DESIGN CRITERIA VS. LINE PIPE REQUIREMENTS FOR OFFSHORE PIPELINES

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ABSTRACT

The offshore pipeline industry is planning new gas trunklines at water depth ever reached before (up to 3500 m). In such conditions, external hydrostatic pressure becomes the dominating loading condition for the pipeline design. Pipe geometric imperfections as the cross section ovality, combined load effects as axial and bending loads superimposed to the external pressure, material properties as compressive yield strength in the circumferential direction and across the wall thickness etc., significantly interfere in the definition of the demanding, in such projects, minimum wall thickness requirements.
The scope of this paper is to introduce fabrication and material issues, as well as geometric tolerance, in relation to ultra deep water pipeline design.

KEYWORDS

Offshore, deep water, pipeline, design criteria, collapse, local buckling, material requirements.

INTRODUCTION

A first requirement for the definition of minimum wall thickness of a pipeline is the containment of internal pressure. Actually, for ultra-deep water conditions, failure modes related to the external pressure are more relevant than bursting: design checks against cross section collapse and propagation buckling under external pressure alone, ovalisation buckling under combined bending, axial and external pressure loads, are the relevant ones.

Further, a considerable risk for the pipeline during installation is buckling propagation, initiated when and where a severe combination of bending and external pressure occurs. Once started at a certain depth, the buckle can run along the pipeline, reaching the depth at which external pressure is no longer able to maintain propagation.

Nevertheless, submarine pipelines to be installed in ultra deep waters (relatively large diameters and low D/t ratio), are more critical than pipelines traditionally designed and installed up to now. This is due to the increased water depth and relevant implications on minimum wall thickness requirements from current limits of pipe mill fabrication technology.

UO/UOE process (U for U-ing cold forming from the plate, O for O-ing cold forming from the U shape, E for expansion to meet the geometric tolerances), affects the actual pipe capacity to sustain the external pressure load, because of the reduction of the compressive yield strength in the pipeline hoop direction, caused by the so-called Bauschinger effect as consequence of cold bending and expansion. For very deep-water applications the reduction of the compressive yield strength is an important factor for wall thickness sizing. Design rules and guidelines take the Bauschinger effect into account, more or less explicitly.

Buckling phenomena have been the subject of a great deal of research from the 1980's up to now [1]. In the first half of the 1990s, the offshore pipeline industry including regulatory authorities in UK and Norway, pushed in the direction of revising design guidelines to be applied for offshore pipeline oil and gas transportation systems. Such review was motivated by the fact that design guidelines in force at that time did not account for modern fabrication technology. A JIP project called SUPERB [5], started with the aim to develop a SUbmarine PipelinE Reliability Based design guideline, including a comprehensive set-up of recommendations and criteria for different load conditions. The guideline included the so-called limit state design approach, with partial safety factors defined using structural reliability methods, in order to fulfil pre-defined safety targets.

In this paper focus is given to the limit state equation regarding the pipe strength capacity to sustain external pressure, in combination with bending and axial loads. Current international codes, as DNV-OS-F101 [2], API RP1111 [3] and API RP2RD [4], all recently issued, cover D/t relevant for ultra-deep water applications.

The choice of a design criterion/equation is to be linked not only to its capacity to fit experimental data but also to the overall safety objective pursued by the code. This is related to the specified mechanical characteristic of the steel material (yield strength and ultimate strength in the hoop and longitudinal directions, etc.) and to the geometrical characteristics of the line pipe (wall thickness tolerances, cross section ovality, etc.). From the review [18] of the most recently issued Reliability Based Limit State (RBLS) design codes, applicable for offshore steel pipelines (API, GL, CSA etc..), though they are comparable from the view point of the design equations, it is concluded that DNV OS-F101 2000 [2] is the most appropriate design guideline for deep offshore pipeline projects mainly because of the link between the design safety factors and the line pipe requirements.

The FE analyses of the production process show that the actual pipe capacity to sustain external pressure load may be optimised in terms of obtained initial ovality versus compressive yield strength in the hoop direction.

1. DESIGN CRITERIA

DNV OS-F101 [2] is considered the most suited LRFD design code for deep water pipeline applications, for the following reasons:

- There is a clear correlation between the design criteria and the relevant partial safety factors with the safety objective (defined through the se called Safety Class concept).
- The developed design criteria have been specifically addressed for submarine pipeline applications, using reliability methods with the aim to target predefined safety objectives expressed in term of acceptable failure probability.
- It provides a more complete set of loading conditions, both in terms of what loads are combined as well as safety factors for all cases. This is not the case for the other codes analysed (as API). Where the codes can be compared, they give similar results.

DNV OS-F101 [2] design code recommends how to appropriately use specified vs. actual material mechanical and pipe geometrical properties, as input for sizing and design checks. In fact, in deep waters there are significant implications of fabrication technology on the relevant design checks, considering the relatively high wall thickness and high grade material line pipe.

As a result, for calculating the collapse resistance of the pipeline, the following equation is recommended [2]:

$$\left(\frac{p_{C,d}}{p_{el,d}} - 1\right)\left(\left(\frac{p_{C,d}}{p_{y,d}}\right)^2 - 1\right) = f_{0,d}\,\frac{p_{C,d}}{p_{y,d}}\frac{D_o}{t} \quad (1)$$

where D_0 is the nominal outer steel diameter, t is the nominal steel wall thickness and $f_{0,d}$ is the pipe initial ovality (not less than 0.5%):

$$f_{0,d} = \frac{(D_{max} - D_{min})}{D_0} \quad (2)$$

D_{max} and D_{min} are respectively the maximum and minimum outer diameter. $p_{el,d}$ is the design elastic collapse pressure given by:

$$p_{el,d} = \frac{2E}{1-\nu^2}\left(\frac{t}{D_o}\right)^3 \quad (3)$$

$p_{y,d}$ is the design yield pressure given by:

$$p_{y,d} = 2 \cdot SMYS \cdot \alpha_{fab} \cdot \alpha_U \frac{t}{D_o} \quad (4)$$

E is the Young modulus of elasticity, ν is the Poisson's ratio and SMYS is the specified minimum yield strength. The factor α_{fab} considers the effect of the fabrication process, which introduces different strength in tension and compression along the circumferential direction of the pipeline, due to cold deformations (Bauschinger effect).
The factor α_U considers the different material qualification levels allowed in [2] i.e. the possibility to apply or not the supplementary requirements for high utilisation (section 6 clause D500). **These supplementary requirements imply (and specify) that the average yield strength is at least two standard deviations above SMYS**.
The design equation for the collapse limit state due to external pressure alone is given by [2]:

$$p_e \leq \frac{P_{C,d}}{1.1 \cdot \gamma_m \cdot \gamma_{SC}} \quad (5)$$

Two design equations for ovalisation buckling/collapse failure under combined action of bending, external pressure and axial loads, are considered [2]:

- in term of compressive longitudinal strain (also referred as Displacement Controlled Condition),
- in term of bending moment (also referred as Load Controlled Condition).

Discussion on their applicability can be found in [2, 6, 7].

2. PIPE STRUCTURAL INTEGRITY VS. PIPE CROSS SECTION OVALITY

The ovality of a pipe cross section is a parameter that affects different failure modes and it is included in the DNV OS-F101 relevant limit state equations. In particular, the pipe ovality affects the following failure modes:

- cross section collapse under external pressure load. This is an ultimate failure mode (ULS) according to [2];
- cross section local buckling under the combined action of bending and external pressure loads. This is an ultimate failure mode (ULS) according to [2];

- maximum cross section reduction for internal inspection i.e. the passage of the inspection pig (or the pigs used during commissioning of the pipeline) should be not impaired by a reduced pipe cross section, where the pig can be stuck. This is generally considered a serviceability failure mode (SLS) according to [2].

The pipe cross section ovality, $f_{0,d}$, is usually described as result of modification of a perfect circle into an ellipse and it is defined by equation (2). In the following each of the above limit states are analysed with respect to the ovality. In addition, in accordance with standards and guidelines [2], the effect of point loads on the pipeline capacity to resist collapse due to external pressure is analysed.

Collapse Under External Pressure

DNV OS-F101 design equations for the collapse pressure (equations (1) to (5)) are used to define the required steel wall thickness assuming the given design values for the input variable according to the safety requirements set in [2].
Figure 1 shows the water depth at which collapse occurs for a given initial ovality $f_{0,d}$. This figure identifies the allowable condition according to the safety requirements of [2] as well as the water depth at which collapse occurs (safety factors 1.1 and both γ_{SC} and γ_m in equation (5) are set to 1.0). It is evident that the structural integrity of the pipe against collapse is ensured under initial/residual ovality of the pipe cross section up to 2.5% at the maximum water depth of 2150m (P_e/P_C=0.69). A residual ovality of 3% or higher is allowed up to 1990 m water depth. It is evident that collapse will not occur under initial/residual ovality of the pipe cross section up to 5% even at the maximum water depth of 2150m.

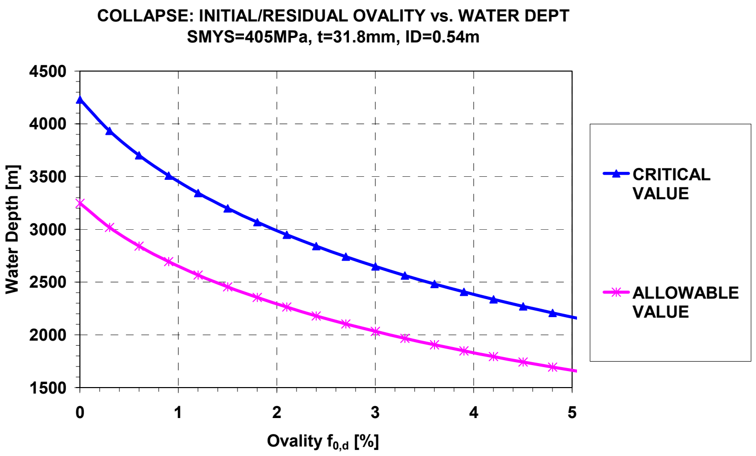

Figure 1 Water depth for given initial/residual pipe cross section ovality for the collapse limit state according to DNV OS-F101 safety requirements for structural integrity.

Figure 1 considers only the initial/residual ovality (fabrication ovality plus any residual effect from construction). This is to be distinguished from the applied ovality under given initial pipe geometry (residual ovality) and external pressure load.

For evaluating the applied ovality analytical formulas (for instance as the one reported in section 12 of [2]) are not general and specific models have to be used. In this paper a FE model developed in the ABAQUS framework [16] has been used. Figure 2 shows the applied pipe cross section ovality as a function of the applied external pressure for different values of the initial/residual ovality. It is evident that at collapse, i.e. the maximum value of the external pressure for each curve, the applied ovality is sensibly higher than the initial one.

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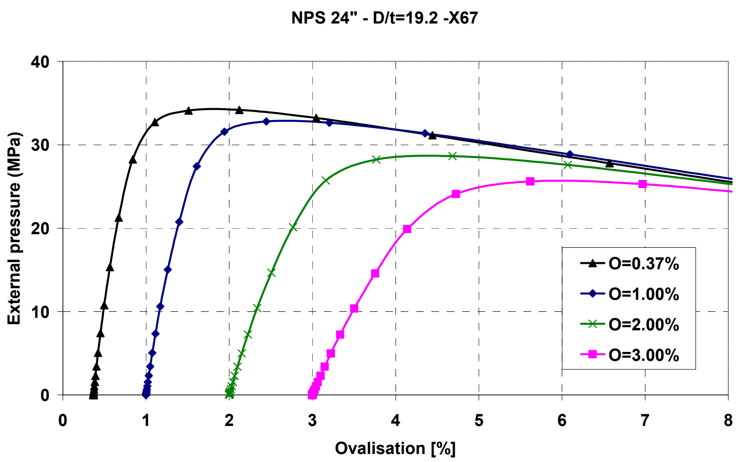

Figure 2 ABAQUS FE analyses: Applied ovality as a function of the external pressure load for various initial ovality.

In particular, for an initial ovality of 1% the applied one at collapse is ca 2.8% while for an initial ovality of 3% the applied one at collapse is ca 6%. It is clear that the applied maximum ovality (to be limited for internal inspection reasons) depends also on the residual ovality. For submarine pipelines this depends on fabrication tolerances (maximum 1%) and/or on eventual damage from accidental events (as a local dent).
From the above considerations the following can be concluded as regards the failure mode of collapse under external pressure load:

- The calculation of the applied allowable ovality for submarine pipelines is not a straightforward analysis and generalisations are difficult.
- To fulfil a safety requirement as stated in [2] the residual and the measured applied ovality must be linked to the applied/allowable pressure load.
- For deep water applications applied ovalities of 3% accepted by international design standards are at the limit of acceptance criteria for structural integrity.

Local buckling Under Combined External Pressure, Axial and Bending Loads

Figure 3 shows the allowable bending moment using DNV OS-F101 equations as a function of the initial/residual pipe cross section ovality for various water depths.

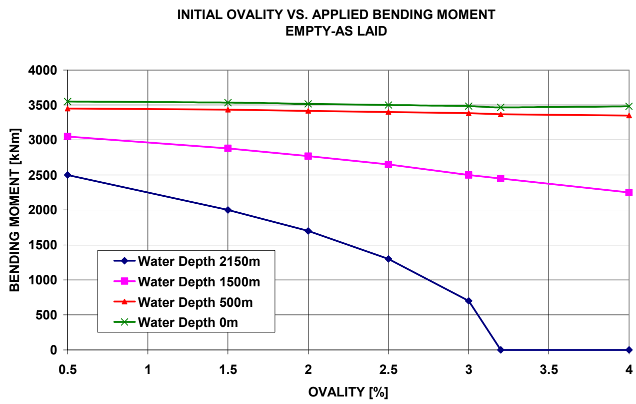

Figure 3 Allowable bending moment for given initial/residual pipe cross section ovality and for different water depths for the local buckling limit state according to DNV 'OS-F101 [2].

It is clear that in the eventuality of a residual dent and/or of increased residual/initial pipe ovality the allowable bending moment has to be reduced in accordance with OS-F101 [2] acceptance criteria for the structural integrity of the pipeline.
In order to understand the variability of the applied ovality under applied external pressure and bending loads a study using the FE model described in the previous section has been made. Figure 4 show the applied ovality as a function of the applied bending moment for different initial/residual pipe cross section ovalities at the maximum allowed water depth. Figure 4 shows that pipe ovality slightly affects the maximum bending capacity and that the applied ovality slightly increases up to the elastic field limit (i.e. within the allowable bending moment in accordance with DNV OS-F101). The decrease in the bending moment at collapse is mainly due to its effect on the pipe ovality which increases so reducing the external pressure load at collapse (see Figure 2).

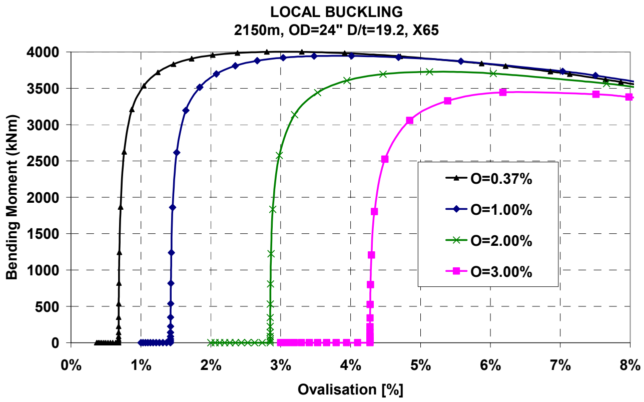

Figure 4 ABAQUS FE analyses. Applied ovality as a function of the bending moment and with external pressure load at 2150 m water depth for various initial ovalities.

Effect of Local Concentrated Loads in Pipe Collapse

Submarine pipelines in deep waters have a thick wall thickness that can sustain relatively high concentrated load normal to the pipe wall. The combined effect of the external pressure (different water depths) and the dent depth caused by a local load normal to the pipe wall has been analysed using the FE model described in [17]. The results of the FE simplified model are shown in Figure 5 where the equivalent ovality is plotted against the local force. The results show that the external pressure at maximum water depth gives circa a 50% reduction of the pipe cross section capacity against a distributed load scenario. The actual value depends also on the actual contact area where the local force is applied. Therefore, it is difficult to evaluate the criticality of the measured ovality against local loads without knowing the actual load condition (geometry, boundaries, etc..).

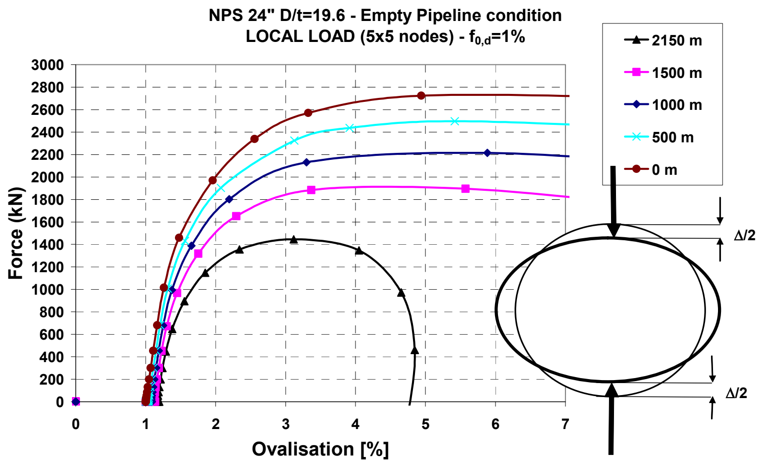

Figure 5 ABAQUS FE analyses. Applied ovality as a function of the applied local load at different water depths.

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Use of Limit State Approach to Qualify Applied/Measured Ovality During Inspection

During commissioning operations, after water filling and system pressure test and before de-watering and drying of the pipeline, a pig is passed inside to evaluate the pipe section ovality along the entire route. This check will put into evidence any problem that may have occurred during construction and commissioning that could leave on the pipeline a residual dent/ovality (impacts, excessive bending, gross human error, etc.). This operation also ensures that the applied ovality will not cause any blockage of subsequent pigs inside the pipeline.

On the basis of the checks made against the relevant failure modes (see above analysis results) it can be said that the maximum acceptable applied ovality during pigging should be limited to 3%. This value is within the allowable value for collapse at the maximum water depth and is in accordance with clause C800 Section 5 of DNV OS-F101 [2].
Nevertheless, the following is relevant:

- bending loads up to the allowable design values have negligible effects on the applied ovality,
- the allowable bending moment in as-laid/empty condition will be reduced if ovality in excess of ca 1.0% (initial from fabrication plus the one caused by the applied bending plus the measurement tolerances) is measured,
- allowable desing bending loads are normally acceptable for measured cross section ovality up to 3% (this limit should be verified on a project basis for very deep water applications).

It is then recommended that, in accordance with clause C800 Section 5 of DNV OS-F101 [2] and in the eventuality of ovality in excess of 3%, specific detailed verification should be made in order to verify the structural integrity of the pipeline under the applied loads in the specific pipe section.

3. PIPELINE MECHANICAL CHARACTERISTICS VS. PRODUCTION TECHNOLOGY

Modern fabrication technology has gained a lot of experience in producing large diameter pipes with relatively high steel thickness (D/t as low as 19) using API 5L X65 and, some times, X70 steel grades. Thermomechanical Controlled rolling process (TMCP) coupled with accelerated cooling are generally used to produce the steel plates for pipe manufacture. These pipes are produced in the form of longitudinal submerged arc weld (SAW) coupled with UOE technique.
The UOE process implies that the pipe thickness undergoes high tensile strain values in the transversal direction. This gives rise to a reduction of the compressive yield strength in the transversal direction, more or less pronounced through the steel wall, due to the so called Bauschinger effect. The reduction of the steel compressive yield strength might reach values of 30% of the one of the plate [9, 10, 13, 14, 15]. The compressive yield strength is one of the main parameters in the definition of the pipe cross-section capacity to sustain external pressure load. A number of studies have been carried out with the objective to evaluate the effect of the cold forming of UOE pipes on the collapse capacity. For this reason a Finite Element Model has been developed (and validated through fully documented experimental findings), in the framework of the multipurpose FE program ABAQUS [16], to simulate the UOE/UO/UOC forming process. Figure 6 shows the results of FE analyses, where both expansion (UOE) and compression (UOC) are simulated after the U-ing and O-ing phases.

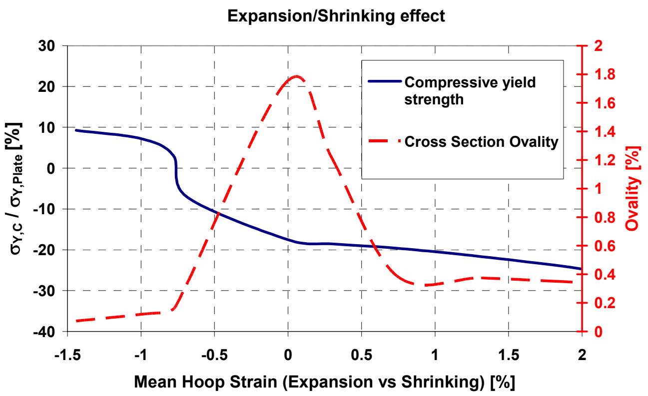

Figure 6 Effect of the UOE/UOC cold forming process on the compressive yield strength in the circumferential direction and on the pipe cross section ovality from fabrication.

The x-axis reports the average hoop strain applied on the pipe during the expansion/compression process, while the y-axis reports the ratio between the compressive yield stress at 0.5% applied strain on the pipe circumferential direction and on the original plate. The former is taken from the FE simulation of the uniaxial compressive test on a specimen that has been subject to the load history relevant for the UOE/UO/UOC forming process (worst location i.e. fibre on the external diameter). It is concluded that the expansion process can produce a reduction in the compressive yield strength up to 25%.
On the other hand the compression process increases the compressive yield strength up to 10% of the original plate value. However, it is not recommend taking benefits of UOC. This is because the heat treatment due to the anticorrosion coating application would likely reduce this benefit.

To account for this depletion of the mechanical resistance, design criteria consider a reduction of the design value for the yield strength (the specified minimum value SMYS): DNV OS-F101 recommends a 15% reduction of the SMYS when collapse is of concern. Nevertheless, project experience showed that a reduction of the compressive yield strength in the hoop direction of the pipe equal to 10% of the SMYS, is achievable for an X65 API grade.
To understand the implications of a 10/15% reduction in the SMYS applied in the design equation (1), the following is relevant:

- Traditionally SMYS is verified during MPQT (Manufacturing Procedures Qualification) tests by performing uniaxial tensile tests in the hoop direction with a flattened specimens (i.e. with a specimen that undergoes a load cycle with the same values, but opposite direction, as the one applied during U-O forming phases). This procedure reduces the tensile yield strength of the specimen with respect to the one of the pipe.
- During the production process (cold forming), the actual tensile yield strength in the hoop direction increases with respect to the one of the plate, due to strain hardening (measured values on the pipe using round bar specimens are 5-10% higher than measured values on the plate).
- In case a submarine pipeline is sized to sustain external pressure load, the evaluation of the actual compressive yield strength in the circumferential direction of the pipe through uniaxial compressive tests with round bar specimen (i.e. not flattened) is recommended.

Both collapse and ovalisation buckling failures are governed by:

- Geometrical imperfections as the cross section ovality and steel wall thickness variations,
- Residual stress distribution across the pipe steel wall due to the U-O-E process.

Figure 6 shows the effect of cold expansion or compression (also called shrinking) on the initial pipe cross section ovality of the produced pipe (dashed line). From the FE simulations hoop compression/shrinking results more effective than expansion in reducing the cross section ovality. In addition, expansion at values of hoop strain over 1% does not reduce significantly the initial ovality. The conclusion of these analyses is that the actual pipe capacity to sustain external pressure load, can be optimised in terms of obtained initial ovality versus compressive yield strength in the hoop direction.

To show the effect of a reduced yield strength in the compressive hoop direction with respect to the longitudinal direction and of the water depth on the capacity of the pipe cross section against ovalisation buckling (i.e. external pressure combined with bending loads), 3D FE analyses have been performed (see [17] for details on the model). Figure 7 shows the results of the FE analyses introducing a material anisotropy through the Hill's theory (implemented in ABAQUS, [16]).

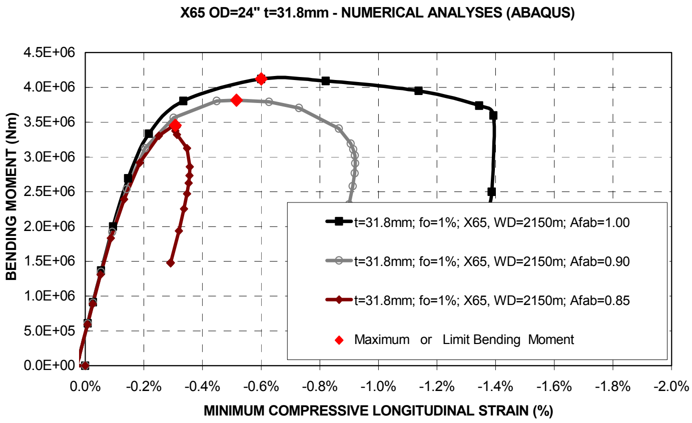

Figure 7 Effect of the compressive yield strength in the circumferential direction on the pipe cross-section capacity against ovalisation buckling failure mode (water depth equal to the maximum allowable one, anisotropy material model).

In particular the yield strength in the hoop direction has been reduced to 90% and 85% of the one in the longitudinal and radial directions. A reduction of 15% on the compressive yield strength in the hoop direction when the pipe is at the maximum water depth, decreases the critical bending moment and the corresponding longitudinal compressive strain to 16% and 50% of the ones without anisotropy, respectively.

The failure mechanism related to the external pressure is governed by cross section instability (for which the bending moment acts as a triggering load) with a sudden lost of strength. Therefore, the safety factors should be defined according to a "brittle" failure mode.

4. ADDITIONAL TOPICS

Seam weld HAZ toughness requirements

It is not a rare event that low toughness at the seam weld heat affected zone (HAZ) is found, particularly in relation to the fabrication of thick line pipes for offshore projects. High grades line pipe nowdays introduced will likely increase the occurrence of low toughness areas in both seam and girth welds.

Both experimental and analytical survey activities have been purpose carried out in the last decade to demonstrate that, despite the low toughness values sometimes measured using Charpy tests, the seam weld HAZ can tolerate even large defect sizes similar to those tolerated in the pipe wall far from the seam weld. Such activities included:

- analysis of material microstructure change in HAZ of both seam and girth welds of high grade pipeline steels, and correlation with the relevant fracture properties;

- failure predictions obtained using engineering criticality assessment (ECA) procedures such as BS 7910 [19];
- failure predictions obtained using advanced ECA procedures i.e. accounting for the constraint effect as in the procedure proposed in R6 [20];
- material testing aiming to suitably qualify toughness at the seam weld HAZ, and to understand the potential implication on the failure mode;
- destructive ring expansion tests;
- Full scale pipe burst tests.

It was concluded that:
- mechanical properties of the TMCP steels can be significantly altered by more complex HAZ microstructures particularly in thick wall pipes;
- correlation between the microstructural change and fracture properties has been identified and metallurgical remedies as well, albeit the presence of certain microstructural features as hard island of high carbon, martensitic – austenitic constituents cannot be excluded; low toughness seam weld HAZ is acceptable provided that hard microstructural features as M.A. constituents cover a small percentage part of the seam weld HAZ;
- ECA's give indication of reduced defect tolerance due to the low toughness of seam weld HAZ, while advanced constraint based ECA's show that the failure behaviour can be assumed as toughness independent;
- toughness independent criteria fit well the test results for both the destructive ring expansion and full scale pipe burst tests.

These findings are a good starting point for the subject analysis, and the approach previously adopted by involved pipe operators area guideline for the present assessment. For the subject assessment a series of BS 7910 based ECA's have been carried out with the aim to define the effect of toughness on the strength capacity of the pipe section to withstand internal pressure loads. The Used pipe size id a 32" NSP with thickness of about 30 mm. Main findings from such ECA's are reported in the following Figure 8. The figure shows that defects height of 2mm (dimensions still far larger than what expected to be able to pass NDT) are not able to jeopardise the pipe capacity to contain the internal pressure.
The applied approach provides conservative indication on the weld tolerance to surface defects.

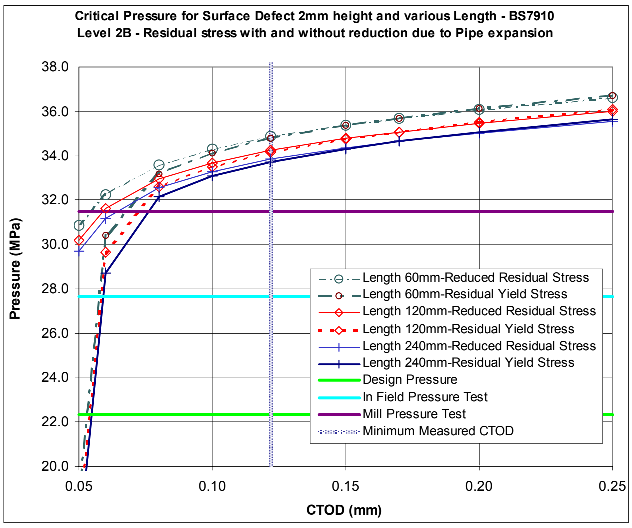

Figure 8 Critical pressure for surface defects in the seam weld 2mm height and various length. Horizontal lines show relevant cases of internal pressure.

There are no specific data that allows one to use an advanced-constraint based ECA as recommended by analysed references (as reported by R6 Rev. 4 [20]). These results confirm experience from other investigations on pipelines, that if the failure is expected to occur in a region of the FAD that can be considered as toughness independent.

According to available data, experience from other projects and engineering judgement, it can be concluded that performed ECA confirm that, under the severest hoop stresses the pipeline is expected to experience, the seam weld HAZ is satisfactorily damage (even significantly larger than the ones that can incidentally escape the on-line NDT) tolerant. Particular attention has been previously paid to POD or Probability Of Detection of defects in the production line, showing that the probability of non detection of defects greater than 1.6 mm is definitely small. In other words, defects of size (in the order of) critical under hydrotest (pressure test and operation less severe than hydrotest), defined using fracture mechanics methods, cannot be (POD about 1) undetected.

Some comments about existing results results on this topic:

- toughness requirements for the HAZ of the seam weld is a topic still under discussion (why such requirements?), as an example early DNV 1996 and current DNV 2000 are different;
- the experimental characterization of toughness is a topic under discussion (the location of the apex just at the fusion line etc..), as well as its use in engineering criticality assessment;
- the results of the experimental campaign should be interpreted with care, particularly the toughness dependency of failure, which requires additional investigation;
- for a gas offshore trunkline, we cannot see longitudinal failure modes that can be directly influenced by the low toughness of the HAZ of the seam weld. Nonetheless, high longitudinal strains in plastic regime are accompanied with comparable plastic hoop strains, so one should consider from one hand if low toughness would mean low deformability, from the other the envisaged load conditions. According to our experience this is not the case, however traditional tests on samples transversal to the weld (the ones carried out to show that the weld is stronger than the parent pipe, as specified e.g. in DNV as proof test for overmatching) should provide a final answer.

Propagating Buckling: Wet vs. Dry

An offshore pipeline installed in deep waters is often collapse-critical due to the ambient external pressure. If the pipe is not sized against propagation when collapse or sectional ovalisation buckling occurs in the depths, the buckle propagates. The buckle propagation pressure has been extensively studied in the last decades and design approaches have been developed and experienced in a number of projects. Research activities, both experimental and analytical, have been dedicated to the development of the most suitable buckle arrestors shape for deep water applications: integral arrestors are the most used for trunklines. New design formula including partial safety factors that meet the safety objective of DNV-OS-F101 for sizing integral buckle arrestors are discussed in [36]. At each end the integral buckle arrestor has a thickness transition section about 100-200 mm long, to fit the same wall thickness as that of the welded pipes.
The phenomenon of buckle propagation arrest has been simulated with dedicated FE model for different submarine pipelines [36]. The applied longitudinal and hoop strain are analysed as a function of the girth weld distance from the buckle arrestor and of the relevant applied external pressure. Figure 9 shows the two deformation mechanisms during propagation and arrest the pipe are subject to, namely:

- The girth weld is subject to a longitudinal stress/strain caused by the bending moments acting across the pipe wall (see figure on the bottom left). This moment inverts its sign during buckle propagation and, therefore, relatively high tensile strains/stresses are applied on both internal and external pipe diameter.
- The seam weld is subject to a hoop stress/strain caused by the bending moments acting across the pipe wall (see figure on the upper right). This moment inverts its sign during

buckle propagation and, therefore, relatively high tensile strains/stresses are applied on both internal and external pipe diameter.

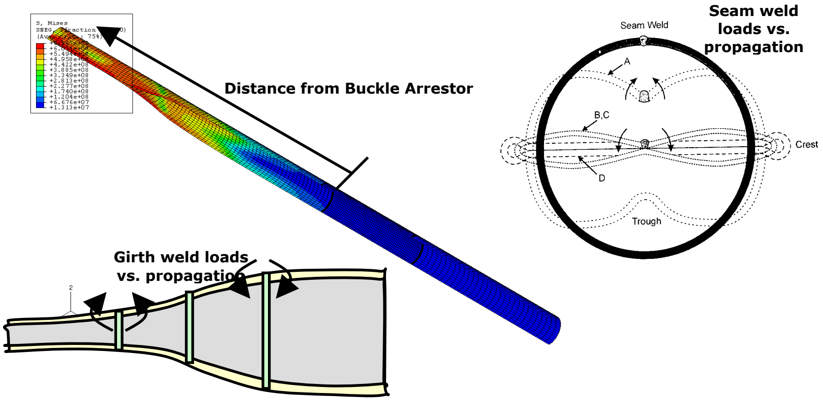

Figure 9 Pipe deformation mechanisms during buckle propagation and arrest.

Figure 10 shows the following (relevant for an applied external pressure equal to 1.1 times the hydrostatic pressure at maximum water depth to include the dynamic external overpressure effect [36]). Figure 10a Figure 10b show the applied longitudinal and hoop strains respectively, at a given applied external pressure as a function of the distance from the line pipe/buckle arrestor interface and of the location around the pipe circumference.

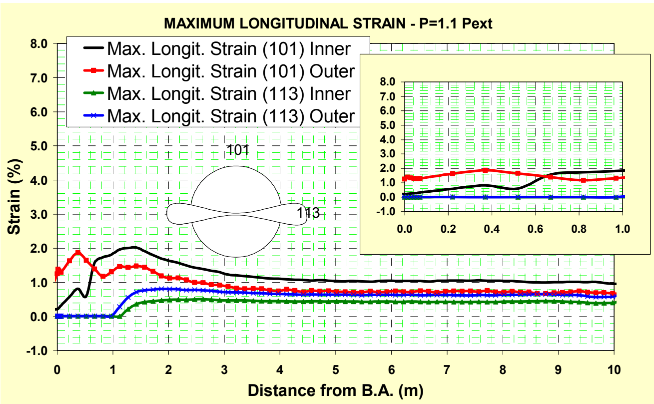

Figure 10a Maximum Longitudinal strain distribution as a function of the distance from the line pipe/arrestor interface and of the location around the pipe circumference.

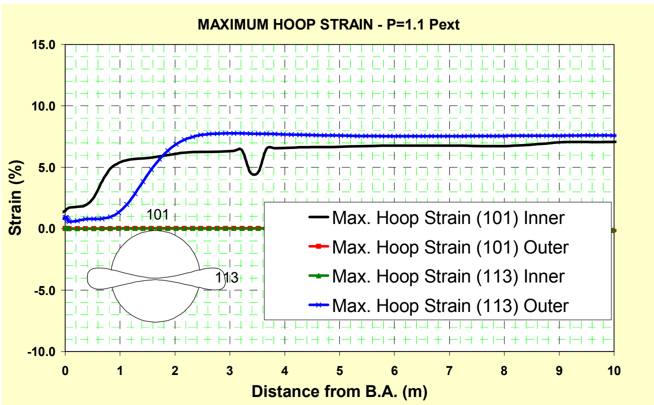

Figure 10b Maximum hoop strain distribution as a function of the distance from the line pipe/arrestor interface.

The following is evidenced:

- The longitudinal tensile strains reach a maximum value near the stiffer (as compared with the pipe) buckle arrestor. Near the arrestor (within 2000 mm from the interface) the longitudinal tensile strains are about 2.0% while far from it they reach a value of about 1.0% (Figure 10a).
- The hoop tensile strains reach a maximum value far from the stiffer (as compared with the pipe) buckle arrestor. Near the arrestor (within 400 mm from the interface) the hoop tensile strains are about 1.0% while far from it they reach a value of 6-7% (Figure 10b).

From the engineering point of view the difference between a girth weld adjacent the buckle arrestor section and those between nominal pipe joints is negligible. In fact, speaking about an applied strain of 1 or 2% is equivalent when assessing the strength capacity of the weld. This is due to both the partial flattening of the buckle arrestor during buckle propagation arrest and the presence of the tapered section which reduces the applied peak strains/stresses. On the other hand, much higher tensile hoop strains seen by the seam weld (more than 5-0%). Therefore, it can be said that the risk of having a wet buckle in the weld adjacent to the buckle arrestor is not any higher than the one relevant for all the other girth welds as well as the one related to the seam weld.

Nevertheless, for the extreme water depth foreseen in the coming deep water projects (more than 3000 m water depth), very thick buckle arrestor will cause even higher strains than showed in the example above. It is therefore important to qualify both longitudinal seam welds and girth welds for resisting to such high strains i.e. to avoid local through thickness fractures which will allow the external water ti enter and fill up the pipe (wet buckle). One kind of such a test is the ring squashing test which consists of flattening a ring of the pipe in a dog-bone shape so that the seam welds will experience the same strains as during propagation (see Figure 9). Other small scale tests with the same principle can be used: as an example a small squared full thickness sample extracted from the produced joints containing the girth weld can be subject to the same cyclic bending as shown in Figure 9.

Ductile Running Shear Fracture and its Arrest

Submarine pipelines for very deep water applications (recent projects are in excess of 2000 m and new planned cover up 3000m depth) are characterised by thick wall due to both high internal operating pressure (Maximum Allowable Operating Pressure higher than 30 MPa, to ensure the long distance transportation) as well as to withstand the external overpressure across the deepest section of the route. High grade line pipe material (API 5L X70 and X80, may be over) is also considered to reduce the required wall thickness and related fabrication and lay requirements.
Accidental conditions, as those related to third party activities, may cause an initial crack, which in turn gives rise to a running shear fracture particularly related to the high internal pressure near the shore approaches. The phenomenon is characterised by gas expansion inside the pipe combined with the propagating fracture of the steel wall running along the pipe axial direction. The gas decompression wave inside the pipe gives rise to an internal pressure decay, which act as a driving force for the propagating longitudinal fracture of the pipe steel wall. The primary fracture control method is to design against fracture initiation.

Work performed during an early phase of a similar project [34], can be used to show that, under the relevant condition of deep water projects, the pipeline will have sufficient toughness to resist fracture initiation from small flaws, with critical flaw sizes much lower than the detect ability limits of non destructive inspection. Specific material tests are to be specified to qualify the line pipe against fracture initiation (actually such tests are not related to ductile fracture propagation arrest requirements).

To minimise the risk of a long distance running shear fracture, activated at a certain location by external damage and maintained by the internal pressure applied at the running crack tip, it is necessary to guarantee the ductile behaviour of the pipeline under the relevant temperature conditions experienced by the running fracture tip, by specifying a minimum line pipe toughness, so to stop any fracture propagation within an acceptable number of pipe joints.
A transition temperature must be defined such that it is ensured that the steel material behaviour in the above conditions is ductile. The definition of such a transition temperature, often compared to the minimum design temperature, and its qualification is made using the Drop Weight Tear Test (DWTT) specimen [22].
In case such requirements cannot be achieved, an alternative can be to install the so-called "crack arrestors" or "crack stoppers" [23], which are able to stop any running (brittle or/and ductile) shear fracture.

Considering line pipe produced with TMCP plates, the basic requirement of ductile behaviour of the steel material under the design temperature is met by ensuring that, in a purpose developed standard test, the absorbed upper shelf Charpy V energy, an indicator of the line pipe toughness, shall be higher than the minimum specified one. Actually such requirement has been extensively studied and defined for on-land pipelines i.e. for internal pressures up to 8-10 MPa, D/t ratios over 50 and line pipe material up to grade X80.

At the design stage, different methodologies for defining line pipe requirements can be used:
- Simplified empirical formulas, based on numerical fitting of full scale experimental tests results;
- Analytical tools (as the Battelle Two Curves Method) based on the comparison between the driving force related to the gas expansion process with the resistance curve related to the line pipe mechanical characteristics;
- FE models that analyse the fracture propagation coupling the gas expansion process with the running shear fracture.

The Battelle Two Curves Method can be has been applied to a typical deep water project (Figure 11) calculating the driving force curve with dedicated commercial software. The A first estimate of this effect showed that a reduction of the required minimum Charpy V energy down to 35 J or less is possible (X70 line pipe, NPS 28", D/t of 18.2 and design pressure of 44 MPa).

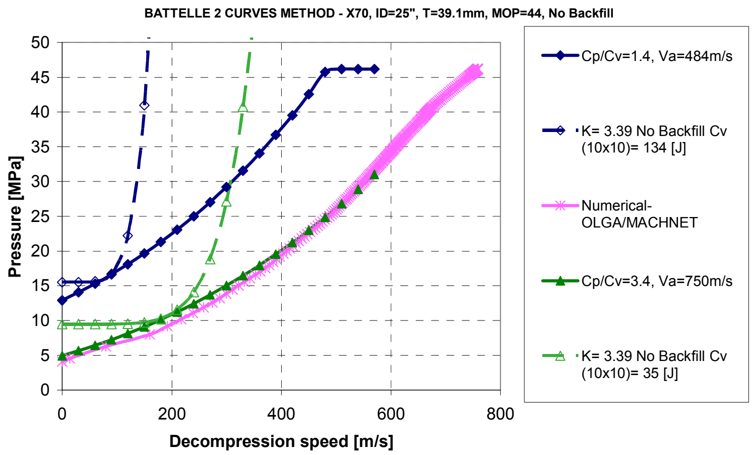

Figure 11 Battelle Two Curves method applied to the numerically calculated gas decompression curve.

Predefined requirements are reported in international standards, based on extensive application of the above mentioned methods (see [24, 25]). The same requirements and methodologies have been extended to offshore pipelines. Actually offshore pipelines are generally characterised by higher internal pressures (44 MPa for the subject case, 15 to 20 MPa are often relevant) and thicker steel wall (about 40 mm for this example, 20 to 30 mm are often relevant) than on-land pipelines, for which the above methodologies have been developed. Design codes for gas transmission pipelines such as ASME B31.8 [26], IGE/TD/1 [27], BS 8010 [28, 29], AS 2885 [30], CSA Z662 [31] and DNV OS-F101 [2] all indicate that pipelines should be designed with a sufficient toughness to arrest ductile fracture propagation. EPRG have produced recommendations [32] for ductile fracture arrest toughness, which have recently been incorporated in the ISO Standard [33] for line pipe.

EPRG Recommendations and DNV-OS-F101 are the most recommended to be used for onshore and offshore pipelines DFPC respectively.

Owing to the different nature of the backfill, ductile fracture propagation in an offshore pipeline differs in certain ways from that in buried pipelines. The most important features which must be considered in this specific case are:

- gas constraining effect;
- flaps opening restraining effect.

The applicability of current requirements for onshore pipelines to deep water offshore pipelines is now under discussion. It is to be considered that offshore pipes with respect to onshore pipes, are subject to the beneficial effect of the surrounding sea water on the capacity of the steel pipe to stop a propagating ductile fracture (the displaced water will absorb part of the energy released by the expanding gas).

The performance of full-scale propagation tests in offshore conditions is much more complicated than the execution of similar tests on onshore. The only two tests in real offshore conditions are those performed by the CSM. For completeness's sake it should be mentioned that even British Gas Technology executed an underwater test on 36" diameter pipeline section, but test conditions and results were not published.

Open issues for the extension/application of the above listed methods to thick offshore pipelines are:

- Gas decompression behaviour; the high internal pressures required by the project are very different from those used during model development and this influences the decompression wave speed versus the internal pressure curve, i.e. the driving force (Figure 11).
- The effect of the high pipe wall thickness (more than 30 mm) produced by modern TMCP technology is not well addressed in the relevant Codes/Standards. It is generally accepted that the analysed methodologies for both the brittle/ductile transition and minimum CV requirements are applicable to thicknesses up to 25-30mm.

Particular attention should be paid to the definition of a rationale minimum test temperature for qualifying the ductile material behaviour. Actually, the test temperature for the Charpy V test is referred to the minimum design temperature. Therefore, the test temperature is reduced to consider the fact that the Charpy V full size specimen has a thickness lower than the pipe thickness (for thick offshore pipeline there is a large difference).
Nevertheless, temperature reduction is more related to brittle/ductile transition behaviour, for which DWT tests are specifically performed, than to CV absorbed energy. In particular, a detailed investigation of the complete brittle/ductile transition temperature using both Charpy V and DWTT

specimens is recommended (possibly comparing them with West Jefferson tests). This will allow a better definition of the required test temperature for both DWT and Charpy V tests.

5. CONCLUSIONS

The failure mechanism related to the external pressure is governed by cross section instability (for which the bending moment acts as a triggering load). The pipe response under bending and external pressure loads shows a sudden lost of strength. Therefore, the safety factors should be defined according a "brittle" failure mode. Considering the relatively low values of the critical bending moment and corresponding longitudinal strains (Figure 7), it is important to control both applied bending loads in the pipeline empty conditions (installation and as-laid) and mechanical/geometrical characteristics of the pipe. Therefore:

- The calculation of the applied allowable ovality for submarine pipelines is not a straightforward analysis and generalisations are difficult.
- To fulfil a safety requirement as stated in [2] the residual and the measured applied ovality must be linked to the applied/allowable pressure load.
- For deep water applications applied ovalities of 3% accepted by international design standards are at the limit of acceptance criteria for structural integrity.

The FE analyses of the production process show that the actual pipe capacity to sustain external pressure load may be optimised in terms of obtained initial ovality versus compressive yield strength in the hoop direction.

The low toughness of HAZ of the seam weld is not a new topic, it has become argument of detailed investigation in recent years, in relation to the concurrence of two aspects:

- increasing wall thickness requirements, and
- high grades.

According to available data, experience from other projects and engineering judgement, it can be concluded that performed ECA confirm that, under the severest hoop stresses the pipeline is expected to experience, the seam weld HAZ is satisfactorily damage tolerant (even significantly larger than the ones that can incidentally escape the on-line NDT).

It is important to qualify both longitudinal seam welds and girth welds for resisting to high strains during buckle propagation i.e. to avoid local through thickness fractures which will allow the external water ti enter and fill up the pipe (wet buckle). One kind of such a test is the ring squashing test which consists of flattening a ring of the pipe in a dog-bone shape so that the seam welds will experience the same strains as during propagation

Ductile running shear fracture for an offshore pipeline is a more complex matter because of the interaction between the escaping fluid and the surrounding water. A recognized available predictive method for DFPC on offshore gas pipelines is the Battelle Two Curves Method. The use of this method for predicting the minimum arrest toughness for an onshore pipeline is considered to be conservative when applied to an equivalent offshore pipeline: more investigations are needed considering the high internal pressure load and the gas expansion process.

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