Deeper, Longer and Thicker: Challenges for the Design of Subsea Pipelines
EPRG programme—pipeline design for thick pipe

• EPRG Projects:
  • 178/2015  Gap analysis for deep-water pipelines
  • 202/2017  Thick-walled pipe under external overpressure
  • 219/2019  Thick-walled pipe under internal overpressure
  • 202a/2020 Improvement of collapse equation

• Paper about applicability of current design formulations for low values of D/t
  • Design governed by internal overpressure (burst) and bending
  • Design governed by external overpressure (collapse) and bending

• Cascading effect of improving collapse-pressure formulation on limit state for combined loading (LCC)
Feedback on typical line-pipe specifications for 6-inch (SMLS) flowline, 16-inch (SMLS) gathering line and 24-inch (SAWL) trunkline, all requiring D/t < 15:

- Operators
  - Prospects requiring D/t < 15 for external-pressure design in water depths up to 3,700 m

- Pipe mills
  - D/t of 15 is generally at the limit of mills’ capabilities for SAWL pipe
  - Manufacturing constraints relate to weldability of the seam weld and O-press capacity
  - For SMLS with small diameter, line-pipe specification necessary for ultra-deep-water application is typically within the pipe mills’ existing capabilities

- Installation contractors
  - No direct limitation regarding the wall thickness
  - Girth welding using proven methods is feasible for wall thicknesses up to 50 mm
Finite-element model used for benchmarking results

- Built using continuum elements (C3D20R) in Abaqus/Standard
- Continuous behaviour over length
- Non-linear material behaviour
- Geometric imperfections
  - Oval-shaped initial ovality
  - Eccentricity (for SMLS pipe)
- Bending applied by rotating ends
Current limit state for combined loading

Limit state under load-controlled condition (LCC) in DNV-ST-F101 (2021)

- **External overpressure**
  \[
  \left[ \gamma_m \gamma_{SC, LB} \frac{|M_{Sd}|}{\alpha_c M_p (t_2)} + \left( \gamma_m \gamma_{SC, LB} \frac{S_{Sd}}{\alpha_c S_p (t_2)} \right)^2 \right] + \left[ \gamma_m \gamma_{SC, LB} \frac{p_e - p_{min}}{p_c (t_2)} \right]^2 \leq 1
  \]

- **Internal overpressure**
  \[
  \left[ \gamma_m \gamma_{SC, LB} \frac{|M_{Sd}|}{\alpha_c M_p (t_2)} + \left( \gamma_m \gamma_{SC, LB} \frac{S_{Sd}}{\alpha_c S_p (t_2)} \right)^2 \right] + \left[ \gamma_p \frac{p_i - p_e}{\alpha_c p_b (t_2)} \right]^2 \leq 1
  \]

Applicability range in previous design-code revisions bounded to \( 15 \leq D/t \leq 45 \).

- Lower-bound limit has been removed by DNV based on EPRG’s work
### Definitions of cases

<table>
<thead>
<tr>
<th></th>
<th>Case 0</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Export</td>
<td>Flowline</td>
<td>Gathering</td>
<td>Trunkline</td>
</tr>
<tr>
<td><strong>Material grade</strong></td>
<td>DNV GL SAWL 450</td>
<td>DNV GL SMLS 450</td>
<td>DNV GL SMLS 450</td>
<td>DNV GL SAWL 450</td>
</tr>
<tr>
<td><strong>Outer diameter</strong></td>
<td>32 inch (812.8 mm)</td>
<td>6 5/8 inch (168.3 mm)</td>
<td>16 inch (406.4 mm)</td>
<td>24 inch (609.6 mm)</td>
</tr>
<tr>
<td><strong>Wall thickness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- External-pressure design</td>
<td>39.0 mm</td>
<td>12.9 mm</td>
<td>35.6 mm</td>
<td>42.0 mm</td>
</tr>
<tr>
<td>- Internal-pressure design</td>
<td></td>
<td>21.1 mm</td>
<td>36.6 mm</td>
<td></td>
</tr>
<tr>
<td><strong>D/t</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- External-pressure design</td>
<td>20.8</td>
<td>13.0</td>
<td>11.4</td>
<td>14.5</td>
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Accuracy of current design formulations

External overpressure

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![Graph showing bending moment vs. external pressure for different cases with D/t values and normalised moment vs. normalised external pressure with FEA and LCC data points.]
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Accuracy of current design formulations

Internal overpressure

![Graph showing bending moment vs internal pressure for different cases.](graph.png)
Design equation for collapse compared with FEA results (for cold-formed pipe with no recovery of Bauschinger effect)

- $D/t \leq 15$
  - (Overly) conservative
- $15 < D/t \leq 30–40$
  - Nonconservative
- $D/t > 30–40$
  - Good agreement
Improved formulation for collapse

Transcendental equation to be solved for collapse pressure $p_c$

\[
[p_{bif}(p_c) - p_c] (p_p^2 - p_c^2) = p_c p_{bif}(p_c) p_p \frac{D}{t} O_0 \psi \sqrt{1 - \frac{1}{4} \left(\frac{p_c}{p_p}\right)^2}
\]

Triaxiality factor

\[
\psi = \frac{2}{\sqrt{3}} \frac{D-t}{D-2t}
\]

Plastic collapse pressure

\[
p_p = \frac{2 t \sigma_y}{D} \psi
\]

Bifurcation pressure

\[
p_{bif}(p_e) = \frac{2E_t (\sigma_{eqv}(p_e))}{1 - \nu^2} \left(\frac{t}{D}\right)^3
\]

Equivalent stress

\[
\sigma_{eqv}(p_e) = \frac{p_e D}{2t} \frac{1}{\psi}
\]
• **Material conditions**
  
  • **As-fabricated:** cold-formed pipe, yield stress reduced by 15% ($\alpha_{\text{fab}} = 0.85$)
  
  • **Heat-treated:** cold-formed pipe, after coating or (light) heat treatment
  
  • **Elastic-perfectly plastic:** typical for virgin steel, representative of seamless pipe
Accuracy of improved collapse-pressure formulation

Proposed (right) analytical prediction much closer to finite-element results than current (left)
Using proposed collapse-pressure formulation in LCC leads to much better prediction
Conclusions

• Current collapse-pressure formulation conservative for $D/t < 15$
  • Lower-bound applicability limit of LCC criterion for external overpressure ($D/t > 15$) is unnecessary

• Predictive accuracy LCC criterion (internal overpressure) independent of $D/t$
  • Lower-bound applicability limit of LCC criterion for internal overpressure ($D/t > 15$) is unnecessary too

• DNV has removed this limit in DNV-ST-F101 (2021) and acknowledged EPRG’s work

• To reduce conservatism in external-pressure design, framework for predicting collapse pressure of thick-walled pipe has been improved
  • Based on fundamental mechanisms underlying collapse (geometrical instability and material yielding)

• Proposed improvement of collapse-pressure formulation leads to cascading improvement of current LCC equation for external overpressure
Recommendations

• FEA results have been used to benchmark analytical results. Recommended to confirm results using medium- or full-scale tests
  • Especially for very low $D/t$, for which not much testing has been done
• Influence of effective axial force has been ignored. Recommended to investigate this effect
• When adopting new design formulations, associated safety factors should be recalibrated
Thank you for your attention.