, the corresponding stress is calculated for the integer pipe as remote stress, using the suitable plasticity model including load combination and sequence, see Figure 6. The local stress is amplified because of geometric or material intensification, e.g. using a suitable approach as Neuber's. Sometimes and in conditions of real criticality, detailed F.E. models are adopted.
- FAD is a curve in the cartesian plane with in abscissa the ratio between the reference stress from the above calculations and yielding stress, in ordinate the ratio between the applied toughness parameter and the material toughness. The curve provides a boundary between the safe region of working stresses and the unsafe region, where a defect can propagate through thickness in stable or unstable fashion. This curve is empirical and provides a functional relationship between specific strength parameters (of weld material, of parent pipe or of fusion line) at the apex of the crack. In advanced ECA, it can be calculated using FEM analysis and actual stress-strain curves of the pipe.

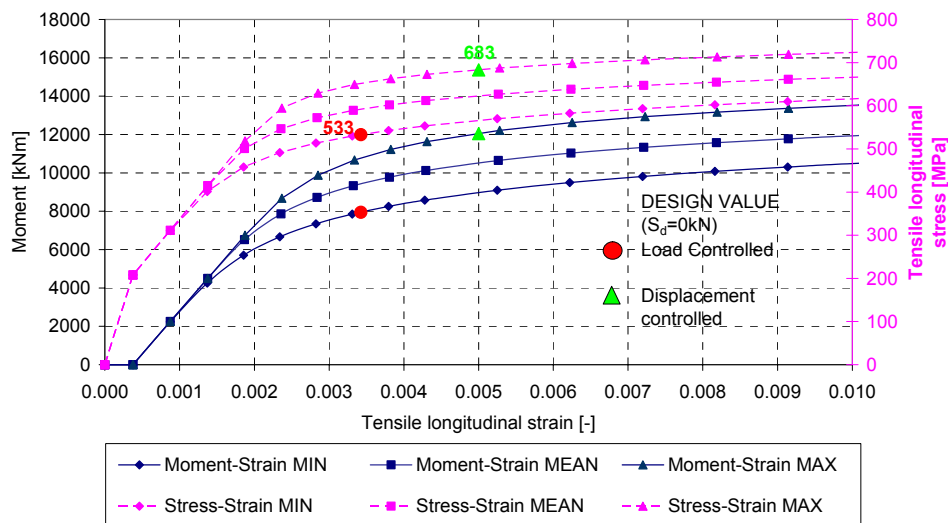


Figure 6 - Moment-strain-stress curves for the minimum, mean and maximum true material behaviour. (Steel axial force equal to internal pressure end effect and internal pressure equal to the design pressure of 18.2MPa).

In a FAD approach to high strain acceptance, in presence of pre-established defect size that cannot be exceeded, the relevant parameters and procedures developed for extending the applicability in the field of plastic strains are as follows:

- Realistic characterization of the toughness for shallow cracks subject to stresses exceeding the yield strength (desk studies on constrain effect on real toughness, development of new tests to define material toughness to be used in FAD as SENT, request for the full R-J resistant curve to allow for the analysis of stable through thickness fracture propagation due to ductile tearing).

- Optimum selection of the weld material strength properties (specified minimum yield, $SMYS_W$, and tensile strength, $SMTS_W$; strain at $SMTS_W$, ϵ_{UW}) to be coupled with parent pipe material strength properties ($SMYS_P$, $SMTS_P$, ϵ_{PW}) suitable to provide the adequate degrees of protection on the weld from any localization of strains in the weld and near weld, HAZ, material (it involves the shape of the stress-strain curve, the chemistry of the parent pipe material in relation to the property to softening of the HAZ etc).
- Detailed calculation models (numerical, analytic) to analyze the state of stress and strains in the proximity of/at the crack for increasing longitudinal (bending and axial load), in presence of internal or external over pressure – biaxial state of stress, and of the relevant parameters of fracture mechanics (crack tip opening displacement, CTOD, or J integral, elastic and plastic).
- Definition of the material dependent FAD, through testing and coupled F.E. modelling to establish a realistic boundary between the region where stresses can develop without causing any crack propagation and the region where crack propagation, possibly stable, may occur (in particular in the field of length references stresses).

A number of R & D have been dedicated on these subjects over the last decade, new ECA approaches proposed, and it is near to come the issue of a new guidance that embodies the findings of such long effects. In particular two international programmes:

- The joint industry research project carried out by SINTEF (Statoil, Hydro, Eni Norge, BP), shortly described in the next sections, addresses to dedicated calculation models for fracture mechanics movement in parallel to experimental qualification tests to establish criteria for plastic collapse and ductile tearing in presence of a biaxial state of stress; with the aim to issue a new guideline for strain based ECA including calibration partial safety factors (/47/, /48/, /49/ and /50/).
- A multi-year project founded by the US Mineral Management Service (MMS) and US Departments of Transportation (DOT), which aims to develop new design and assessment guidelines for pipelines that may experience high strains in service (/51/).

The efforts above mentioned include both desk studies to establish an interpretative analytical model and experimental work to provide the suitable characterization of relevant parameters. In this field it is relevant the huge industrial and research activity carried out by the University of Gent (Denys et al., /52/). The proposed approach is apparently more direct than the one based the FAD, and it is based on simple basic requirements:

- For girth welds characterized by good toughness, it can be asserted that the relevant failure mode that can be activated by increasing longitudinal stresses/strains is the plastic collapse. So that risk of brittle fracture can be removed from ECA, and in any way the findings of recent R&D efforts on constrain provide further support to this early instruction (late eighties, early nineties).
- The material performance at high strains (of the parent pipe, of the HAZ and of the weld) is the main variable that effects the development of the ultimate response of a circumferential crack (the geometry of the weld, whether narrow or wide etc.). From this, a minimum requirement of weld material strength overmatching the parent pipe strength results, so that risk of localization of strains in the proximity of a crack in the weld material including the fusion line is minimize because of sheltering provided by more deformable parent pipe.

These statements are backed by huge experimental activity in laboratory and full scale testing, particularly in development of curved wide plate (CWP) tests that reflect at best (or, infinitely better than other traditional tests, in terms of constrain) the actual behaviour of a crack on the girth weld

of pipes. At the moment, a huge data base of fully documented experimental performance (defect which is limited by the experimental approach) is available, and Denys proposes an empirical (and simple) formula that correlates overmatching, defect size and permissible strains. CWP testing is unique and simplest way to back defect acceptance criteria in the region of very high strains as current projects are considering.

Such huge experience (possibly, a limitation of experimental evidence for long shallow circumferential defects at small plastic strains, typical for offshore pipelines in installation, and due to the mono-axiality of the imposed load condition), coupled with the findings of modern FE Modelling, shows that minimizing risk of localisation of strain at girth welds requires plenty of attention on material specification related issues as:

- for parent pipe material, stress-strain relationship has to be qualified in both transversal (traditional) and longitudinal direction (for strain bend design, where considered strains are usually longitudinal)
- for parent pipe material, chemistry has to be optimized to minimize excessive softening of the HAZ, in relation to the envisaged welding procedures and relevant parameters (heat input, rate etc..)
- for weld material, overmatching properties have to be referred to line pipe specification as above and must be continuously tuned onto measured projects from early line pipe production;
- of strength and toughness variability from batch-to batch line pipe, from weld materials and electrode batches, from welding procedure combination, from around circumference weld properties shall be suitably qualified by performing a dedicated test campaign on the material as welded.

Nonetheless, best engineering practices coupled with full scale pipe bend or curved wide plate tests available at the moment are not enough in cases where pipelines may experience high applied strains in operation. Full scale validation pipe bend test including internal pressure are recommended, particularly addressed on to the development of local strains in pipeline girth welds and HAZ regions or for the purpose, coupling with a numerical laboratory as discussed in /53/ is needed to minimize the minutes of test and minimize the information that can be got.

ECA analyses have been performed to assess defect sizes according the following advanced approaches based on BS7910. Calculated critical defect height versus length is given in Figure 7. The first four lines labelled a CTOD refer to the ECA level 2B traditional methodology while the black curves refer to the level 3B advanced methodology.

In the level 3B the critical defect sizes are calculated according to the tangency criterion between the FAD and the applied load effect curve. The continuous black line gives the critical defect height versus its length while the dotted black line gives the calculated defect crack height growth (Δa) for given initial defect length and height.

For design applications where applied loads may cause strains up to 2.0-3.0% (earthquake driven faults movements, ice gauging in arctic areas, etc.) defect allowance shall be limited to typical workmanship (3 x 25mm). The possible ductile tearing i.e. defect crack growth must be assessed under increasing applied strains so to adopt a rational safety factor against the maximum strain at the unstable defect fracture. This can be done using advanced level 3B procedures (Figure 8).

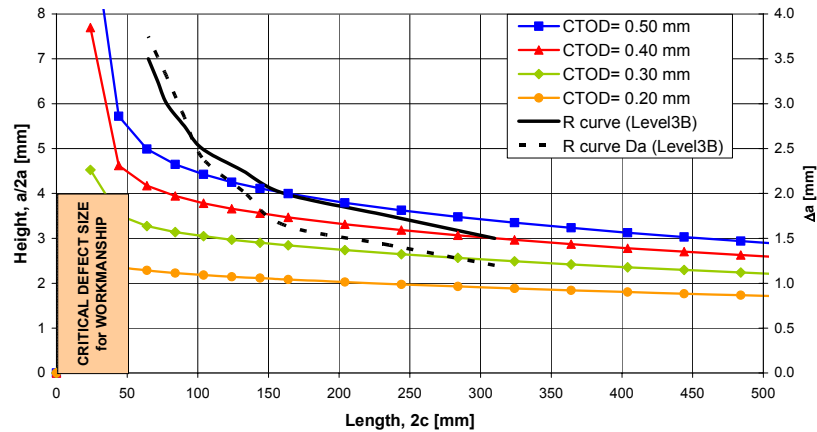


Figure 7 - Traditional and advanced ductile tearing ECA results against WMS results.

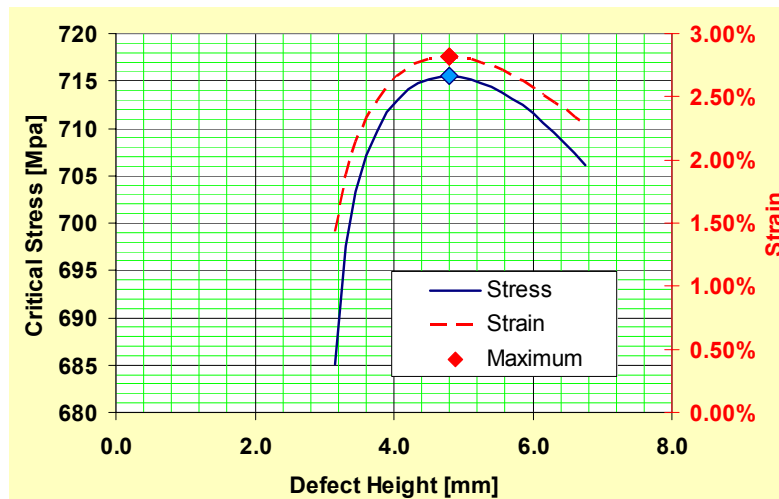


Figure 8 - Strain based ECA analysis results. Load instability curve.

CONCLUSIONS

The increase of the world gas demand and supply will favour the entry of new producing and consuming countries into the gas market, with a consequent need for new long distance gas transport systems (the Middle East, Central Asia, China and the Far East, the Indian Subcontinent, etc.).

Land pipelines are a real competitive technological option involving design codes for rational (safety target) sizing, high grade steels, thick wall line pipes, heavy equipment for handling & construction, high performance welding & NDT technology, efficient machinery for operation, Inspection-Maintenance-Repair (IMR) technology, etc.

In the last decade project circumstances required the adoption of strain based criteria and International Design Guidelines did not always cover areas of potential application. At present, efforts have been dedicated to rationalising the application of strain based criteria e.g. using limit state and reliability methods to calibrate partial safety factors. The adoption of strain based criteria requires the use of advanced engineering tools and expertise in order to anticipate complex non-linear response to applied loads.

Experience made on difficult projects (mountains, slides and hydro-geo-seismic hazards on land, deepwaters and bottom roughness offshore) shows that advanced multi-disciplinary engineering,

supported by information and communication technology, is crucial to optimise solution in hostile environment.

Cost savings related to the extended utilisation of pipe strength capacity should not overrule basic principles of structural mechanics and pipeline integrity requirements.

REFERENCES

- /1/ D. Brkic (2005): "The International Scenario for Gas production and large Transmission Lines"; 1st International Conference *Super High Strength Steels*, Rome, Italy, 2-4 November, 2005.
- /2/ EFI Conference (2000): "Gas-to-Market-Options"; San Francisco-Ca, Oct. 2000.
- /3/ N. Sanderson, B.K. Ohm and M. Jacobs (1999): "Study of X 100 Line Pipe Costs Points to Potential Savings"; *Oil & Gas Journal*, March 15.
- /4/ Bruschi R., Spinazze' M., Tomassini D., Cuscuna' S. and Venzi S. (1995): "Failure Modes for Pipelines in Landslide Areas"; the 14th Int. Conf. on Offshore Mechanics and Arctic Engineering, Copenhagen.
- /5/ R. Bruschi, M. Spinazzè, D. Tommassini, S. Cuscunà and S. Venzi (1995): "Failure Modes for Pipelines in Landslide Areas"; *Proceedings of the 14th International Conference on Offshore Mechanics and Arctic Engineering*, Vol. V, Pipeline Technology, Copenhagen, Denmark.
- /6/ T. Sotberg, R. Bruschi and K.J. Mørk (1996): "The Superb Project: A New Safety Philosophy for Submarine Pipeline Design"; *Proceedings of the 15th International Conference on Offshore Mechanics and Arctic Engineering*, Vol. V, Pipeline Technology, Florence, Italy.
- /7/ Zimmerman (1997): "Pipeline Limit State Design Developments in North America"; *Proceedings of the IBC Conference on Risk Based & Limit State Design & Operation of Pipelines*, Aberdeen, Scotland.
- /8/ T. Sotberg and R. Bruschi (1992): "Future Pipeline Design Philosophy – Framework"; *International Conference on Offshore Mechanics and Arctic Engineering*, ASME – OMAE, Calgary.
- /9/ G. Jiao, T. Sotberg and R. Bruschi (1992): "Probabilistic Assessment of the Wall Thickness Requirement for Pressure Containment of Offshore Pipelines"; *Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering*, Vol. V-A, Pipeline Technology, Calgary, Canada.
- /10/ G. Jiao, T. Sotberg, R. Bruschi, R. Verley and K.J. Mork (1996): "The Superb Project: Wall Thickness Design Guideline for Pressure Containment of Offshore Pipelines"; *Proceedings of the 15th International Conference on Offshore Mechanics and Arctic Engineering*, Vol. V., Pipeline Technology, Florence, Italy.
- /11/ DNV Rules for Submarine Pipeline Systems (1996), and Offshore Standard OS-F101 (2000): "Submarine Pipeline Systems", Det Norske Veritas, Høvik, Norway.
- /12/ ISO 13623 (2002): "Petroleum and Natural Gas Industries – Pipeline Transportation", January 2002.
- /13/ ISO/DIS 16708 (2005): "Petroleum and Natural Gas Industries – Pipeline Transportation System – Reliability Based Limit Static Methods".
- /14/ Stewart G. (1994): "An Analytical Model to Predict the Burst Capacity of Pipelines"; *Proc. of the 14th Int. Conf. on Offshore Mechanics and Arctic Engineering*.
- /15/ Gresnigt A.M., Van Foeken R.J. and Chen S.L. (1996): "Effect of Local Buckling on Burst Pressure"; *Proc. of the 6th - Int. Offshore and Polar Engineering Conf.*, Los Angeles CA.

- /16/ Bruschi R., Monti P., Bolzoni G. and Tagliaferri R. (1995): "Finite Element Method as Numerical Laboratory for Analysing Pipeline Response Under Internal Pressure, Axial Load, Bending Moment", the 14th Int. Conf. of Offshore Mechanics and Arctic Engineering, Copenhagen.
- /17/ Zimmerman T.J.E., Stephens M.J., De Geer D.D. and Chen Q. (1995): "Compressive Strain Limits for Buried Pipelines"; Proc. of the 14th International Conf. on Offshore Mechanics and Arctic Engineering, Copenhagen.
- /18/ Willoughby A.A. (1982): "A Survey of Plastic Collapse Solutions Used In Failure Assessment"; Welding Institute Report 191/1982.
- /19/ Wilkowski G.M. and Eiber R.J.; "Review of Fracture Mechanics Approaches To Defining Critical Size Girth Weld Discontinuities"; Welding Research Council Bulletin 239, pp.-25.
- /20/ Denys R. and Glover A.G. (1993): "Fracture Assessment of Overmatched and Undermatched Weld Metal Yield Strength"; PRC/EPRG Biennial Joint Technical Meeting on Linepipe Research, Houston, May.
- /21/ Bruschi R., Curti G., Dumitrescu A. and Vitali L. (1994): "Strength Criteria for Hot Pipelines Susceptible to Euler-bar Buckling"; the 3rd Int. Offshore Mechanics and Polar Eng. Conf., Osaka.
- /22/ Gresnigt A.M. (1986): "Plastic Design of Buried Steel Pipelines in Settlement Areas"; HERON, The Netherlands.
- /23/ Gresnigt A.M., Dijkstra O.D. and Van Rongen H.J.M. (1994): "Design of Pipelines in High Strength Steel"; Proc. of the 4th Int. Offshore and Polar Engineering Conf., Osaka.
- /24/ V. Pistone, R. Legori and D. Ercolani (2000): "High Pressure Long Distance Pipelines: New Technologies for Natural Gas Transportation; 21st WGC, Nice -F, June.
- /25/ Boyle J.T.: "Plastic Design Concepts"; in Pressure Vessel Design Concepts and Principles, ed. by J. Spence and A.S. Tooth, E & FN SPOW, 1994.
- /26/ Xia Z. and Ellyin F.: "Biaxial Ratcheting Under Strain or Stress-Controlled Axial Cycling with Constant Hoop Stress"; Trans of the ASME, J. of Applied Mechanics, Vol. 61, June 1994.
- /27/ Tomkins B. (1992): "High Strain Fatigue"; SIRIUS, M2001, Metal Fatigue.
- /28/ Bouwkamp J.G. and Stephen R.M. (1973): "Large Diameter Pipe under Combined Loading", Journal of the Transportation Engineering, Vol. 99, No. TE3, August 1973, pp. 521-536.
- /29/ Sherman D.R. (1976): "Tests of Circular Steel Tubes in Bending", Journal of the Structural Division, Vol. 102, No. ST11, November 1976, pp. 2181-2195.
- /30/ Gresnigt A. M. (1986): "Plastic Design of Buried Steel Pipelines in Settlement Areas", HERON, Vol. 31, No. 4, edited by Stevin-Laboratory and TNO-Institute for Building Materials and Structures.
- /31/ Mohareb M. et al. (1994): "Deformational Behaviour of Line Pipe", Structural Engineering Report No. 202, Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G7.
- /32/ Yoosef-Ghodsi N. et al. (1994): "Behaviour of Girth-Welded Line Pipe", Structural Engineering Report No. 203, Department Of Civil Engineering, University Of Alberta, Edmonton, Alberta, Canada T6G 2G7.
- /33/ Vitali L. et al. (1999): "HOTPIPE Project: Capacity of Pipes Subject to Internal Pressure, Axial Force and Bending Moment", Proc. 9th Int. Offshore and Polar Engineering Conference, 1999.
- /34/ Vitali L. et al. (2005): "HOTPIPE II PROJECT- Experimental Test and FE Analyses", OMAE Paper No. 67526, Proc. 24th OMAE Conference, Halkidiki, Greece, 12-17 June 2005.
- /35/ Timoshenko, S. P. and J. M. Gere (1963): "Theory of Elastic Stability", Second Edition, McGraw Hill Book Company.

- /36/ Batterman S. (1964): "Plastic Buckling of Axially Compressed Cylindrical Shells", AIAA Journal, Vol. 3, No. 2, pp. 316-325.
- /37/ Batterman, S.C. (1967): "Tangent Modulus Theory for Cylindrical Shells: Buckling under increasing Load", Int. J. Solids Struct., Vol. 3, p. 501.
- /38/ Batterman, S.C. (1969): "Plastic Stability of Spherical Shells", J. Engng Mech. ASCE, Vol. EM2, pp. 433-446.
- /39/ Kim H. O. (1992): Plastic Buckling of Pipes under Bending and Internal Pressure", Proceedings of the Second International Conference on Offshore Mechanics and Arctic Engineering, Houston, Texas.
- /40/ N. Suzuki and M. Toyoda (2002): "Seismic Loadings on Buried Pipelines and Deformability of High Strength Line Pipes", Proceedings of the Pipe Dreamer's Conference, Yokohama, Japan.
- /41/ Sreekanta D. et al. (2001): "Wrinkle Behaviour under Cyclic Strain Reversal in NPS12 Pipe", Proc. of 20th OMAE Conference, June 3 8, 2001, Rio de Janeiro, Brazil.
- /42/ Sreekanta D. et al. (2000): "Laboratory Study of Local Buckling, Wrinkle development, and Strains for NPS12 Linepipe", Proc. of 2000 International Pipeline Conference, ASME 2000, Vol. 2, pp. 909 915.
- /43/ Chitoshi M. et al. (2000): "Deformation and Fracture Properties of Steel Pipe Bend with Internal Pressure subjected to In-plane Bending", Proceedings of the 12th WCEE.
- /44/ BS 7910: "Guide on methods for assessing the acceptability of flaws in metallic structures", 1999.
- /45/ Bratfos H.A (2003): "Use of Strain Based ECA for the assessment of flaws in pipelines girth welds subjected to plastic deformations Defect Size"; Pipe Conference of High- C. Line Pipes H. Environment, Yokohama.
- /46/ Miller A.G. (1998): "Review of Limit Codes of Structures Containing Defects", International Journal of Pressure Vessels and Piping, Vol. 32.
- /47/ Østby E. (2005): "Fracture Control – New Strain-Based Fracture Mechanics Equations Including the Effects of Biaxial Loading, Mismatch and Misalignment", OMAE, Greece.
- /48/ Thaulow C. Skallerud B., Jayadevan K. R. and Berg E. (2005): "Fracture Control – Advantages of Using Direct Calculations in Fracture Assessments of Pipelines", OMAE, Greece.
- /49/ Nyhus B., Østby E., Knagenhjelm H. O., Black S. and Røstadsand P. (2005); "Fracture Control – Offshore Pipelines Experimental Studies on the Effect of Crack Depth and Asymmetric Geometries on the Ductile Tearing Resistance", OMAE, Greece.
- /50/ Sandvik A., Østby E., Naess A. And Sigurdsson G. (2005): "Fracture Control – Probabilistic Fracture Assessment of Circumferentially Surface Cracked Ductile Pipelines Using Simplified Equations", OMAE, Greece.
- /51/ Mohr B., Gordon R., Smith R. (2005): "Strain based design guidelines for pipelines"; Pipeline Technology Conference, Vol 1, Ostenda.
- /52/ Denys R., De Waale W., Lefevre A., De Baets P. (2004): "A Engineering Approach to the production of the Folerable for strain-bend design"; Pipeline Technology Conference, Vol 1.
- /53/ Bruschi R., Bartolini L., M., Spinazzè M., Torselletti E., Vitali L. (2005): "A Numerical Lab to Predict the Strength Capacity of Offshore Pipelines"; OMAE, Greece.