Methods for calculating Fatigue Stresses in Flexible Pipes – An Overview

by

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- Some historical perspectives
- Lifetime prediction
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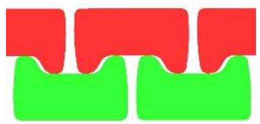
Structural components

Carcass

Liner

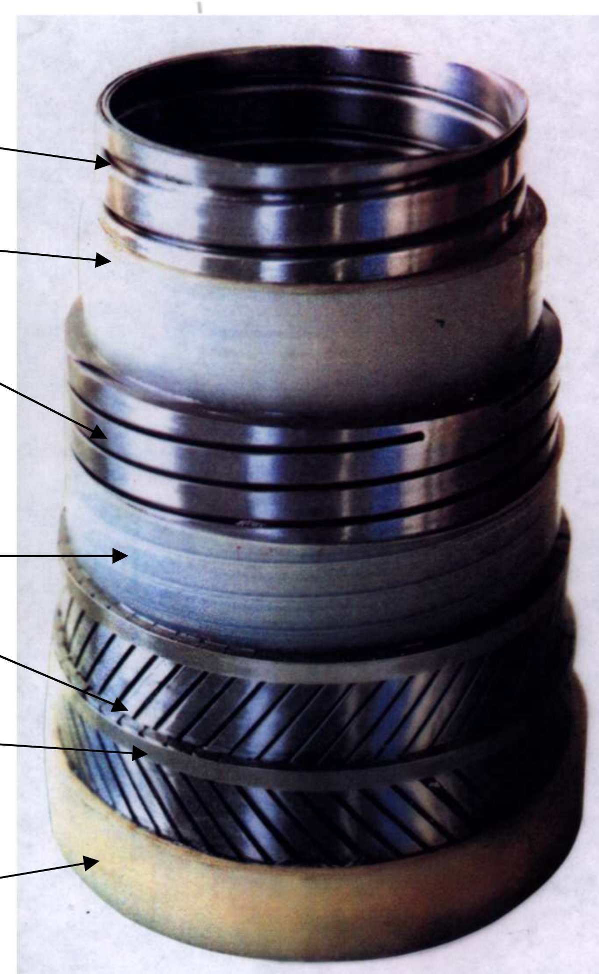
Pressure spiral profile:



Anti-wear

Tensile armor profile:

Outer sheath



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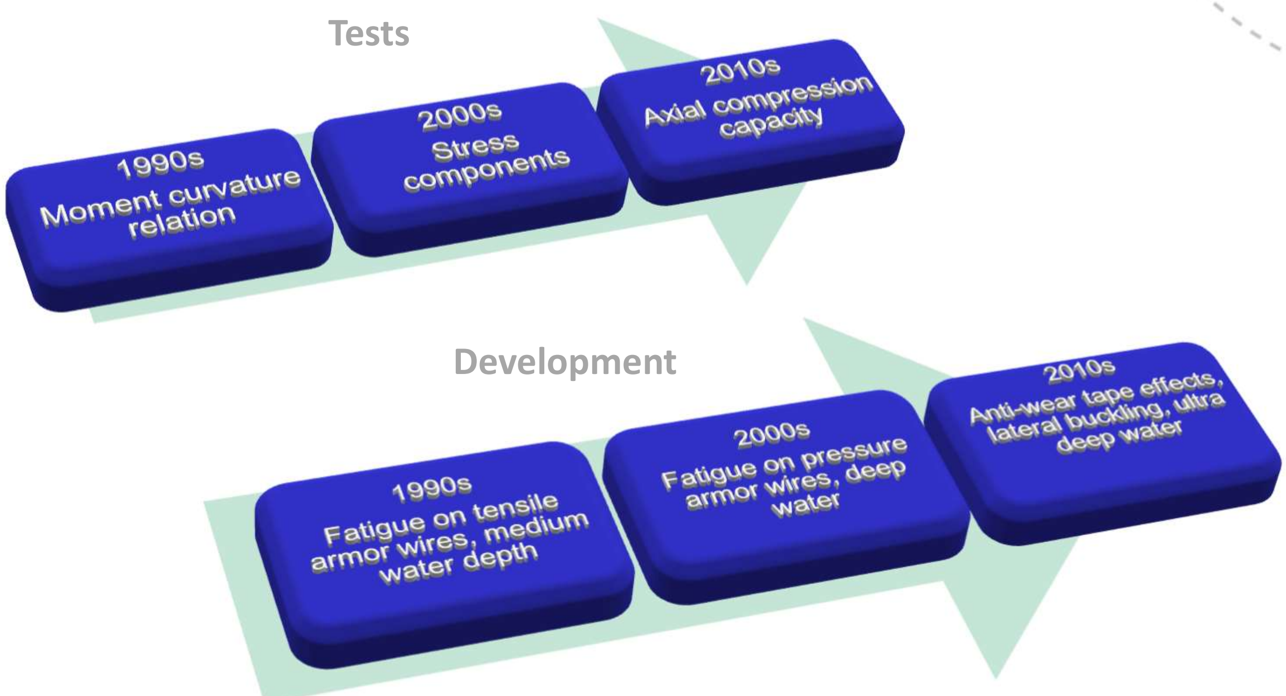
Some historical perspectives



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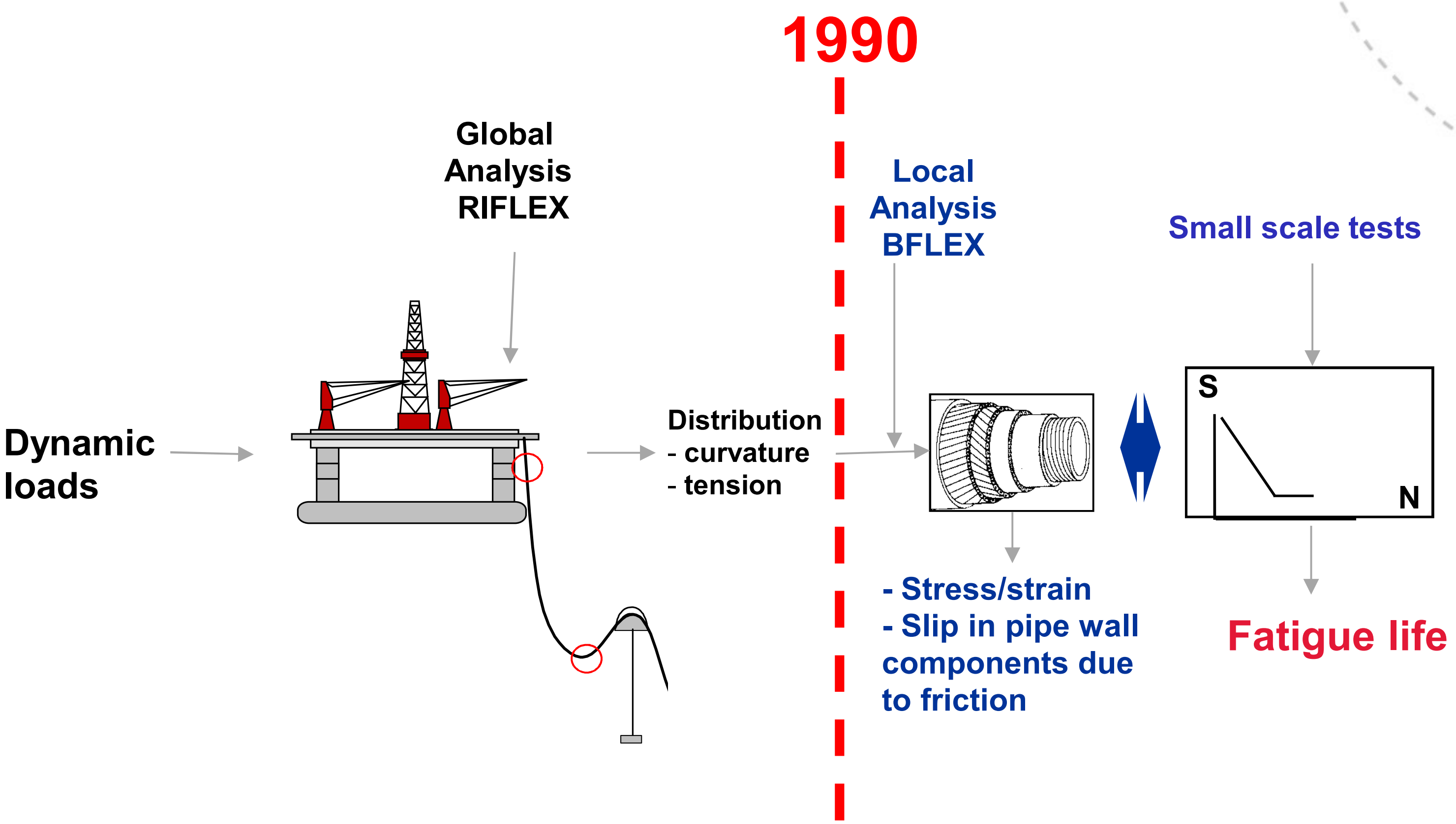
Lifetime prediction



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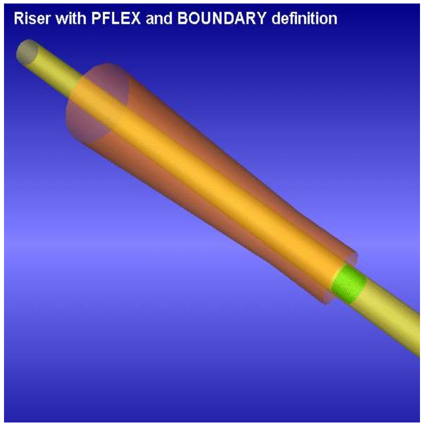
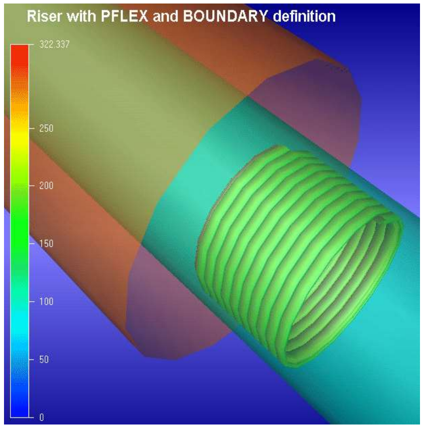
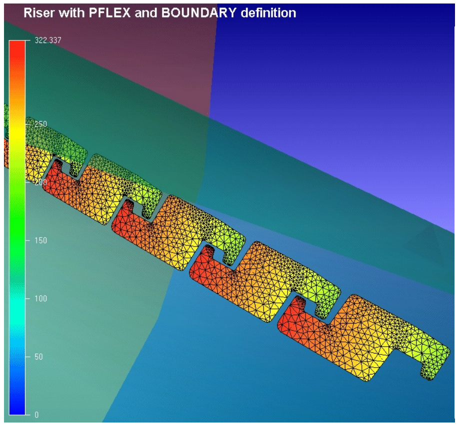
The Bflex FE Program (1996->)



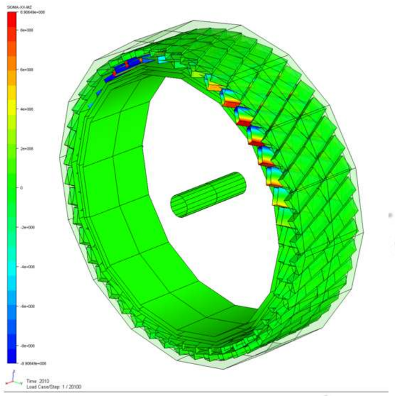
Global BFLEX model



Local PFLEX model



Local BOUNDARY model



RUC model

- 3D non-linear static and dynamic stress & fatigue analysis of helical structures (SINTEF Ocean)
  - A variety of special purpose finite structural and contact elements
  - Curved beam and line contact
  - Several friction formulations
- Developed in 2019 to also include lateral buckling with in-layer contact (RUC model above)

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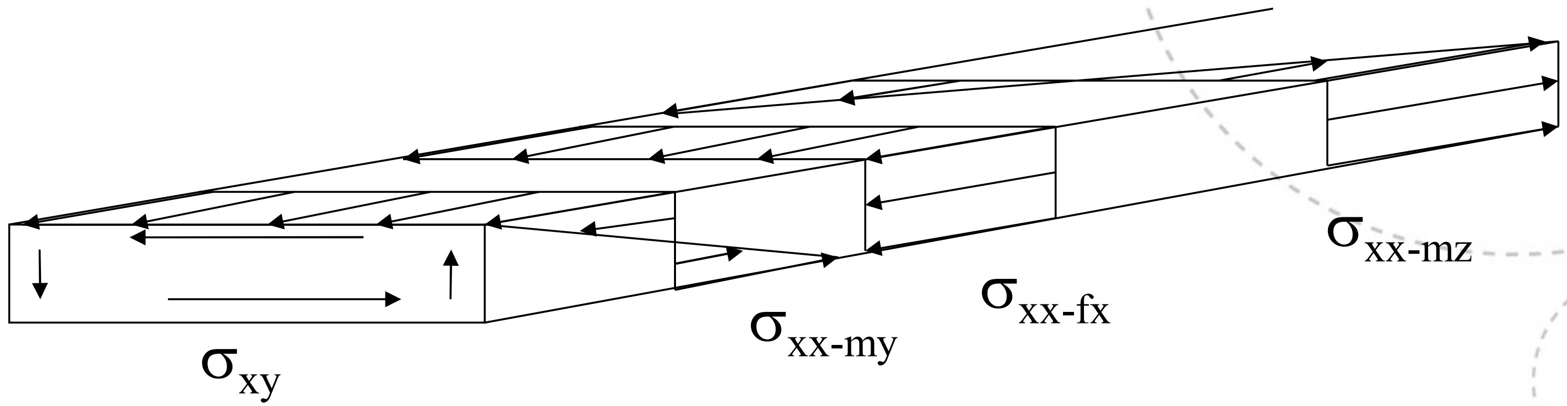
Governing stress components:



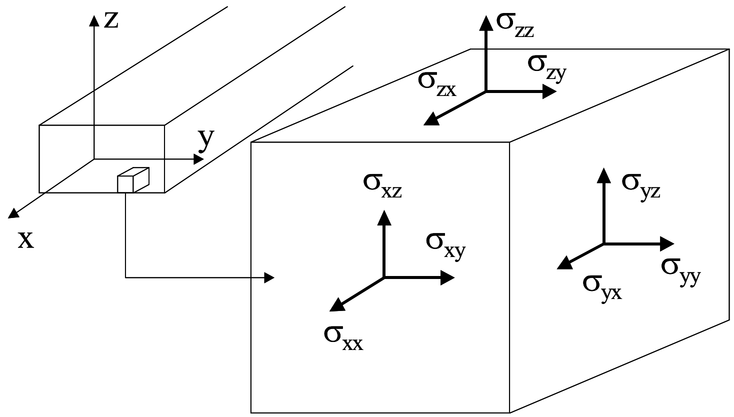
$\sigma_{xx\text{-}fx}$ is the *axial stress* which is constant over the entire cross-section and is a result of the F_x axial force from the pressure (hoop and end-cap effects), the riser tension and torsion moment *and for the tensile armour also due to friction.*

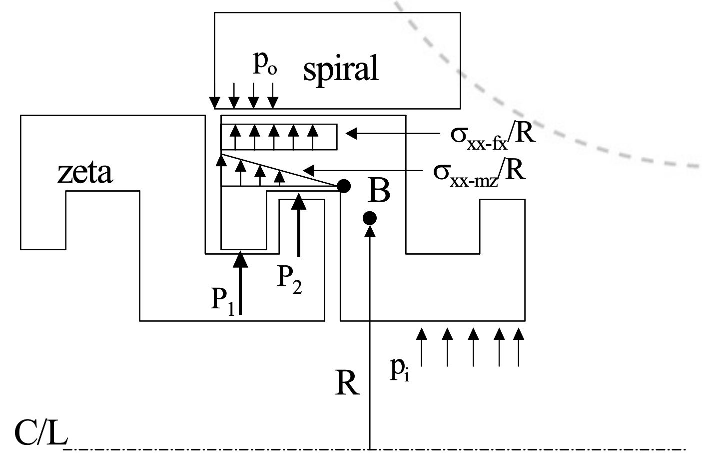
$\sigma_{xx\text{-}my}$ is the *normal curvature stress* which has its maximum at the outer and inner surface of the armour tendon at the tensile/compressive side of the riser and is a result of the M_y bending moment introduced primarily due to riser bending, *for the pressure armour also due to bending stiffener reaction forces*.

$\sigma_{xx\text{-}mz}$ is the *transverse curvature stress* which has its maximum at the sides of the armour tendon at the neutral axis of the riser and is a result of the Mz bending moment introduced by global riser bending *and in the Zeta case also due to the rotation of the cross-section due to internal pressure.*

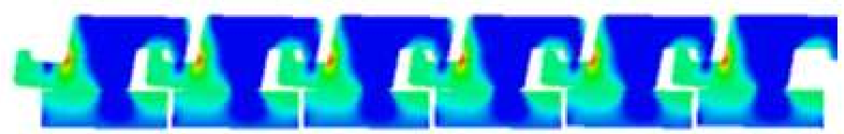
σ_{xy} is the *torsion stress* due to bending (normally small)

Additional stress components of pressure armours:





- σ_{yy}, σ_{zz} and σ_{yz} stresses will occur in addition to σ_{xx}
- Not important for static loads
- Governing for dynamic loads and fatigue in pressure armour
- Both longitudinal and transverse crack growth need to be checked



Alternative modelling approaches

- Global analysis by either using:
  - Standard linear elastic beam elements applying the sliding bending stiffness
  - Resultant based beam elements that capture the hysteresis (curves describing moment-curvature, tension-axial strain, torque – torsion obtained from e.g. BFLEX and based on a 2D assumption)
- Output to local stress and fatigue analysis in the form of either:
  - Time series of tension and curvature for cases where the exposed (loaded) section is long away from end fitting
  - Time series of tension and angles for cases where the exposed (loaded) section is close to end fitting

Alternative modelling approaches - tensile armours

- By assuming that the cross-section is long away from end-fittings:
  - The stress will only be a function of the angular position of the material point
  - Then it is possible to apply the 2D assumption for the local stress model:
    - Converting the global model time series in terms of tension and curvature directly into time series of stress
    - Perform fatigue calculations
- In the opposite case, 3D models are required to capture the end (BC) effect:
  - By a beam or shell element modelling approach. Both approaches require a spring (penalty) formulation for friction.
  - By full 3D modelling with brick elements. This enables the use of «exact» contact and friction formulations by a Lagrange multiplier approach.
  - Input from global analysis in terms of tension and end angle time series.

2D stress models

Traditional approach for tensile armour:

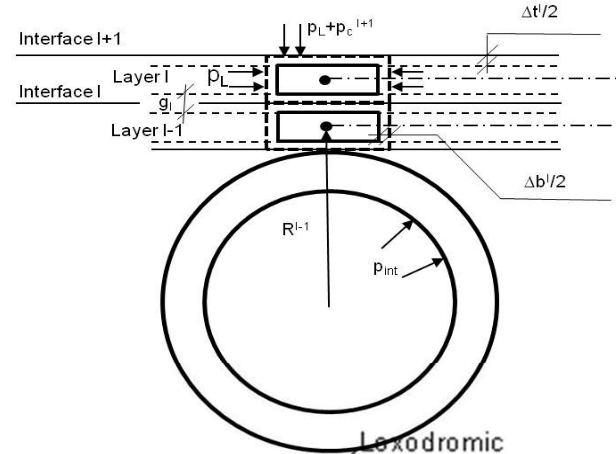
- Axisymmetric stress (tension,pressure, torque) first established from concentric layer models:
  - Simplified geometry description - concentric layers
  - 3D Hooke's law
  - «Exact» contact by Lagrange multipliers
  - Curved beam + thin shell/thick shell
  - E.g. Caflex (1989), Bflex(1996), Helica(2012)
- Bending fatigue stresses in tensile armour:
  - The elastic bending terms are obtained from differential geometry assuming loxodromic/geodesic curves
  - The friction stress is found by adding up friction shear line load over a quarter pitch
- Moment-curvature relation from 2D approach

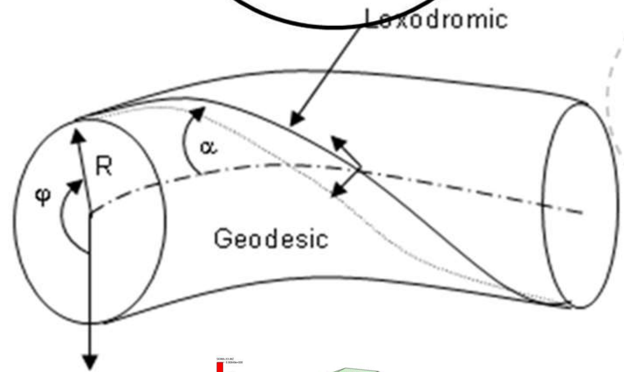
Alternative approach for tensile armour by RUC modelling:

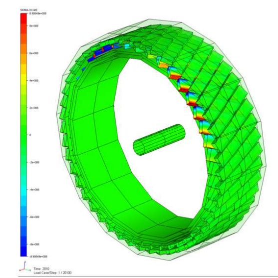
- Axisymmetric and bending stresses are treated simultaneously
- No curve assumptions needed
- The effect og sliding on friction stresses captured

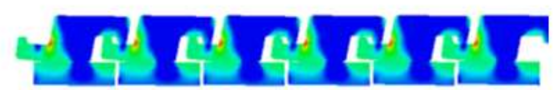
Bending fatigue stresses in pressure armour is treated by separate models:

- In BFLEX pressure armour stresses are obtained by combing curved beam elements with BEM





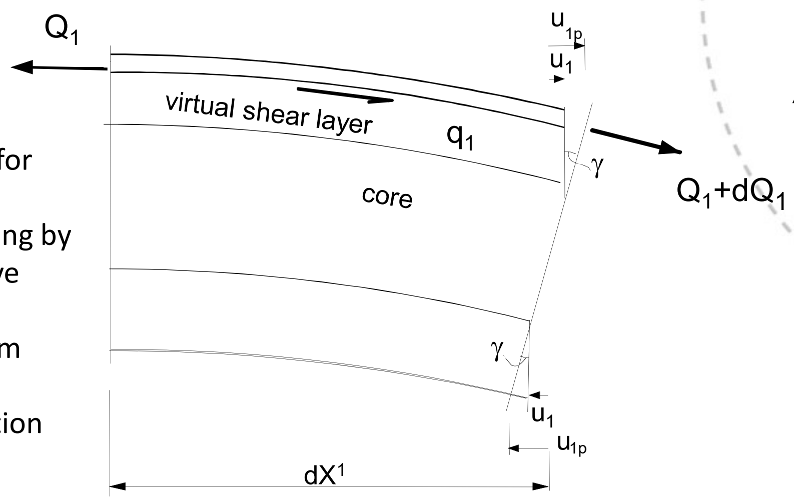




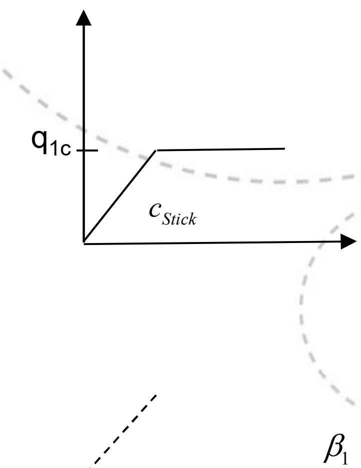
3D stress models for tensile armour

Sandwich beam FE (e.g. Bflex)

- Curved beam elements
- Smooth surface penalty contact to account for radial flexibility
- Axial friction stress is solved with full coupling by means of the **c**-parameter (s) and the relative displacement between the tendon and the prescribed plane surfaces remain plane beam motion
- **c** can be replaced by **k** to take shear interaction stiffness into account
- Longitudinal end effects can be evaluated

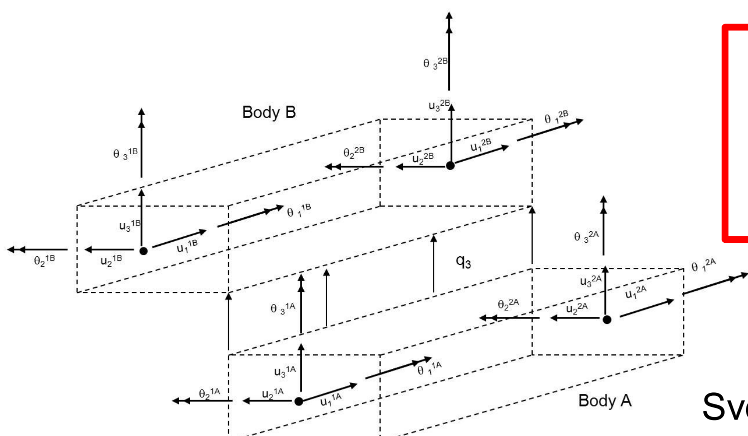


$$\beta_1 = u_1 - u_{1p}$$



$$W_i = \int_0^l EA(\beta_{1,1} + u_{1p,1})\delta(\beta_{1,1} + u_{1p,1}) + GI_t(\omega_1 + \omega_{1p})\delta(\omega_1 + \omega_{1p})$$
$$+ EI_2(\omega_2 + \omega_{2p})\delta(\omega_2 + \omega_{2p}) + EI_3(\omega_3 + \omega_{3p})\delta(\omega_3 + \omega_{3p})dX^1$$

$$c_{Stick} = \left(\frac{1}{F_{tol}} - 1\right)\frac{EA\sin^2\alpha}{R^2}$$



$$\Delta\pi = -\int_{S_c}(q_3 + \Delta q_3)\cdot u_3 ds - \frac{1}{2c_n}\int_{S_c}\Delta q_3^2 ds$$
$$-\int_{S_c} q_t \cdot \Delta\beta ds - \frac{1}{2}\int_{S_c}\Delta q_t \cdot \Delta\beta ds$$

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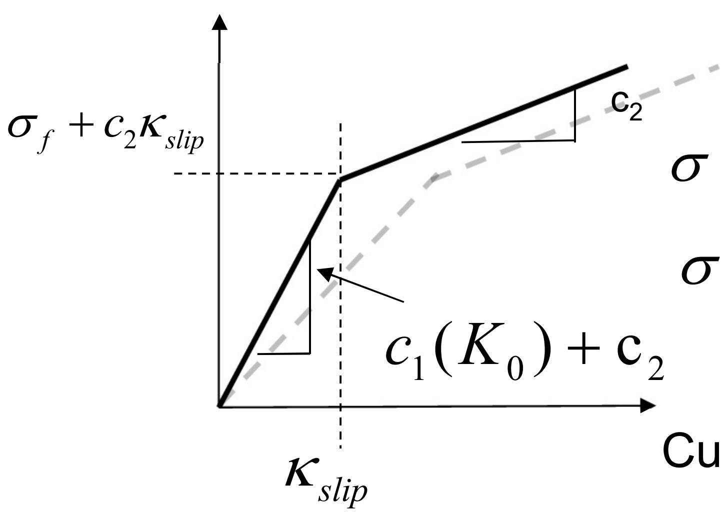
General 3D FE models

- Brick/shell elements
- Arbitrary BC & geometries
- Extensive material libraries
- Exact surface-surface contact & friction by Lagrange mutipliers
- Time consuming due to the aspect ratio requirements limiting element size

Tensile armor shear interaction effects

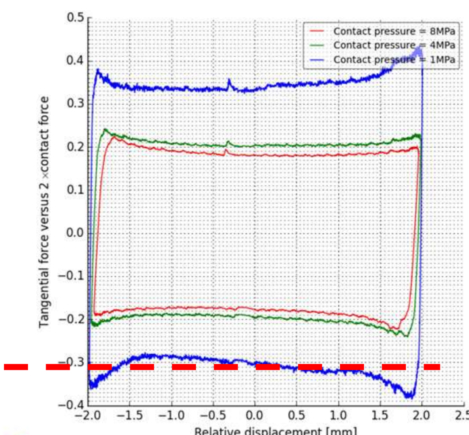
- Stress variation at an arbitrary point in tensile armor



$$\sigma = c_1(K_0)\cdot\kappa + c_2\cdot\kappa \quad for \quad \kappa \le \kappa_{slip}(\mu, p_c)$$

$$\sigma = \sigma_f(\mu, p_c) + c_2\cdot\kappa \quad for \quad \kappa > \kappa_{slip}(\mu, p_c)$$

- K_0 is a shear stiffness parameter governing the stress in the stick domain
- The friction coefficient (taken as an average value from testing) governs the slip curvature and the friction stress amplitude



Tensile armor shear interaction models - including shear deformations in plastic layers

- Modified slip curvature for moment model:

$$\beta_{2c} = \left[1 + \frac{EA\sin^2\alpha}{kR^2}\right]\frac{\mu(q_3^I + q_3^{I+1})}{EA\cos^2\alpha\sin\alpha}$$

- Sandwich beam model is unaffected:

$$u_{1c} = \frac{\mu(q_3^I + q_3^{I+1})}{k}$$

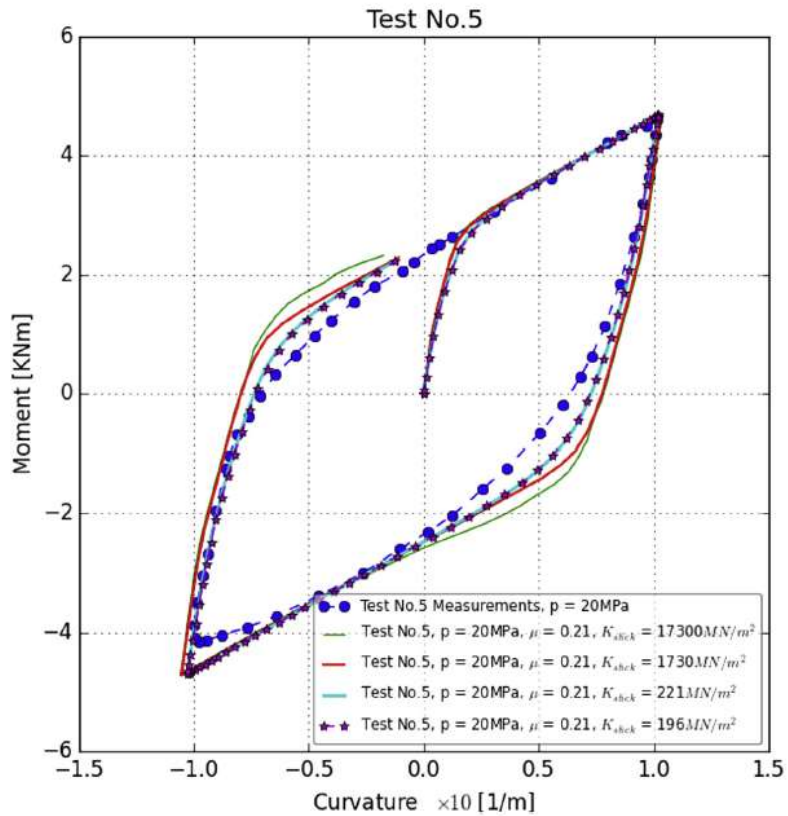
- The shear stiffness parameter

$$k = G\frac{b}{t}$$

Model validation – moment versus curvature from 1990

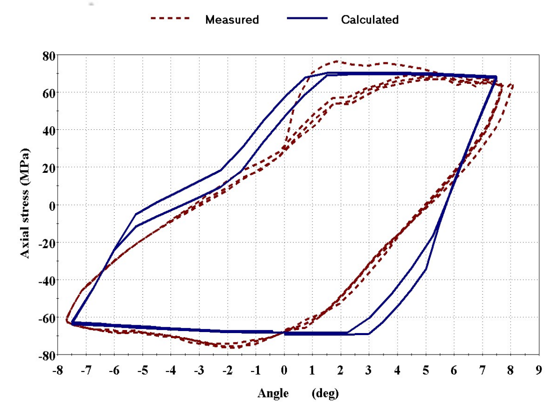
Tuning the shear stiffness parameter and evaluation of friction coefficient using sandwich beam model

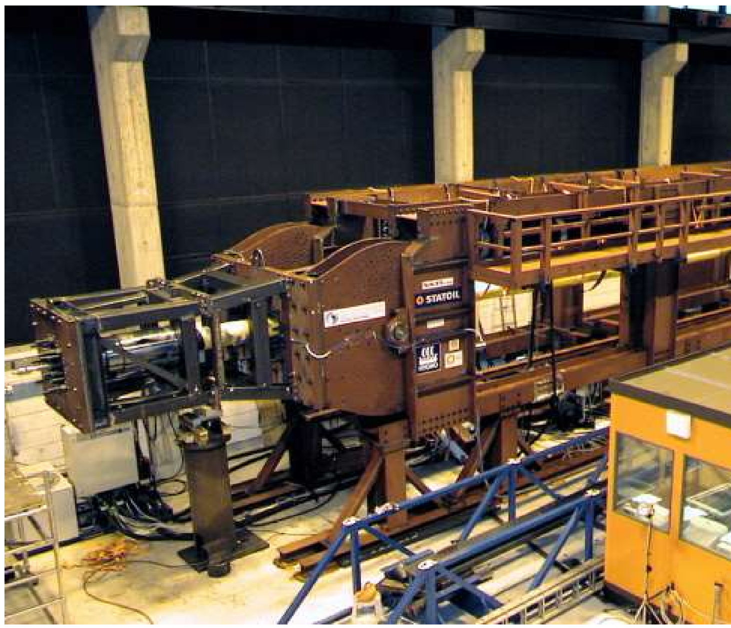
- A shear stiffness parameter K_0=196 MPa was found sufficient to represent the bending moment correctly in the analysis.
- Good correlation with data obtained from small scale testing!
- Best fit friction moment obtained at dynamic friction coeff. 0.21 - good correlation with small scale test!

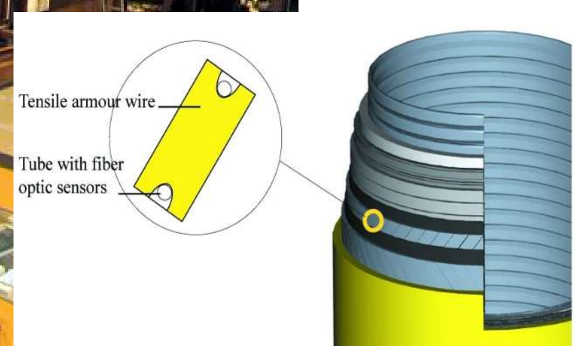


Model validation

- Stress measured by FBG in 2002 (Internal pressure, axial load, bending)
- A lot of failure/no-failure validation points

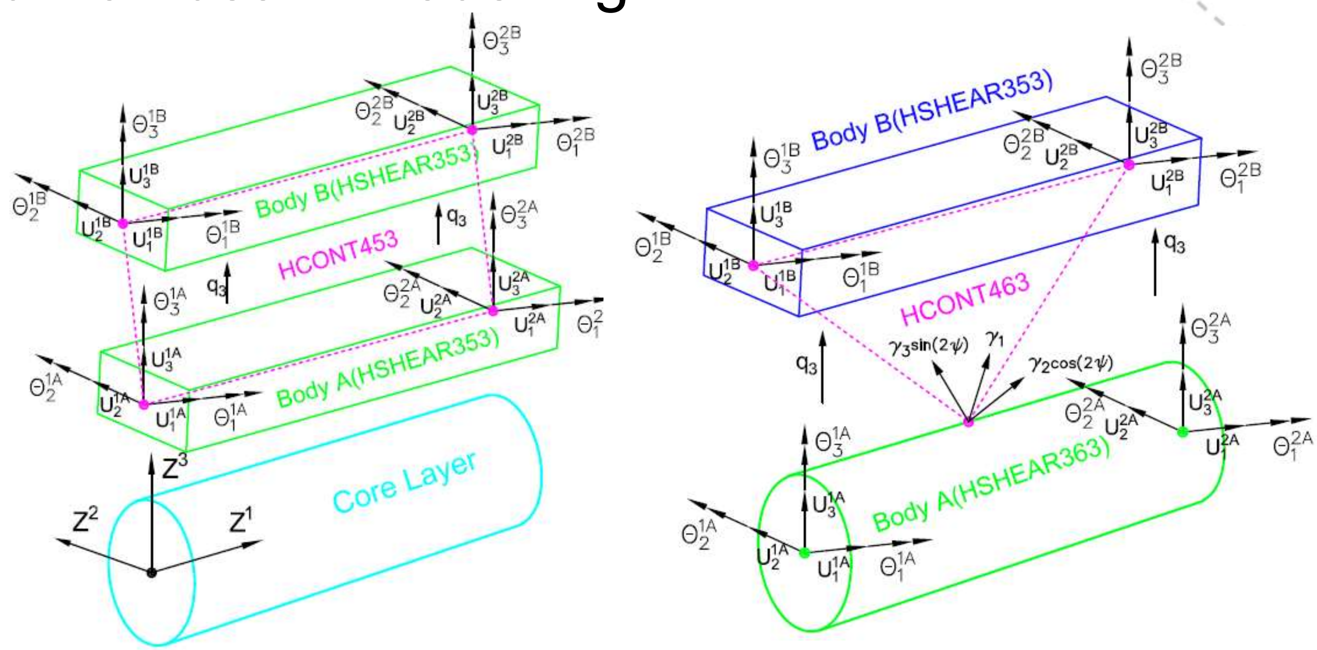






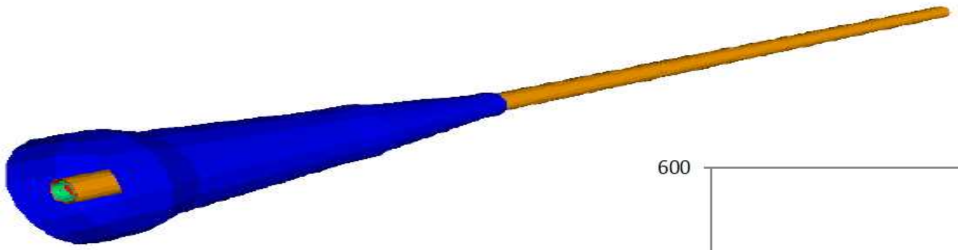
Tensile armor stress amplifaction due to BS being close to end fitting

- Applying resent BFLEX features for sandwich beam modelling:

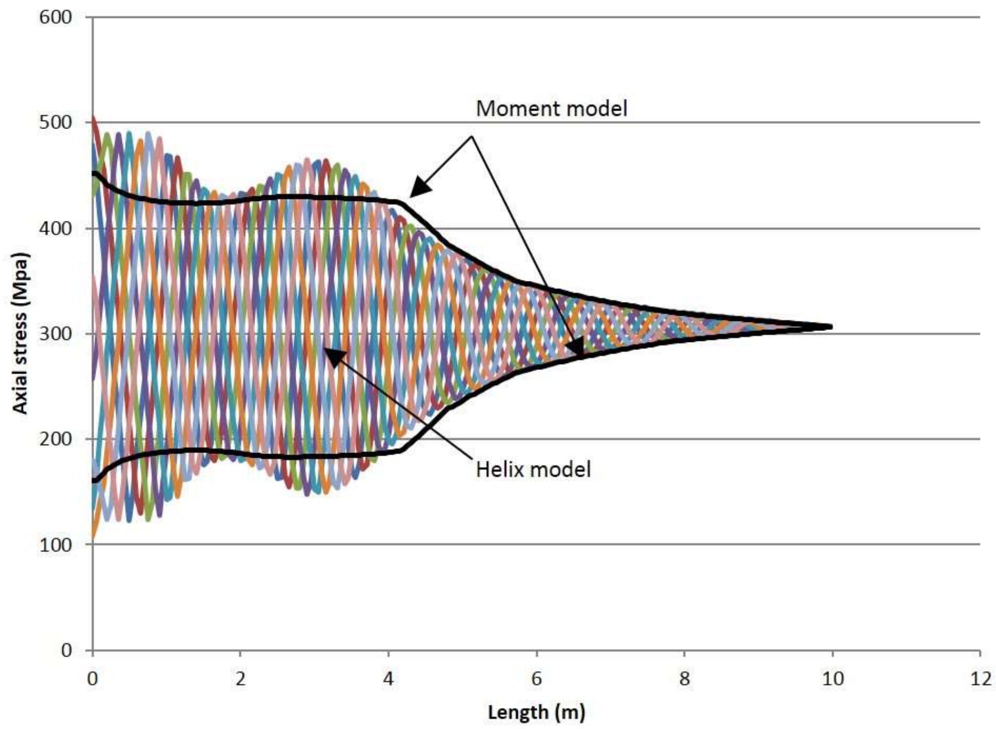


Tensile armor stress amplifaction due to BS being close to end fitting

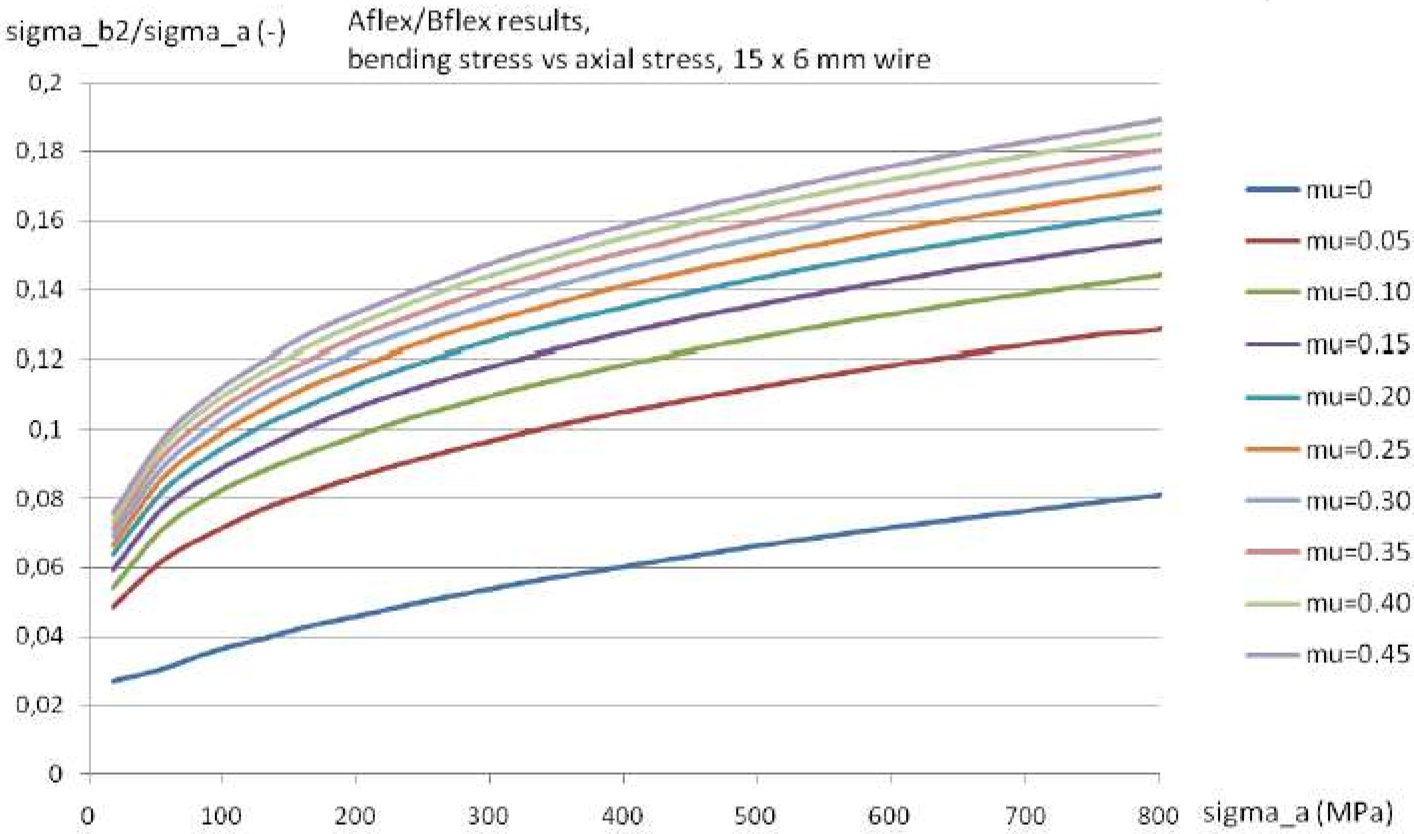
- Bend stiffener



- BFLEX moment and sandwich beam(helix) models results

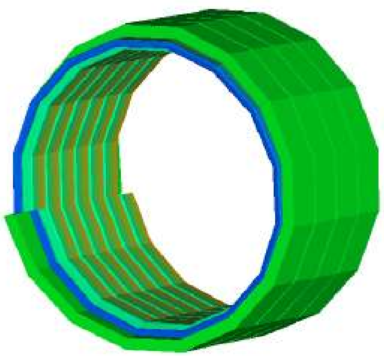


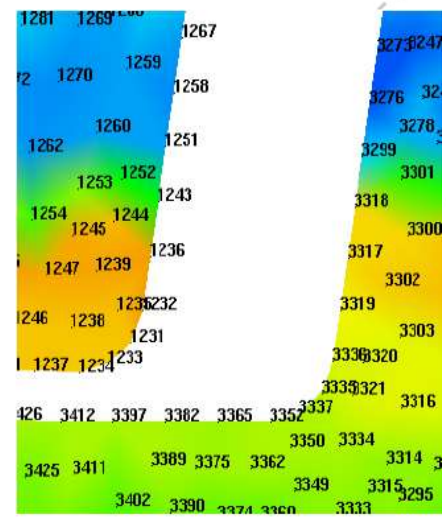
Additional bending stress about tensile armour strong axis at end fitting pipes exposed to dynamic tension



Fatigue stresses in pressure armour

- For low pressure pipes, tensile armor fatigue normally govern
- Both longitudinal and transverse failure modes need to be checked
- Normally governed by longitudinal failure mode due to stresses in the cross-section plane
- Residual stresses in pressure armor wires plays a role in mean stress correction:





Node	Before FAT	After 15000 psi	After 15600 psi	After 17108 psi
3337	335	290	250	195
2791	-375	-250	-235	-200
2774	315	150	125	95

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Thank you for your attention!