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DEEPER, LONGER AND THICKER: CHALLENGES FOR THE DESIGN OF SUBSEA PIPELINES

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ABSTRACT

The world's population needs a lot of energy to be able to live its life. These days, a growing share of that energy is extracted from renewable sources. This does not mean that fossil fuels are obsolete—they are much needed in the foreseeable future. Many conventional and easily accessible reservoirs have been depleted. New discoveries are often challenging to produce or located far away from the end user. Long subsea pipeline systems are a means of transporting the produced fluids. Sometimes, it is inevitable that these pipelines traverse very deep water or are subjected to extremely high internal pressure and temperature. These conditions require a pipe with an extremely thick wall.

The European Pipeline Research Group completed a review (EPRG Project 178/2015) of the status of deep-water-pipeline technology in 2015 [1]. This work included a gap analysis in which certain areas that require additional research were identified. A long-term research programme was the next step. Its purpose was to understand and help to overcome the existing technological barriers that are relevant for pipelines operating in ultra-deep water or under extremely high internal pressure.

The applicability of the limit-state formulations for local buckling of a pipe loaded by a combination of bending, axial force and pressure in DNVGL-ST-F101 [2], a prevailing standard for the design of submarine pipelines, was bounded at a wall-thickness-to-outer-diameter ratio (D/t) of 15. As such, walls thicker than 1/15 of the diameter could not be designed in compliance with the design standard.

To overcome this issue, two studies on the structural capacity of pipelines under a combination of loads have been performed: one (EPRG Project 202/2017) for external overpressure [3,4] and another (EPRG Project 219/2019) for internal overpressure [5,6]. It was concluded that the limit-state formulations can be used for pipe with very thick walls, too, without reducing the formulations' underlying conservatism. This has ultimately resulted in the elimination of the validity limit for thick walls in the most recent version of the design standard, DNV-ST-F101 [7].

DISCLAIMER

However, it was observed that the current design equations are, in fact, overly conservative for predicting the load capacity of extremely thick-walled pipe loaded by external overpressure. This could hurt project economics or compromise the technical feasibility of some frontier developments altogether. A final study (EPRG Project 202a/2020) was launched to understand whether the predictive formulation for the collapse pressure could be improved [8,9]. An improved formulation based on fundamental principles has been proposed so that the capacity of thick-walled pipe loaded by external overpressure can be predicted more consistently.

1. BACKGROUND

1.1. Challenges for Pipelines in Ultra-deep Water

Pipelines installed in ultra-deep water require very thick walls to cope with an extremely high hydrostatic pressure. Currently, there are prospects for pipelines in water depths of up to 3,700 m. To be able to operate in such environments, the ratio between a pipe's outer diameter and its wall thickness (D/t) must be very low—sometimes even lower than 15.

In 2015, Intecsea conducted a gap analysis focusing on the then-current status of deep-water-pipeline technology for EPRG's Design Committee [1]. It was concluded that there was a lack of adequate and validated design equations for thick-walled pipe and that the manufacturability of such pipe would be approaching the industry's limits. The latter is especially relevant for medium- to large-diameter longitudinally submerged-arc-welded (SAWL) line pipe that is cold formed from plate material.

A new EPRG project ("Pipeline Design for Thick Pipe (D/t ratio below 15)") was launched in 2017. The project started with a review of design, manufacturability and welding of pipe with low D/t aimed to collect best practices on the design aspects related to local buckling, to determine what can be achieved by the world's leading pipe mills in terms of line-pipe geometrical and mechanical properties, and to determine the practicably achievable high-low (geometrical) misalignments at girth welds for thick-walled pipe. As part of this review, pipe mills, operators and installation contractors that are members of EPRG were consulted via questionnaires. Their feedback was interpreted, and the relevant findings were used throughout the project. In summary, the following market feedback was received:

- Operators: there are ultra-deep-water prospects that would require a D/t lower than 15 for external-pressure design in water depths up to 3,700 m.
- Pipe mills: the required combination of diameter and wall thickness for welded line pipe is generally at the limit of the mills' current capabilities. The constraints for manufacturing thick-walled pipe primarily relate to the weldability of the seam weld and the O-press capacity. For SMLS (seamless) line pipe with a smaller diameter, the line-pipe specification necessary for ultra-deep-water application is typically within the pipe mills' existing capabilities.
- Installation contractors: there is no direct limitation regarding the wall thickness; girth welding using proven methods is feasible for wall thicknesses up to 50 mm.

The above findings emphasize the importance of assessing the validity and applicability range of the pipeline design framework that is currently in place.

1.2. Compliance Validity of Design Formulations

The design criteria for local buckling under combined loading in DNVGL-ST-F101 [2], one of the prevailing standards for the design of submarine pipelines, are stated to be valid only for pipelines with D/t between 15 and 45. This means that pipelines with walls thicker than $D/15$ cannot be designed using just the formulations provided by the design standard.

In DNVGL-ST-F101, differentiation is made between the load-controlled condition (LCC) and the displacement-controlled condition (DCC). The focus of the EPRG project has been the load-controlled condition. This condition is the one in which the structural response of the pipeline is primarily governed by imposed loads. The load-controlled local buckling limit state applicable for pipe members subject to bending moment, effective axial force and external overpressure is defined by:

$$\left[\gamma_{\mathrm{m}}\,\gamma_{\mathrm{SC,LB}}\frac{|M_{\mathrm{Sd}}|}{\alpha_{\mathrm{c}}\,M_{\mathrm{p}}(t_2)}+\left(\gamma_{\mathrm{m}}\,\gamma_{\mathrm{SC,LB}}\frac{S_{\mathrm{Sd}}}{\alpha_{\mathrm{c}}\,S_{\mathrm{p}}(t_2)}\right)^2\right]^2+\left[\gamma_{\mathrm{m}}\,\gamma_{\mathrm{SC,LB}}\frac{p_{\mathrm{e}}-p_{\mathrm{min}}}{p_{\mathrm{c}}(t_2)}\right]^2\leq 1 \tag{1}$$

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$$\left[\gamma_{\mathrm{m}}\,\gamma_{\mathrm{SC,LB}}\frac{|M_{\mathrm{Sd}}|}{\alpha_{\mathrm{c}}\,M_{\mathrm{p}}(t_2)}+\left(\gamma_{\mathrm{m}}\,\gamma_{\mathrm{SC,LB}}\frac{S_{\mathrm{Sd}}}{\alpha_{\mathrm{c}}\,S_{\mathrm{p}}(t_2)}\right)^2\right]^2+\left[\gamma_{\mathrm{p}}\frac{p_{\mathrm{i}}-p_{\mathrm{e}}}{\alpha_{\mathrm{c}}\,p_{\mathrm{b}}(t_2)}\right]^2\leq 1 \tag{2}$$

Equations 1–2 are often referred to as the “LCC equations” and the value of their left-hand side as the “LCC”. Descriptions of the individual parameters are provided in DNVGL-ST-F101 [2].

To assess the applicability of the design equations for thick wall pipe, EPRG members—including pipeline operators, line pipe manufacturers and installation contractors—were consulted to establish three representative case studies that require a D/t below 15. The cases have been defined to capture a range of geometries and line pipe manufacturing methods:

- Case 1: 6-inch flowline (SMLS);
- Case 2: 16-inch gathering line (SMLS); and
- Case 3: 24-inch trunkline (SAWL).

The selected material grade is DNV(GL) 450 for all cases. The selected D/t varies between cases and is in the range 8.0–14.5. For the scenarios characterised by external overpressure, the required wall thickness had been calculated using a pipeline-installation scenario in a water depth of 3,500 m. The critical location is the lay catenary’s sagbend, in which the pipe is loaded by a combination of extreme external pressure and substantial bending. For the scenarios characterised by internal overpressure, the required wall thickness is calculated using the pressure-containment (i.e., burst) limit state. Depending on the case, the design pressure was chosen between 440 bar and 750 bar in combination with DNV safety class “high”. An additional Case 0 (trunkline, outer diameter of 32-inch, wall thickness of 39 mm, and material grade SAWL 450) was included as a benchmark as its D/t of 20.8 is within the formal applicability bounds of the DNVGL-ST-F101 formulations.

2. ACCURACY OF DESIGN FORMULATIONS

One of the objectives was to evaluate whether the existing design equations could also be used for thick-walled pipe with D/t below 15 without affecting the level of conservatism underlying the code framework. The applicability of the load-controlled local buckling formulation in DNVGL-ST-F101 has been studied for both thick-walled pipe under external pressure [4] and internal pressure [6].

Finite-element analysis (FEA) has been employed to evaluate the response of thick-walled pipe. A short pipe model (ring model) built using continuum elements was used to evaluate the combined effect of pressure, bending and effective axial force. The ring model can accommodate geometric imperfections.

Analytical models generally quantify material strength using a single parameter (e.g., the yield stress at 0.2% plastic or 0.5% total strain). The FEA model can account for the nonlinear relationship between stress and strain (the stress–strain curve).

The model's target is to establish the cross-section capacity against local buckling caused by a combination of pressure and bending. The results were compared with analytical results as per the DNVGL-ST-F101 framework.

2.1. External Overpressure

For each case study, the FEA model has been used to evaluate the bending-moment capacity under the action of various levels of external pressure. The effective axial force was ignored because during installation its contribution is typically negligible. Figure 1 shows the results. The markers are the numerical results. The continuous lines represent the analytical capacity as per the LCC equation (Eq. 1) in which the application limits have been ignored. The aim was to compare the predictive capacity of both models. Hence all load and resistance factors have been set to unity. The design value of the external pressure corresponding to a water depth of 3,500 m (which accounts for the resistance factors γ_{m} and $\gamma_{\mathrm{SC,LB}}$) is included as a reference.

For easier interpretation, the results on the horizontal and vertical axes have been normalised by dividing by the analytical capacities against external pressure (p_{c}) and that against bending ($\alpha_{\mathrm{c}}\ M_{\mathrm{p}}$), respectively. If the FEA results lie outside the LCC capacity envelope, this means that the analytical framework is conservative compared with FEA and vice versa.

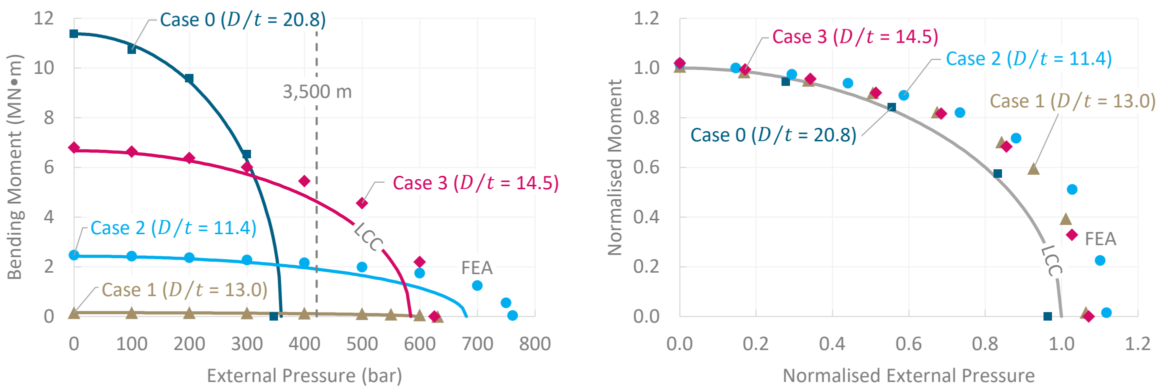

Figure 1: Nominal (left) and normalised (right) capacity under external overpressure and bending

For Case 0 (D/t = 20.8), the LCC equation predicts a capacity similar to that predicted by the FEA model. All results are within a 5% margin. This is not always true for Cases 1–3 (for each D/t < 15), in particular when the external pressure is relatively close to the collapse pressure. The lower the D/t ratio, the more the LCC and FEA predictions differ and the LCC capacity can be more than 10% lower than the FEA capacity. The prediction of bending-moment capacity under relatively low external pressure is similar for both the LCC equation and the FEA model.

The results indicate that the applicability range of the existing LCC design equation for external overpressure can be extended without compromising on underlying design safety. Moreover, the identified conservatism in the collapse-pressure formulation for very thick walls can be used to improve the associated design formulations. This will help to reduce the wall-thickness requirement of pipe whose governing loading scenario includes external overpressure. The responses to the questionnaires indicate that such an accomplishment can be essential for the technical and commercial feasibility of seam-welded pipe intended for applications in ultra-deep water.

2.2. Internal Overpressure

Internally pressurised pipelines behave differently than externally pressurised pipelines. Like the study performed for externally pressurised pipe, the validity of the existing design equation for local buckling under internal overpressure and load-controlled conditions (Eq. 2) was investigated using finite-element analysis.

The FEA model is used to calculate the capacity under a combination of internal pressure and bending moment. The results are presented in Fig. 2. The markers denote the FEA results, and the lines denote the capacity predicted by the predictive LCC equation. The internal pressure is plotted on the horizontal axis and the associated bending-moment capacity on the vertical. Load combinations within the area enclosed by the curves are envisaged not to lead to structural failure, the ones outside will. Effective axial force and cross-section imperfections were disregarded to focus on the effect of changing only the diameter and the wall thickness (and as such the effect of D/t).

Since substantially different pipe dimensions were specified for each case, it is difficult to compare the results directly. Therefore, all results have been normalised again. The applied internal pressure and associated bending-moment capacity are divided by the analytical capacity against internal pressure ($\alpha_c \, p_b/\gamma_p$) and that against bending ($\alpha_c \, M_p$), respectively. The distance between the FEA prediction and the LCC-predicted curve provides valuable information on the intrinsic conservatism in the LCC formulation compared with FEA results.

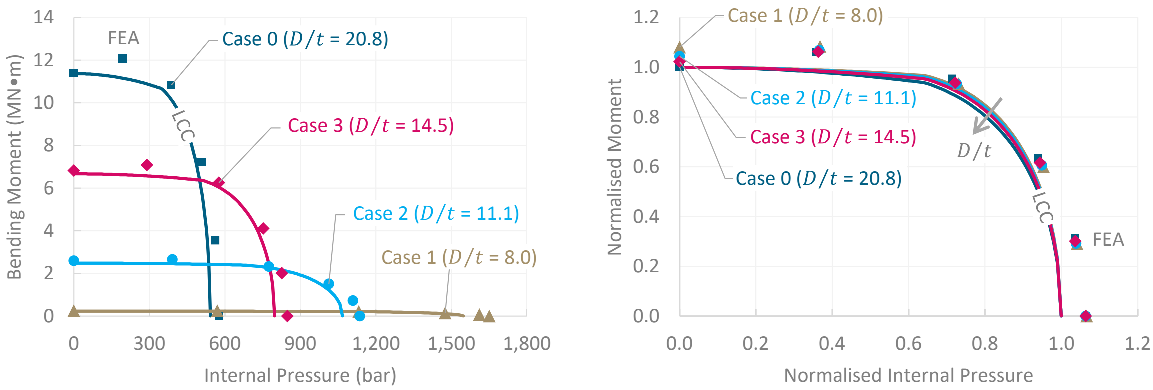

Figure 2: Nominal (left) and normalised (right) capacity under internal overpressure and bending

Again, the results for Case 0, for which D/t is within the applicability range of the LCC equations, are included in the figures as a reference. Except for pure-bending behaviour, the normalised results of the various cases coincide for the whole considered D/t range. This indicates that the LCC formulation's predictive capacity does not depend on D/t. Hence it can be used for design against local buckling under internal overpressure when D/t < 15, too. As opposed to external-overpressure conditions, the underlying accuracy does not depend on the diameter-to-wall-thickness ratio.

As part of the study, a fundamental review of the LCC criterion under internal overpressure was performed. The formulation in DNVGL-ST-F101 is a simplification of the complete formulation, based on several assumptions. It is primarily suitable to characterise the interaction between pressure and bending loads. It can account for effective axial force, another important global pipeline load, but only when it is sufficiently small. The current LCC formulation is formally valid up to an effective axial force of 40% of the fully plastic capacity. It was found that the influence of effective axial force predicted using the LCC equation is less than estimated through FEA. This means that predictions associated with a relatively large effective axial force are less conservative than predictions associated with a smaller force. The effect becomes apparent at values of about 20% of the fully plastic axial capacity, either in tension or compression.

3. IMPROVEMENT OF DESIGN EQUATIONS FOR EXTERNAL OVERPRESSURE

The results presented in Fig. 1 indicated that the analytical limit-state equations for external overpressure included in DNVGL-ST-F101 do not work well for pipe with extremely thick walls. It is known as well that collapse-pressure predictions are increasingly conservative for smaller D/t [4]. Improving this prediction, which is a key input to the limit-state equations for external overpressure, has been identified as a key target. The conservatism in the design standard's equations will lead to over-dimensioned pipelines in ultra-deep water. This can culminate in manufacturing requirements that hurt project economics or threaten the technical feasibility altogether. Therefore, a study was launched to improve the analytical framework for calculating the collapse pressure. Like the formulation included in DNVGL-ST-F101, the proposed formulation reflects the fundamental underlying and interacting physics of material yielding and geometric instability.

3.1. Collapse

In DNVGL-ST-F101 [2], the collapse pressure p_{c} is defined using the following equation:

$$(p_{\mathrm{el}} - p_{\mathrm{c}})(p_{\mathrm{p}}^2 - p_{\mathrm{c}}^2) = p_{\mathrm{c}}\, p_{\mathrm{el}}\, p_{\mathrm{p}} \frac{D}{t} O_0 \tag{3}$$

In which p_{el} denotes the elastic collapse pressure, p_{p} the plastic collapse pressure and O_0 the initial ovality. Detailed descriptions of these parameters can be found in DNVGL-ST-F101. The analytically predicted collapse pressure can differ substantially from FEA results. Figure 3 shows various FEA predictions that have been normalised by the corresponding analytical predictions for various values of D/t.

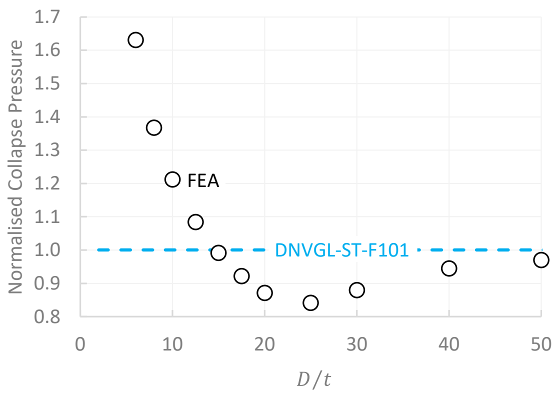

Figure 3: Predictive capacity of current design formulations for as-fabricated material of grade DNV(GL) 450

The design equations would be considered good predictors if the normalised FEA results were at the unity line. Where the FEA results lie above this line, the analytical predictions are considered conservative; however, if they lie below this line, they are nonconservative. Three regions can be distinguished:

- $D/t \leq 15$: the design formulations are (overly) conservative;
- $15 < D/t \leq 30$–40: the design formulations are nonconservative; and
- $D/t > 30$–40: the design formulations are in good agreement with the FEA predictions.

To improve consistency between the predictive model and finite-element analysis, the analytical model has been extended to account for behaviours that were not yet included: triaxiality of stress and plastic bifurcation [9]. The result is an elegant set of equations that can be used to evaluate the collapse pressure. The formulations are based on triaxial yielding and thick-wall assumptions. The triaxiality factor ψ is defined as:

$$\psi = \frac{2}{\sqrt{3}} \frac{D - t}{D - 2t} \tag{4}$$

The collapse pressure p_c must satisfy the following transcendental equation and can be found by applying a root-finding algorithm (e.g., Newton–Raphson method):

$$[p_{\mathrm{bif}}(p_{\mathrm{c}}) - p_{\mathrm{c}}]\left(p_{\mathrm{p}}^2 - p_{\mathrm{c}}^2\right) = p_{\mathrm{c}}\, p_{\mathrm{bif}}(p_{\mathrm{c}})\, p_{\mathrm{p}} \frac{D}{t} O_0\, \psi \sqrt{1 - \frac{1}{4}\left(\frac{p_{\mathrm{c}}}{p_{\mathrm{p}}}\right)^2} \tag{5}$$

In which the plastic collapse pressure is given by:

$$p_{\mathrm{p}} = \frac{2\, t\, \sigma_{\mathrm{y}}}{D} \psi \tag{6}$$

The triaxiality factor ψ boosts the plastic collapse pressure compared with the equivalent uniaxial formulation, which is currently adopted in Eq. 3. It accounts for the influence of the thick wall and the triaxial stress state provided that the pipeline is unrestrained in the axial direction (i.e., the effective axial force is small). The proposed bifurcation pressure is a function of the tangent modulus (E_{t}) associated with the acting equivalent stress [10], which itself is a function of the external pressure:

$$p_{\mathrm{bif}}(p_{\mathrm{e}}) = \frac{2E_{\mathrm{t}}\left(\sigma_{\mathrm{eqv}}(p_{\mathrm{e}})\right)}{1 - \nu^2}\left(\frac{t}{D}\right)^3 \tag{7}$$

The average, acting equivalent stress is defined by:

$$\sigma_{\mathrm{eqv}}(p_{\mathrm{e}}) = \frac{p_{\mathrm{e}} D}{2t} \frac{1}{\psi} \tag{8}$$

Pipeline collapse has been studied for two different material grades—DNV(GL) 450 and 485—and for three different material conditions—as-fabricated, heat-treated and elastic–perfectly plastic. Figure 4 presents the normalised collapse-pressure predictions for the evaluated conditions of DNV(GL) 450. In the left chart, the FEA predictions have been normalised against the analytical prediction as per the current formulation (Eq. 3). In the right chart, the FEA predictions have been divided by the collapse pressure as per the proposed formulation (Eq. 5). The more the normalised results deviate from unity, the less accurate the predictive model is. Narrow scatter bands around the unity line imply that the model predicts collapse accurately and, consequently, associated design factors can be smaller.

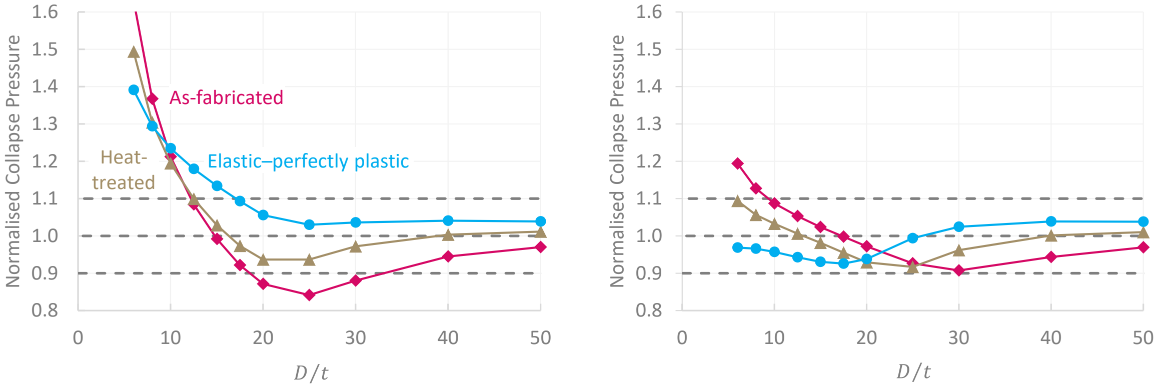

Figure 4: FEA results normalised by current (left) and proposed (right) analytical collapse-pressure formulation for material grade DNV(GL) 450

The proposed formulation leads to predictions much closer to FEA results than the current analytical formulation does. Although the focus of this study was thick-walled pipe, the improvements lead to better collapse-pressure predictions for pipe with thinner walls too.

3.2. Combined Loading

In reality, a pipeline is often loaded not only by external pressure but by a combination of loads. As per DNVGL-ST-F101, the integrity of a pipeline that is subjected to a combination of global loads—bending moment, effective axial force and external pressure—is verified using the limit-state criterion for combined loading under load-controlled conditions (Eq. 1). The equation was found to provide increasingly conservative results for lower values of D/t if the external pressure is relatively close to the collapse pressure.

The collapse pressure is an important parameter in the criterion. As such, it has been investigated whether adopting the proposed collapse-pressure formulation—instead of the current one—in the criterion for combined loading leads to better predictions. This effect is shown in Fig. 5. The left chart shows the same results as the normalised chart in Fig. 1. The right chart, on the other hand, shows the results normalised against the collapse pressure calculated using the proposed set of equations (Eq. 5).

For the evaluated cases of D/t, which were in the range of about 10–20, the predictions using the newly proposed collapse-pressure formulation show a very good agreement and they are closer to the finite-element results than those obtained using the current formulation.

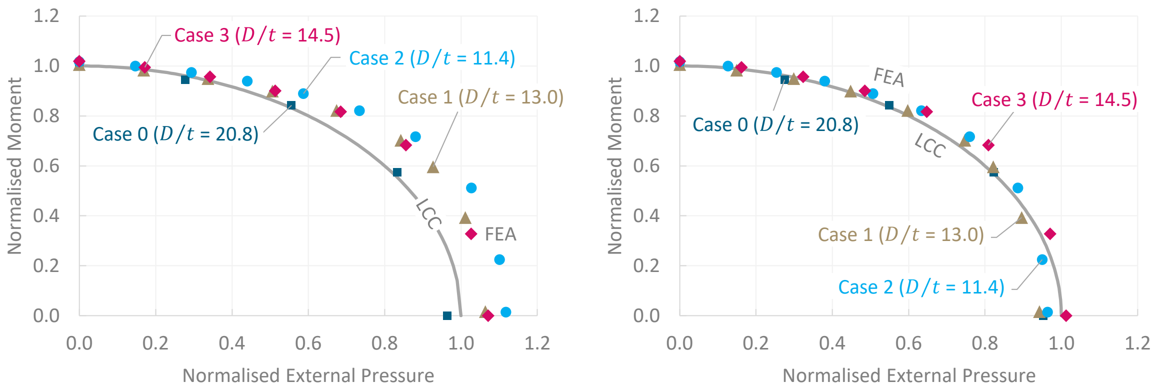

Figure 5: Predictive capacity of current (left) and proposed (right) formulations compared

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

The three subsequent studies that were conducted for the EPRG Project "Pipeline Design for Thick Pipe (D/t ratio below 15)" have resulted in the following main conclusions:

- Load-controlled design criteria for pipelines loaded by a combination of external overpressure and bending (Eq. 1) are conservative (5%–10% underestimation of pressure capacity compared with FEA results) when the overpressure is relatively close to the collapse pressure and D/t < 15. This is attributed to the conservatism underlying the current collapse-pressure formulation, more so for smaller D/t and in particular when D/t < 15. Therefore, there is no reason that the applicability of the LCC criteria for external overpressure should be limited to D/t > 15.
- Load-controlled design criteria for pipelines loaded by a combination of internal overpressure and bending (Eq. 2) have a similar predictive capacity for the whole range of D/t that was evaluated (i.e., 8.0–20.8). Hence the design formulations for combined loading under load-controlled conditions can be applied to thick-walled pipe with D/t < 15 too without losing any underlying reliability.
- Based on the presented work, DNV has omitted the lower-bound validity limits of the LCC equations for internal and external overpressure in the latest revision of their standard for the design of submarine pipelines, DNV-ST-F101 [7]. EPRG's contribution has been duly acknowledged.
- To reduce conservatism in external pressure design, an improved framework for predicting the collapse pressure of thick-walled pipe has been developed. Even though the study targeted to improve the predictive formulation for the collapse of thick-walled pipe (10 ≤ D/t ≤ 20) only, the proposed framework improves the prediction for pipe with thinner walls as well.
- The proposed framework is based on the same fundamental mechanisms underlying the collapse behaviour as those that are the foundations of the current framework [2]: geometrical instability and material yielding. The new framework provides improved formulations to describe the two individual mechanisms as well as their interaction. One of the strengths of the proposed framework is that it is based on physics and not on empirical relations.
- The proposed improvement of the collapse-pressure formulation leads to a similar, cascading improvement of the current LCC equation for external overpressure (by simply replacing the collapse-pressure term with the new formulation). The predicted bending-moment capacity is closer to the FEA results when using the proposed collapse-pressure formulation than when using the current formulation.

4.2. Recommendations

Based on the outcome of the presented study, the following is recommended:

- This study was a desk-top study. Analytical predictions have been compared with finite-element results, which were assumed to be a proxy of reality. Of course, FEA depends on various modelling assumptions that will introduce errors or inaccuracies. Therefore, it is recommended to confirm the results of this study using medium-scale or full-scale test results—especially for the wall-thickness and D/t ranges for which not much testing has been done to date. This is mainly the case for very thick walls and low values of D/t (e.g., below 15).

- The proposed collapse-pressure formulation was derived based on the assumption of no effective axial force, which means no external axial load. In reality, pipelines will be subjected to external loads such as lay tension or axial loads generated by thermal expansion. This affects the acting axial stress and hence the pipe's capacity to resist pressure without yielding. It is recommended to investigate the influence of effective axial force on the collapse pressure. This applies to thick-walled pipe in particular because the influence of material yielding on the collapse behaviour depends on the pipe's relative wall thickness.
- The criteria presented in DNVGL-ST-F101 [2] do not aim to predict nominal failure. Instead, they aim to ensure a certain safety margin against failure. A suitable margin is achieved by including load and resistance factors in the criteria. These factors have been calibrated against test data and results of numerical analyses. This means that their values are specific to the adopted design formulations. If the proposed formulation for collapse pressure is to be adopted as a design equation, all associated load and resistance factors need to be revisited and recalibrated to ensure suitable and consistent safety against failure. Considering that the predictive capability of the proposed formulation is better—meaning more consistent and closer to the FEA results—than that of the current formulation, it can be expected that the overall safety factor could be reduced.

5. REFERENCES

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