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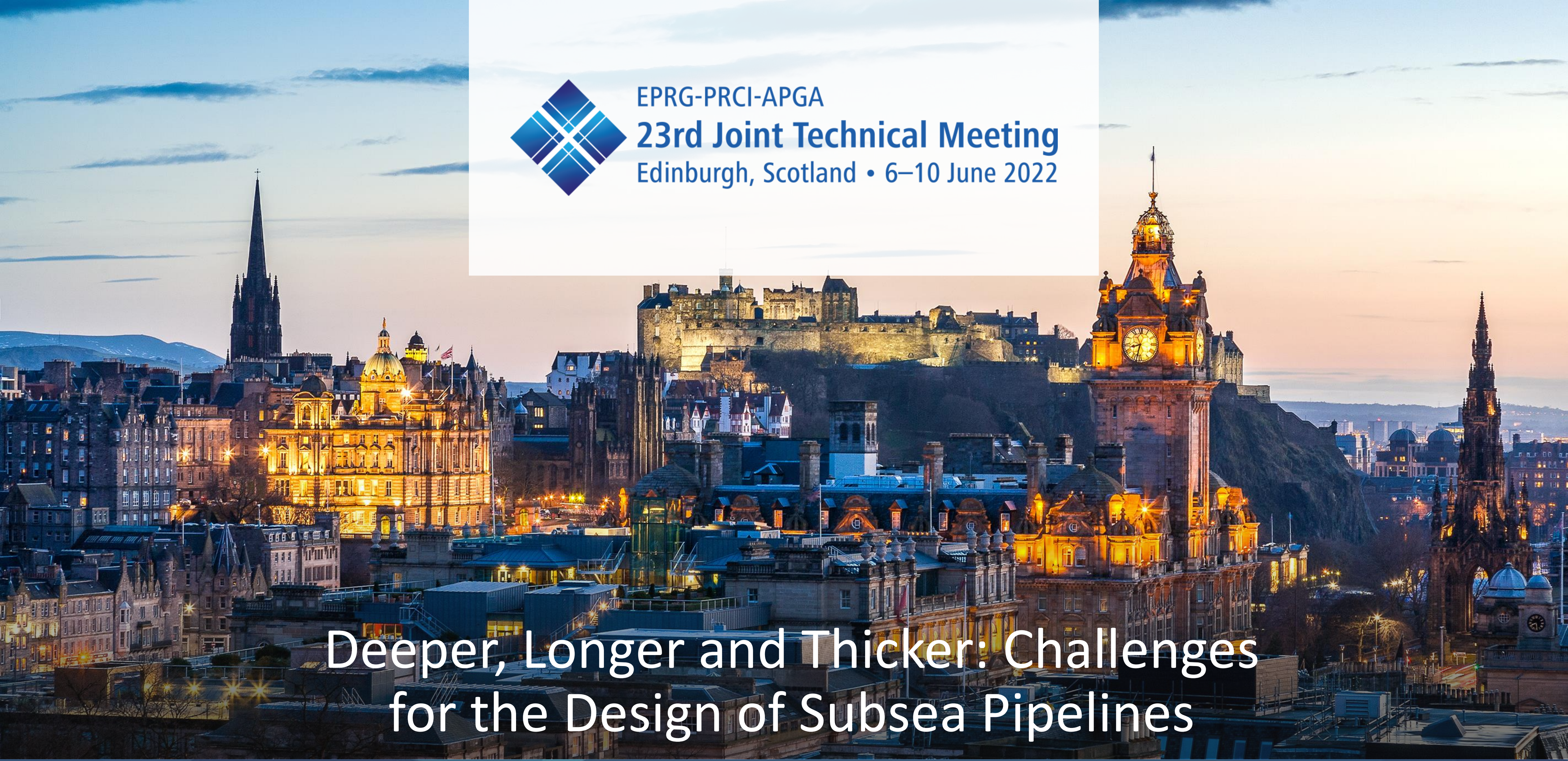


Deeper, Longer and Thicker: Challenges for the Design of Subsea Pipelines

9 June 2022

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)

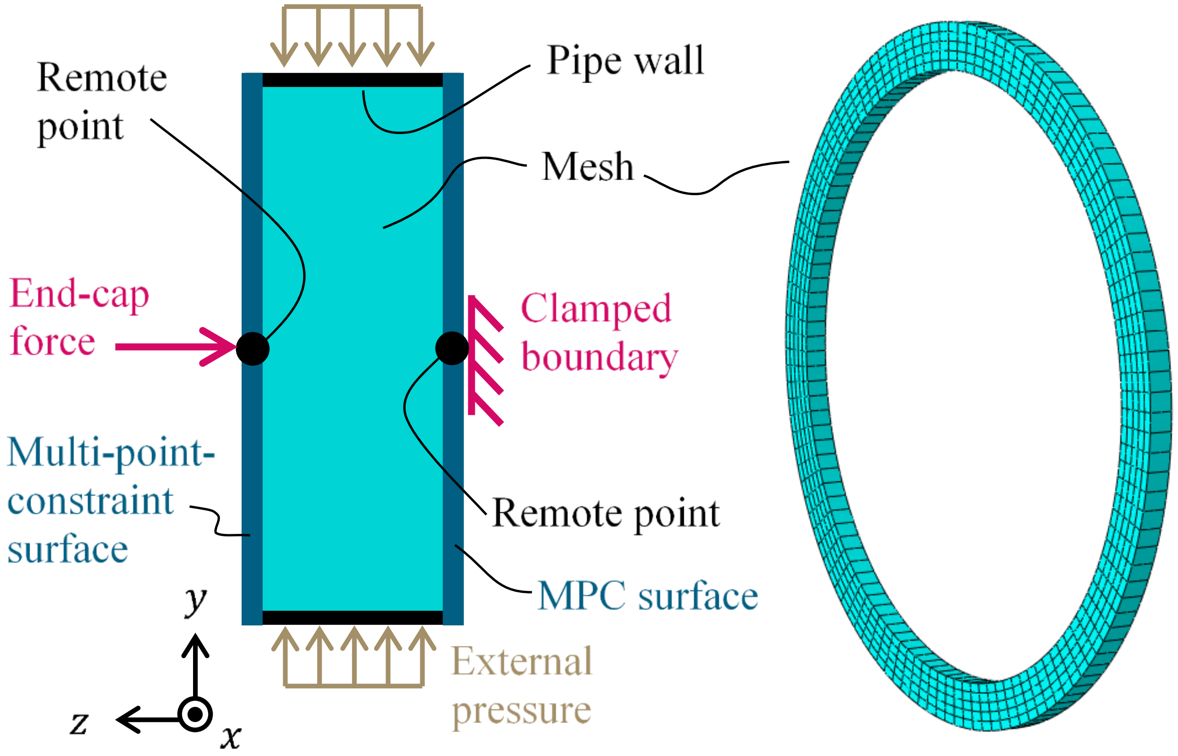
Gap analysis and questionnaire results

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

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

- Internal overpressure

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

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

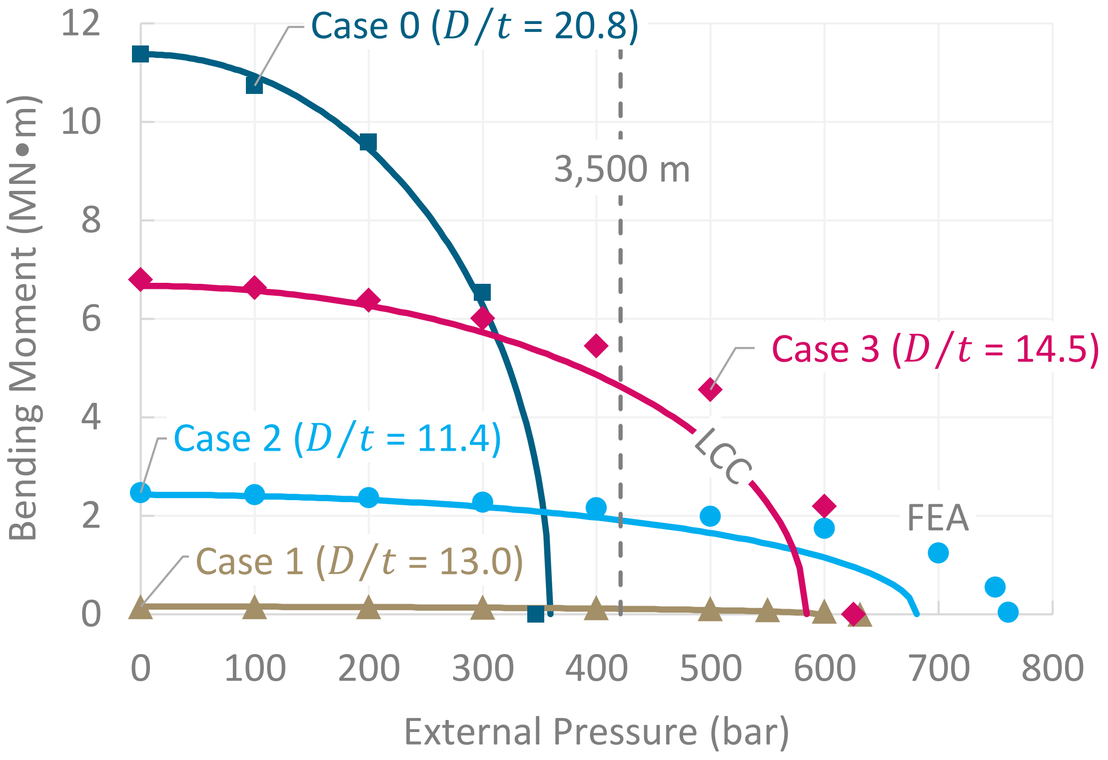
- Lower-bound limit has been removed by DNV based on EPRG's work

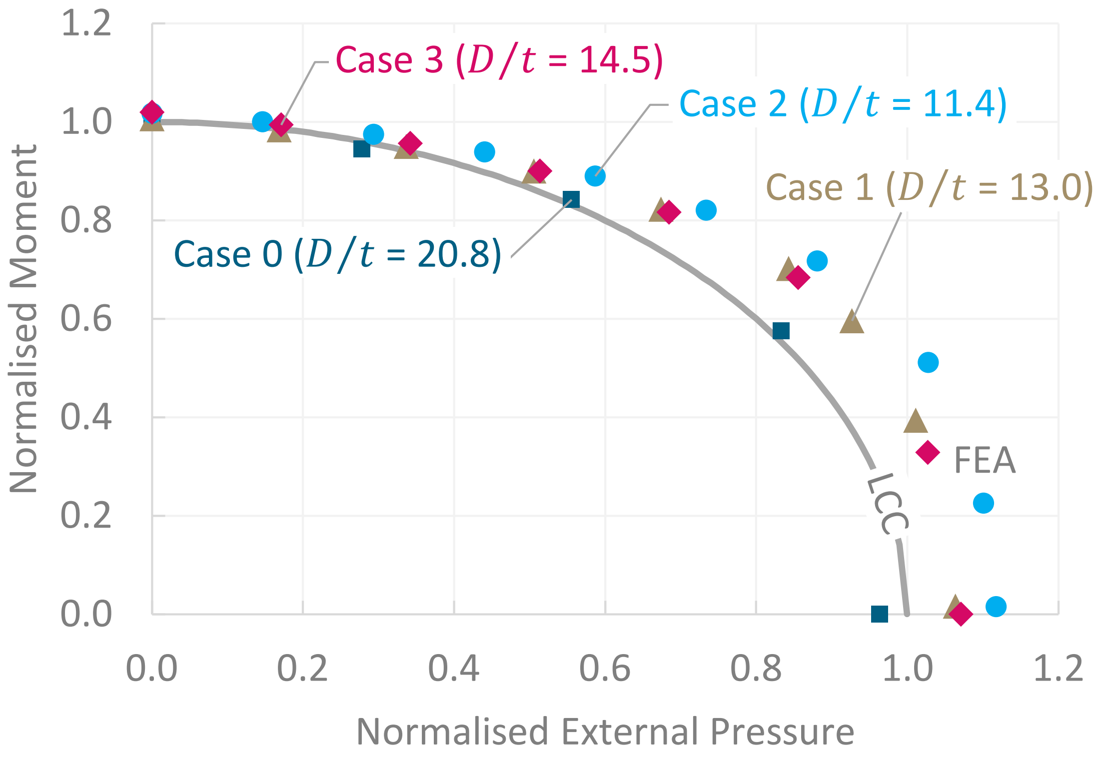
Definitions of cases

	Case 0	Case 1	Case 2	Case 3
Type	Export	Flowline	Gathering	Trunkline
Material grade	DNV GL SAWL 450	DNV GL SMLS 450	DNV GL SMLS 450	DNV GL SAWL 450
Outer diameter	32 inch (812.8 mm)	6 5/8 inch (168.3 mm)	16 inch (406.4 mm)	24 inch (609.6 mm)
Wall thickness - External-pressure design - Internal-pressure design	39.0 mm	12.9 mm 21.1 mm	35.6 mm 36.6 mm	42.0 mm
D/t - External-pressure design - Internal-pressure design	20.8	13.0 8.0	11.4 11.1	14.5

Accuracy of current design formulations

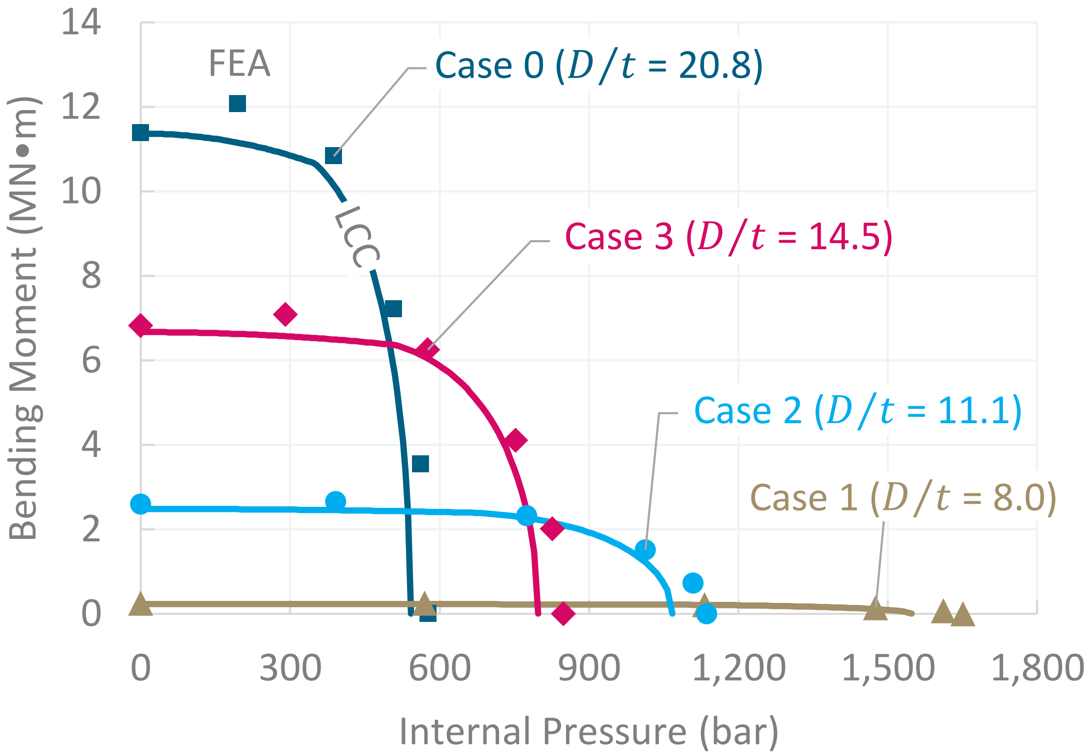
External overpressure

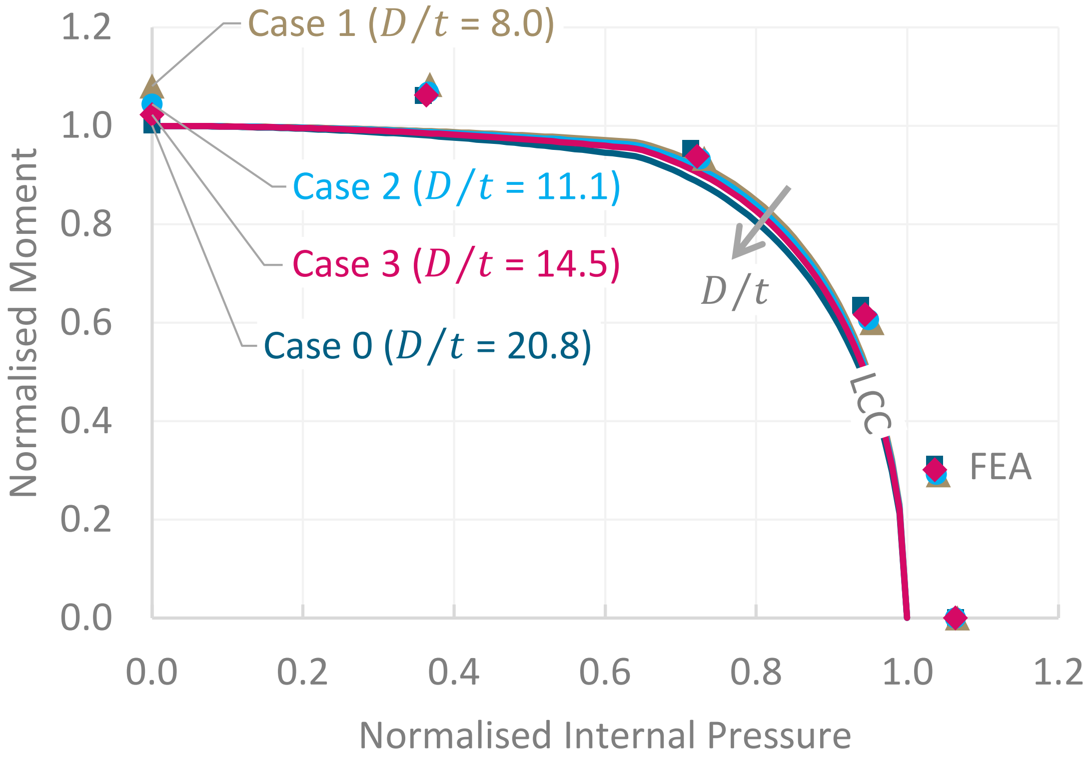




Accuracy of current design formulations

Internal overpressure

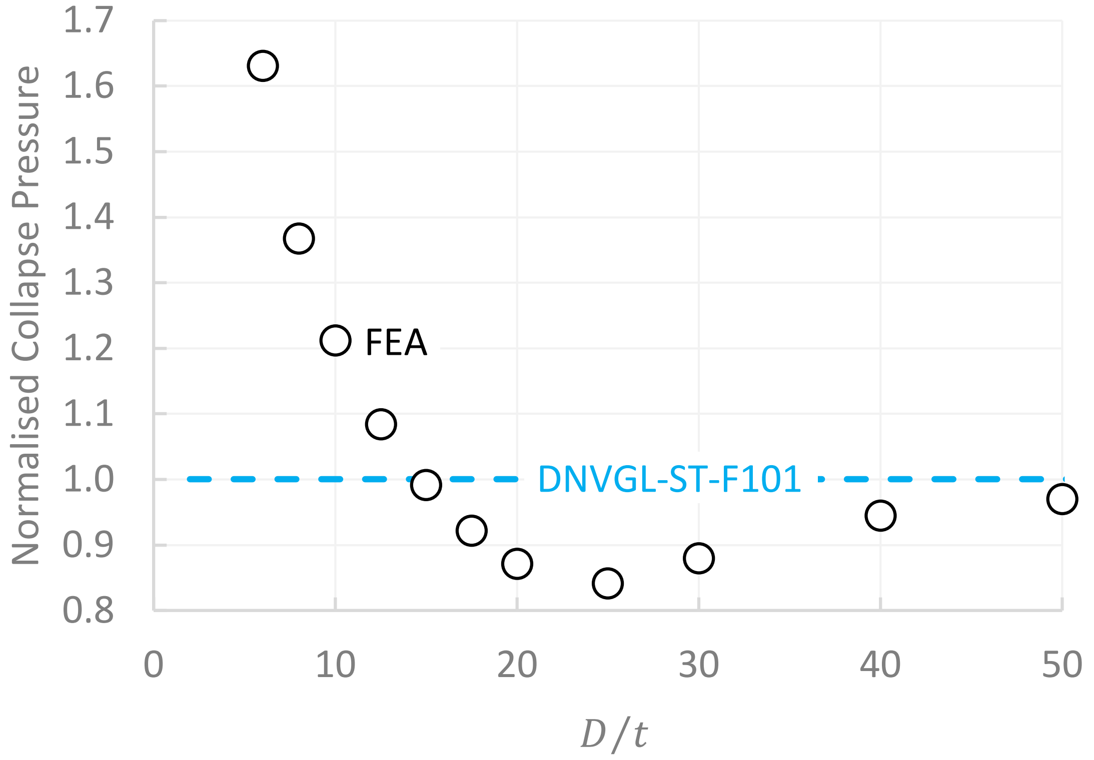




Accuracy of current design formulations

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

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

Triaxiality factor $\psi = \frac{2}{\sqrt{3}} \frac{D-t}{D-2t}$

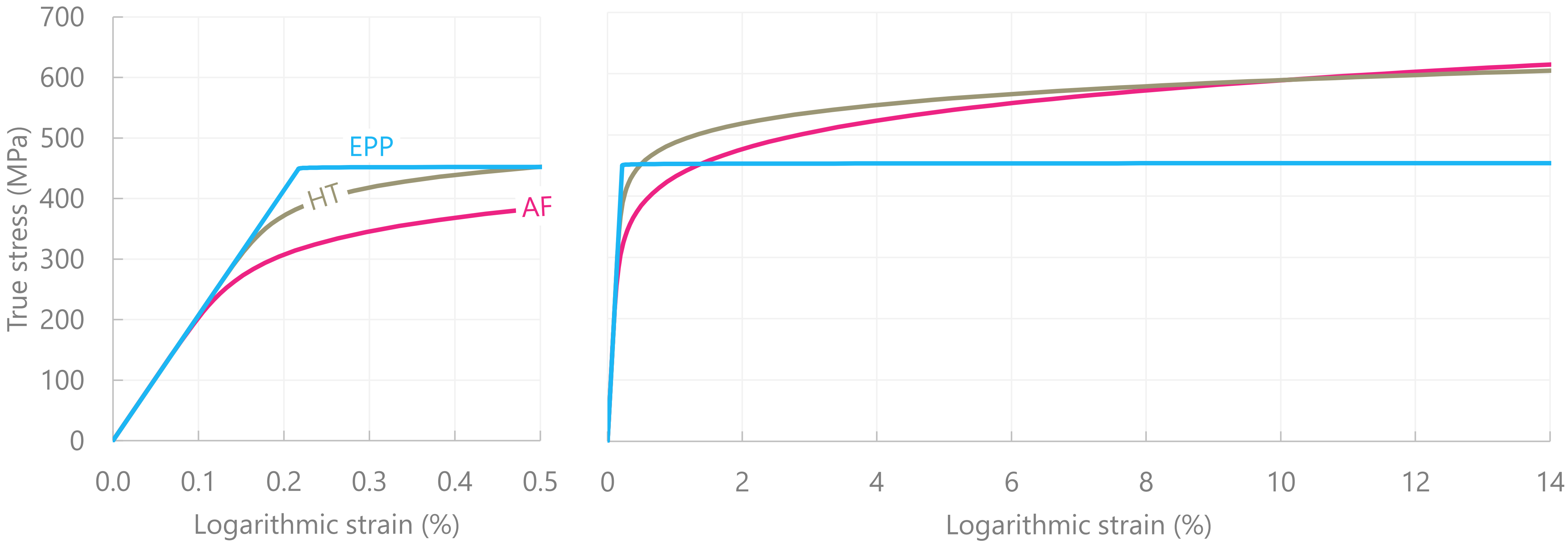
Plastic collapse pressure $p_\mathrm{p} = \frac{2\, t\, \sigma_\mathrm{y}}{D} \psi$

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

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

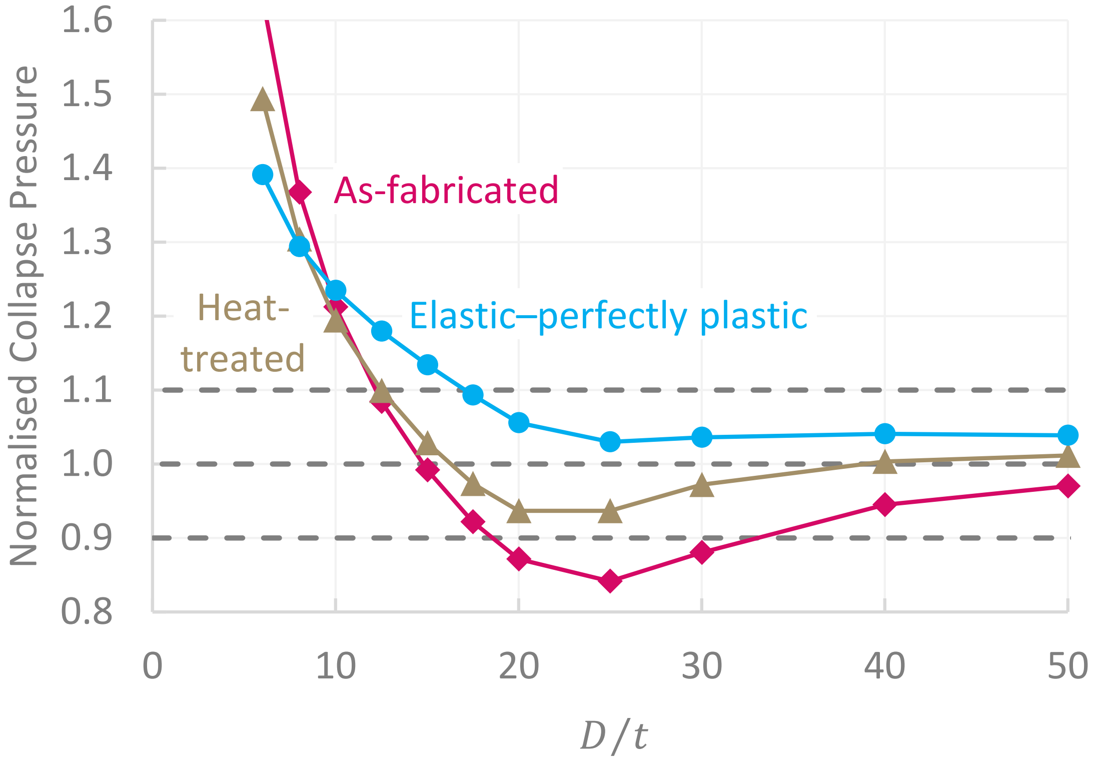
Stress-strain curves (DNV 450)

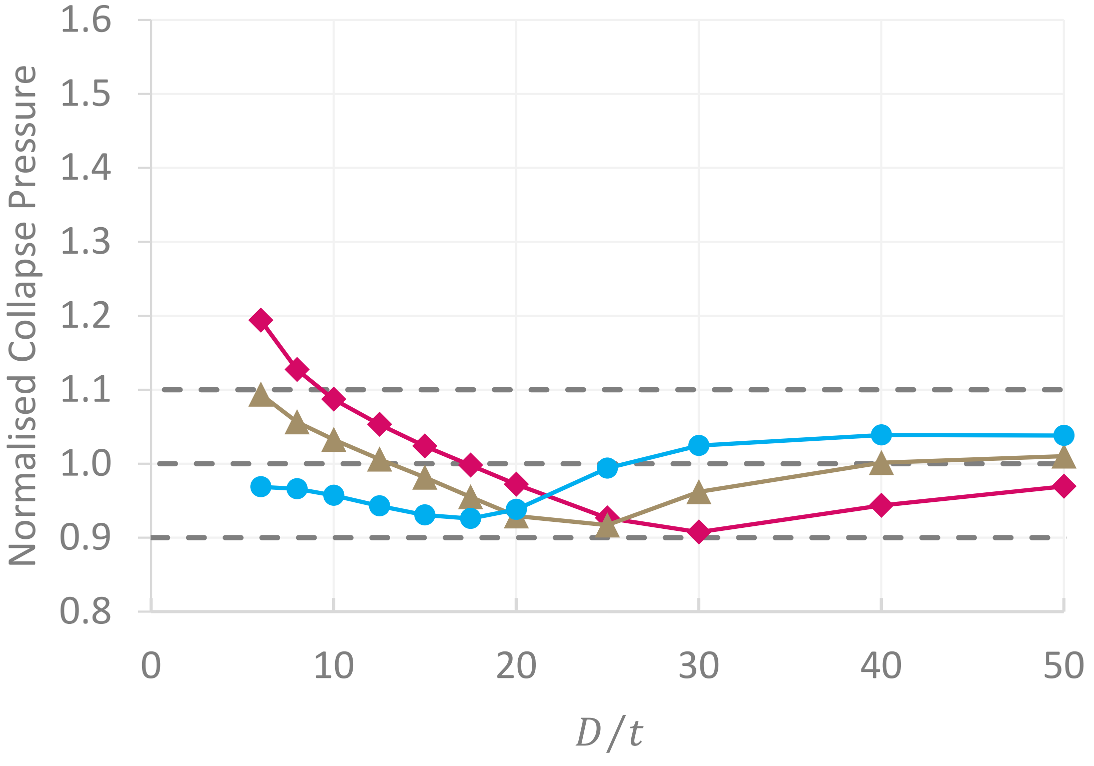
- Material conditions
  - As-fabricated: cold-formed pipe, yield stress reduced by 15% (α_{fab} = 0.85)
  - Heat-treated: cold-formed pipe, after coating or (light) heat treatment
  - Elastic-perfectly plastic: typical for virgin steel, representative of seamless pipe



Accuracy of improved collapse-pressure formulation

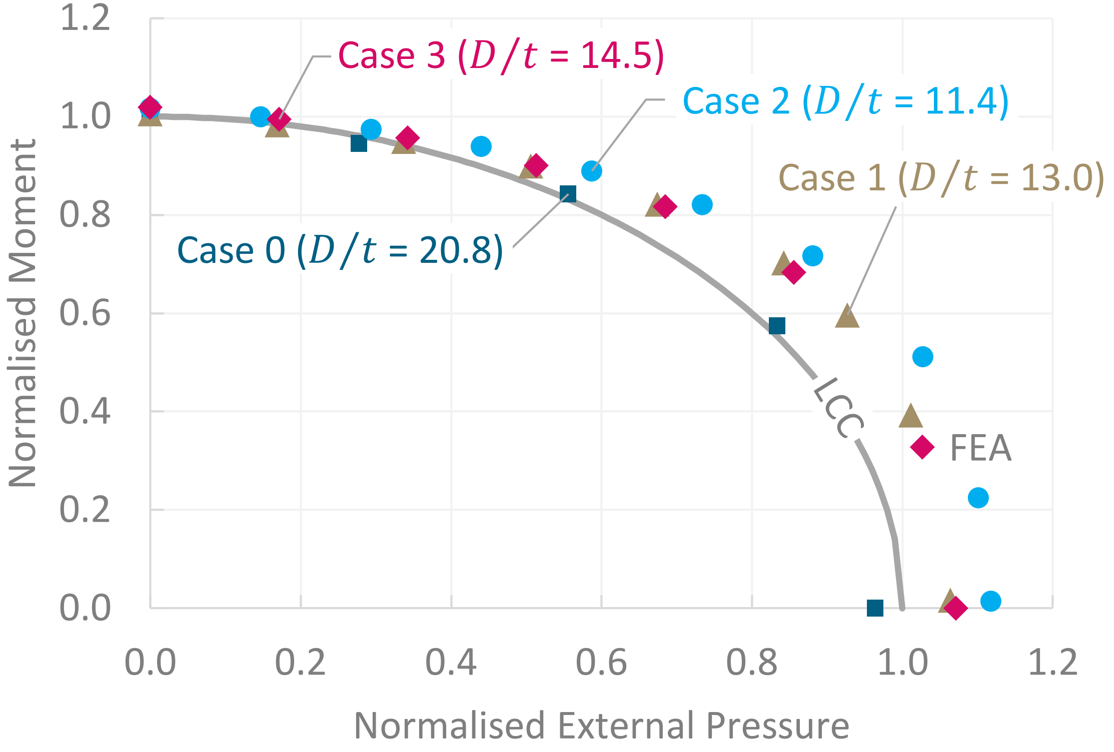
Proposed (right) analytical prediction much closer to finite-element results than current (left)

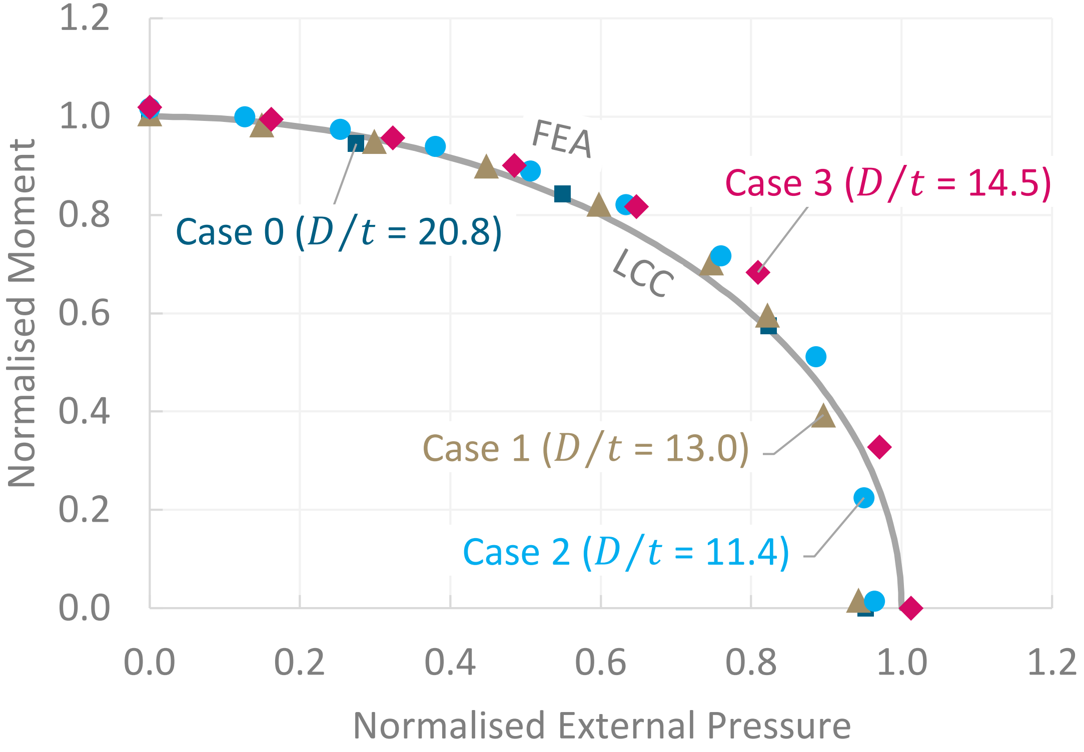




Current v proposed

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.