The History of Stress and Fatigue Analysis versus Experimental Qualification of Flexible Risers

by

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Contents

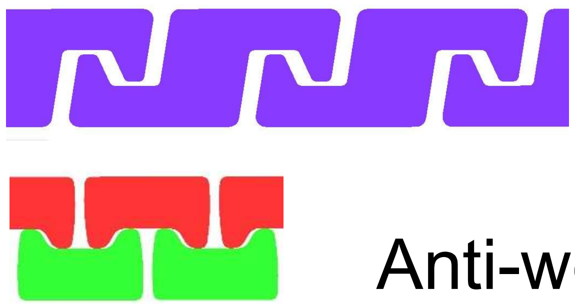
- What are we dealing with?
- Governing stress components
- Lifetime estimation – some historical perspectives
- Important milestones 1992-2011
- The BFLEX program system (1996-2010)
- Validation by experimental testing
- Milestones reached after 2012
- The BFLEX program system 2025
- Concluding remarks
- Some references

What are we dealing with?

Carcass

Liner

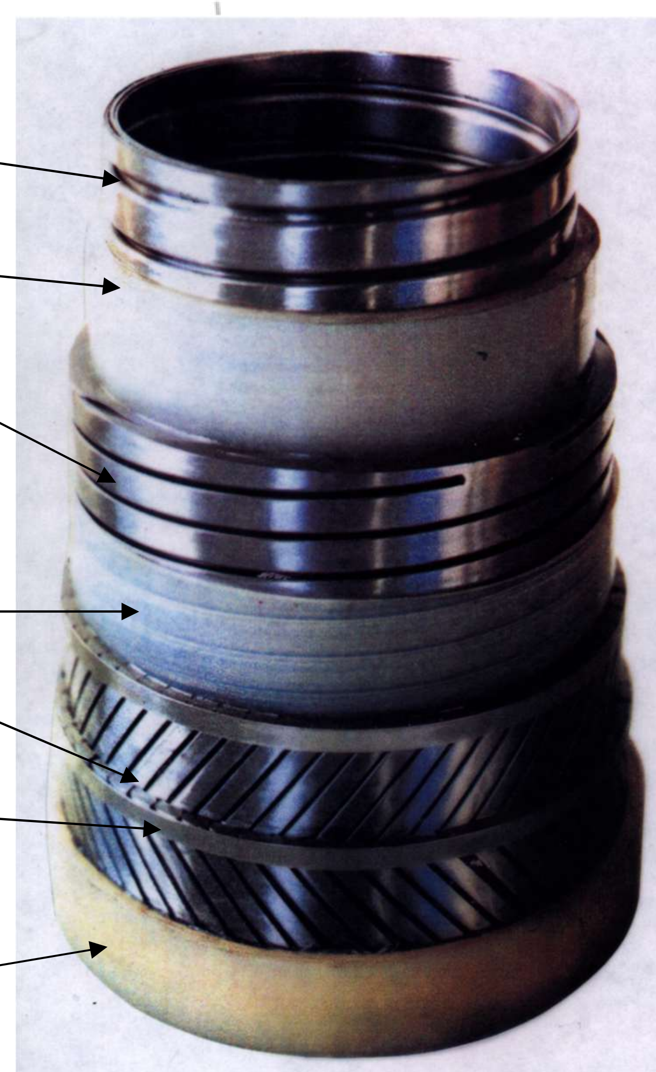
Pressure spiral profile:



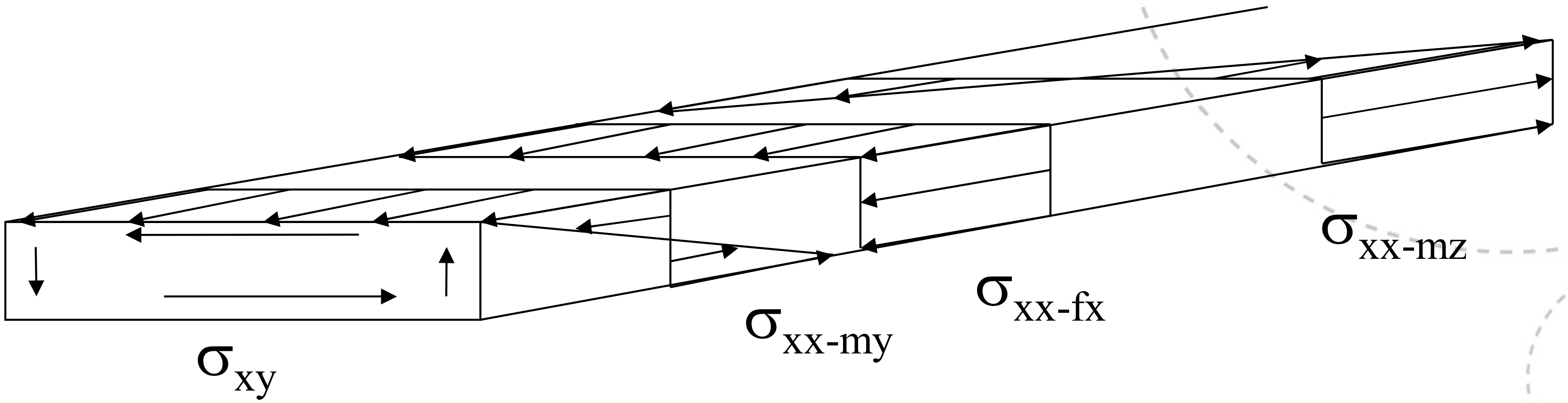
Anti-wear

Tensile armor profile:

Outer sheath



Governing longitudinal stress components – armour layers:



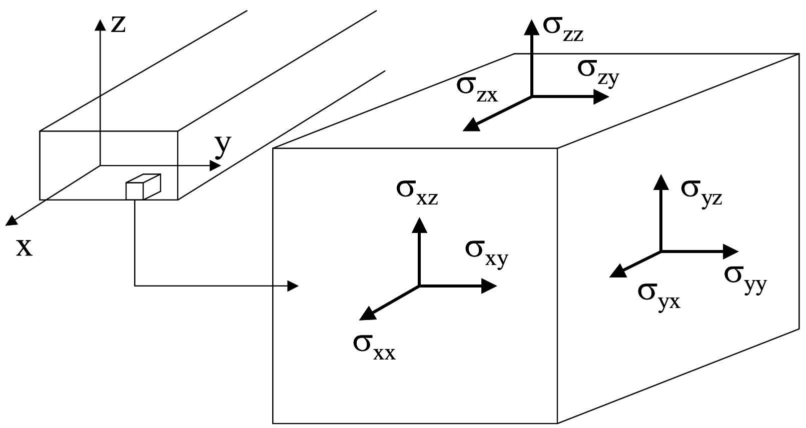
$\sigma_{xx\text{-}fx}$ is the *axial stress* which is constant over the entire cross-section and is a result of the F_x axial force from the pressure (hoop and end-cap effects), the riser tension and torsion moment ***and for the tensile armour also due to friction.***

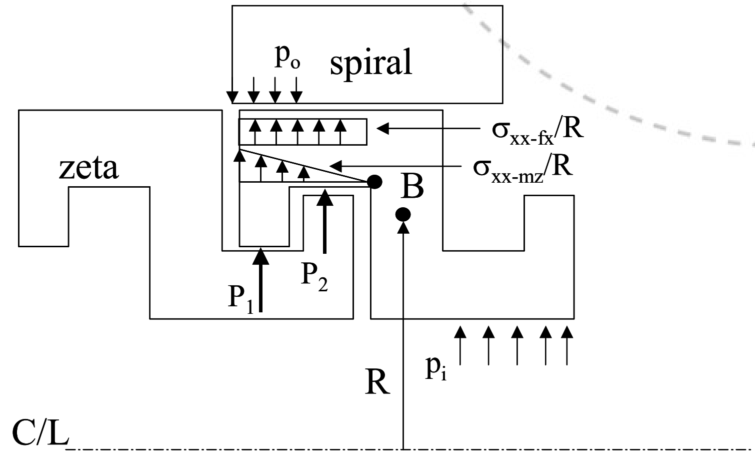
$\sigma_{xx\text{-}my}$ is the *normal curvature stress* which has its maximum at the outer and inner surface of the armour tendon at the tensile/compressive side of the riser and is a result of the M_y bending moment introduced primarily due to riser bending, ***for the pressure armour also due to bending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

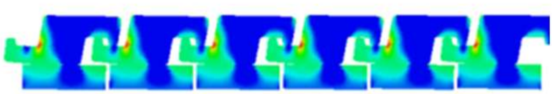
σ_{xy} is the *torsion stress* due to bending (normally small)

Other stress components of relevance - pressure spiral layers:





σ_{yy}, σ_{zz} and σ_{yz} stresses will occur in addition to σ_{xx}



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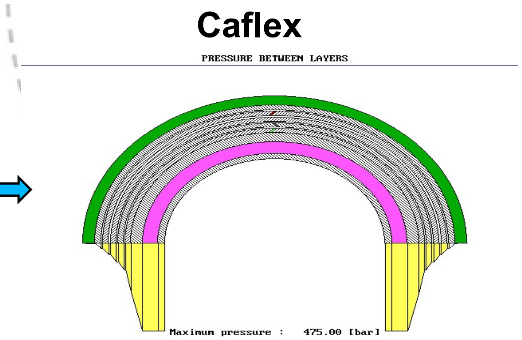
Lifetime prediction – historical perspectives

The FPS2000 project (1988-1991):

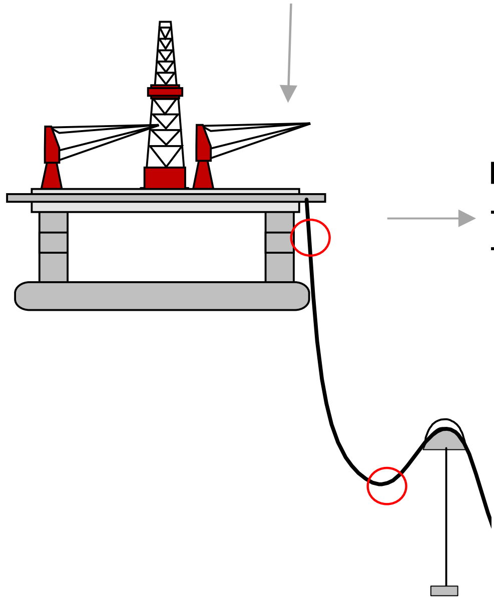
- Riflex program for global analysis
- Caflex program for axisymmetric stress analysis (layered IFP model with 3D/2D Hooke's law) including an analytical fatigue stress and lifetime predicition model
- 1st Flexible pipe handbook



1990

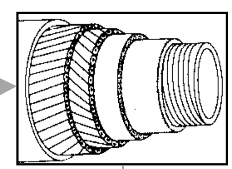
Global Analysis RIFLEX

Dynamic loads



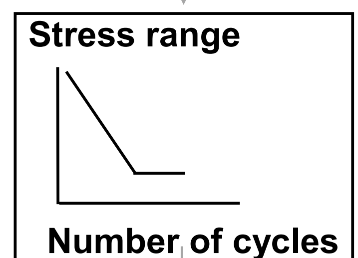
Distribution
- curvature
- tension

Local Analysis BFLEX



- Stress/strain
- Slip in pipe wall components due to friction

Small scale tests



Fatigue life

Svein Sævik - NTNU, November 2025

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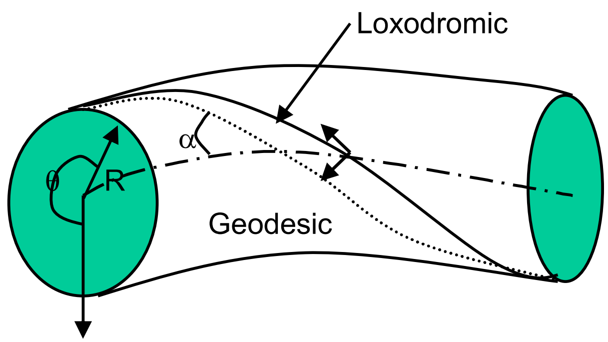
Stress and fatigue prediction before 1990

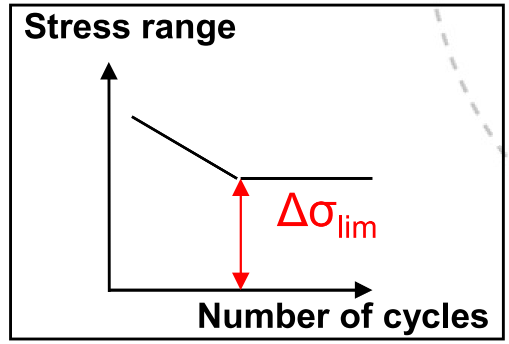
- Only considering the tensile armour
- Analytical 2D stress and slip model (Tension and curvature) based on the geodesic curve assumption:



- Fatigue limit approach assuming dry annulus condition and considering the effect of wear by using Archards formula:

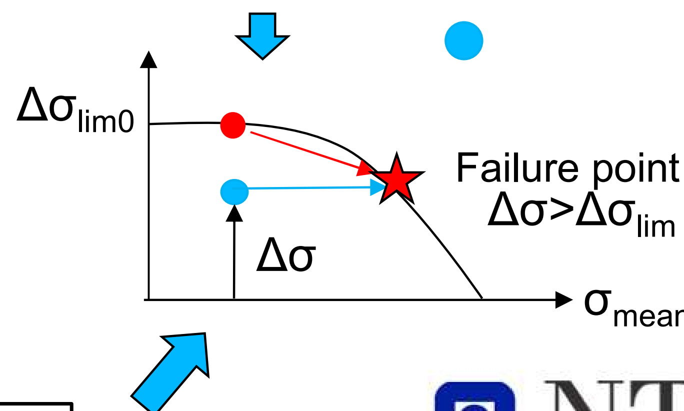
$$V_w = \frac{k_w P_N u}{3 p_h}$$

S-N curve:



Analytical stress and slip model

Gerber mean stress correction model:



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Some important milestones 1992-1996

- The Aflex model for tensile armours (SS. Ph.D Thesis)
  - solves the equilibrium equation for one tendon exposed to a given curvature distribution
  - End effects included but no consideration of second order effects
  - Proving that the tendon does not follow a geodesic curve during dynamic bending, but kept at the loxodromic curve
- Update of tensile armour dynamic stress model from geodesic to loxodromic – implemented by industry
- CSO SLPM model for pressure spiral:
  - analytical approach for stresses
  - Sines criterion including residual stresses

Some important milestones 1996-1999

- Joining Marintek - The Bflex tensile armour model development – Sandwich beam model 1996- Jun. 1997 (NH)
- **Experienced outer sheath failures– dry annulus condition assumption failed => The Corrosion fatigue JIP (2001-2019)**
  - **Sea water corrosion – From outside**
  - **CO_2 & H_2S – Even from inside!**
- Tensile armour model calibration towards full scale strain gauge data from 15” riser outer armour - OMAE paper July 1998
- Integration of the Bflex development project into the Testrig JIP June 1998 introducing us to long lasting cooperation with Seaflex
- Pflex pressure armour longitudinal stress model 1998-1999 – Interface to Mark model (from Seaflex) for cross-section stresses
- A lot of qualitative experimental data calibration studies (by Seaflex)
- Temperature model development work Sep. 98 - Jul.99

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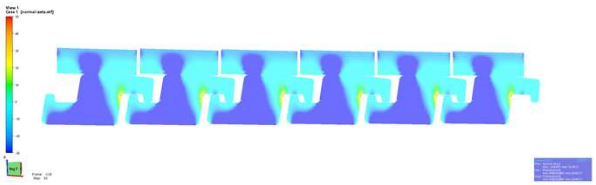
Some important milestones 1999-2011

- Pflex presented at MARINFLEX 99 conference in London May 99
- DEMO 2000 project to develop FBG sensor technology to monitor inner armour
- The Boundary model development work Sep. 98 - Jan. 2000 including the residual stress model
- The moment curvature resultant beam model for tensile armour 2001
- Tensile armour model calibration towards full scale strain FBG data from 8" NKT riser – OTC paper 2001, Computers & Structures 2011



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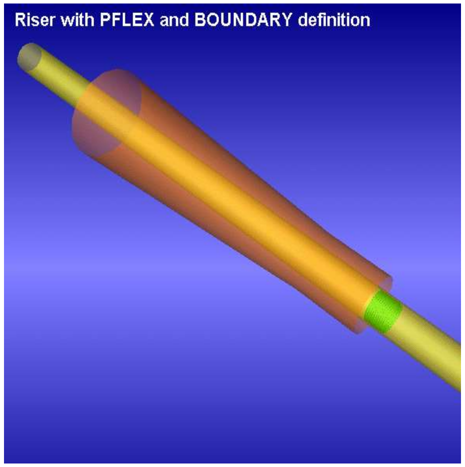
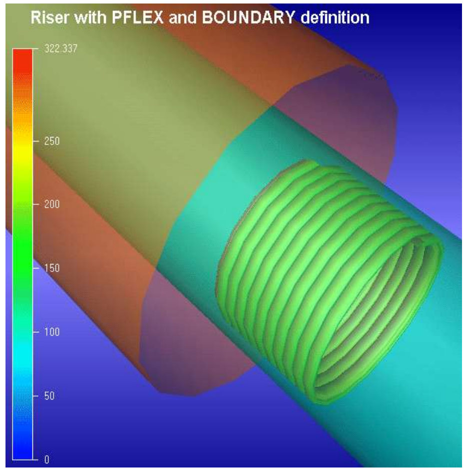
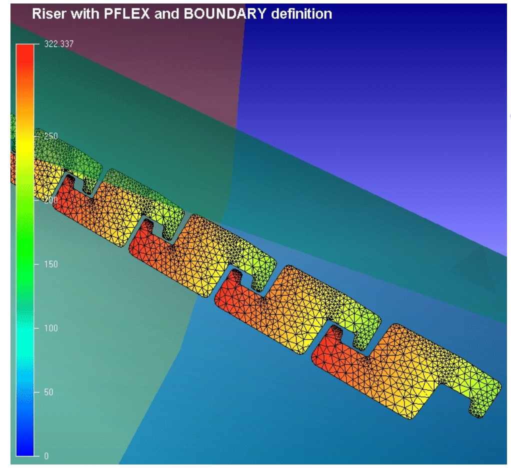
The Bflex Program System (1996-2010)



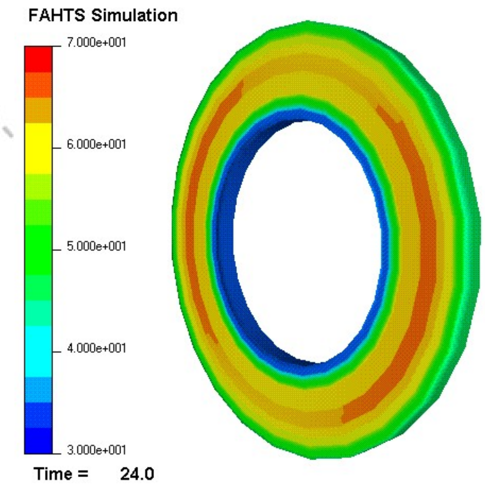
Global BFLEX model



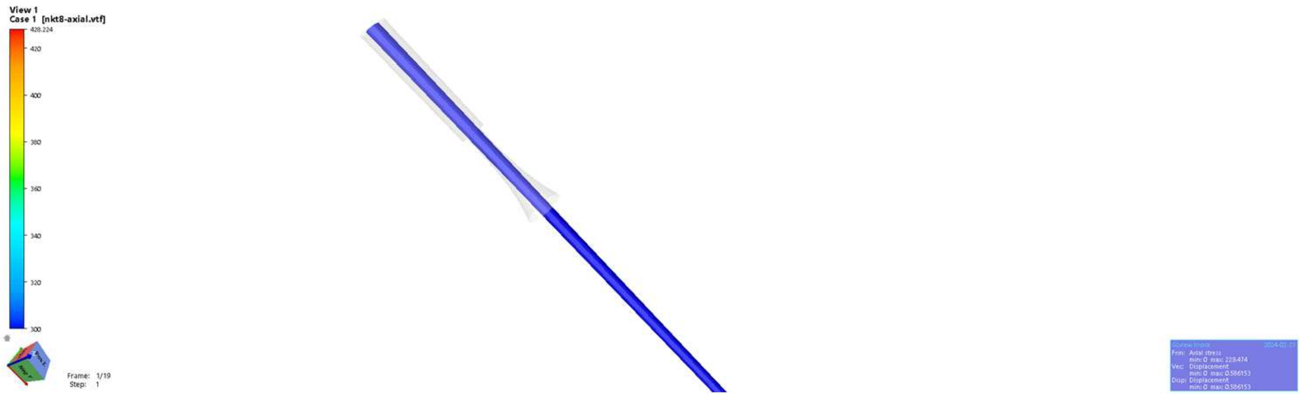
Local PFLEX model

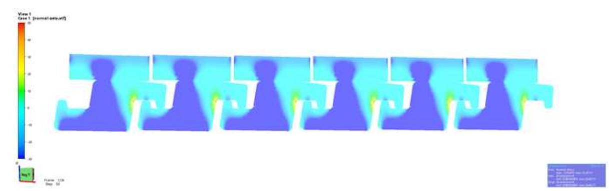


Local BOUNDARY model



Temperature model





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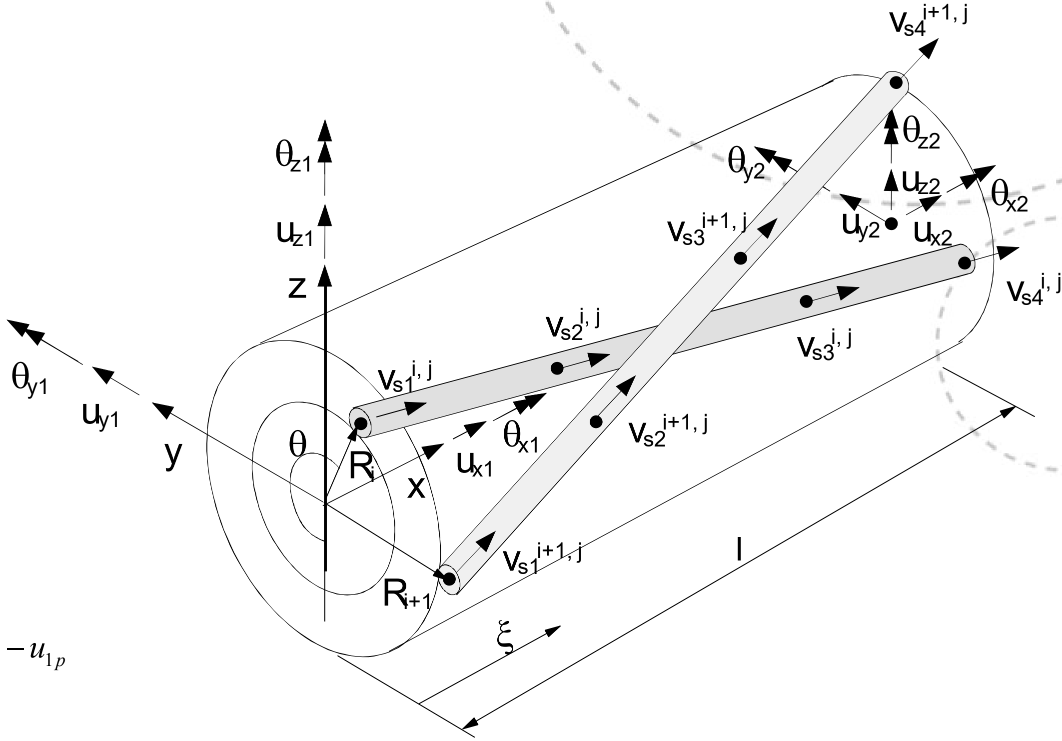
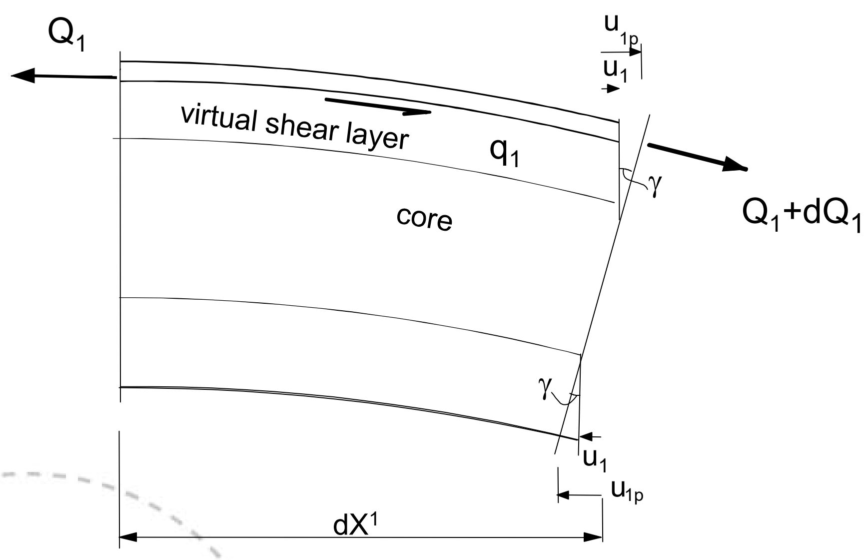
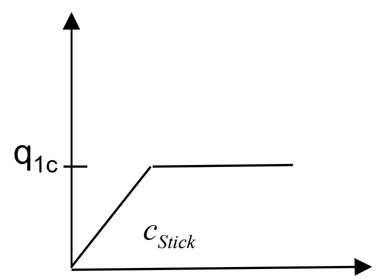
The first Bflex tensile armour model was based on sandwich beam theory

- Caflex model used for axisymmetric analysis
- Beam model for core element including the elastic beam stiffness contribution from all layers
- Sandwich beam model for tendons
- Linked to core by non-linear shear springs
- Local bending moments by differential geometry
- Tendon follows loxodromic curve
- Later a moment-curvature model was included to improve compuational efficiency





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



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Validation - some qualitative correlation studies w.r.t. Testrig JIP experimental data

No	Failure in tensile armour		Failure in pressure armour			
			Transverse failure		Longitudinal failure	
	Observed	BFLEX	Observed	BFLEX	Observed	BFLEX
1	**No**	**No**	**Yes**	**No**	**Yes**	**Yes**
2	**Yes**	**Yes**	**No**	**No**	**No**	**No**
3	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**-**
4	**No**	**No**	**Yes**	**Yes**	**No**	**-**
5	**No**	**No**	**No**	**No**	**Yes**	**Yes**
6	**No**	**No**	**No**	**No**	**No**	**-**
7	**No**	**No**	**No**	**No**	**No**	**-**
8	**No**	**No**	**No**	**No**	**No**	**-**
9	**No**	**No**	**No**	**No**	**No**	**-**
10	**No**	**No**	**No**	**No**	**No**	**No**
11	**No**	**No**	**No**	**No**	**No**	**-**
12	**No**	**No**	**No**	**No**	**No**	**No**
13	**No**	**No**	**No**	**No**	**Yes**	**Yes**
14	**No**	**No**	**Yes**	**Yes**	**No**	**No**
15	**No**	**No**	**No**	**No**	**No**	**No**
16	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**No**

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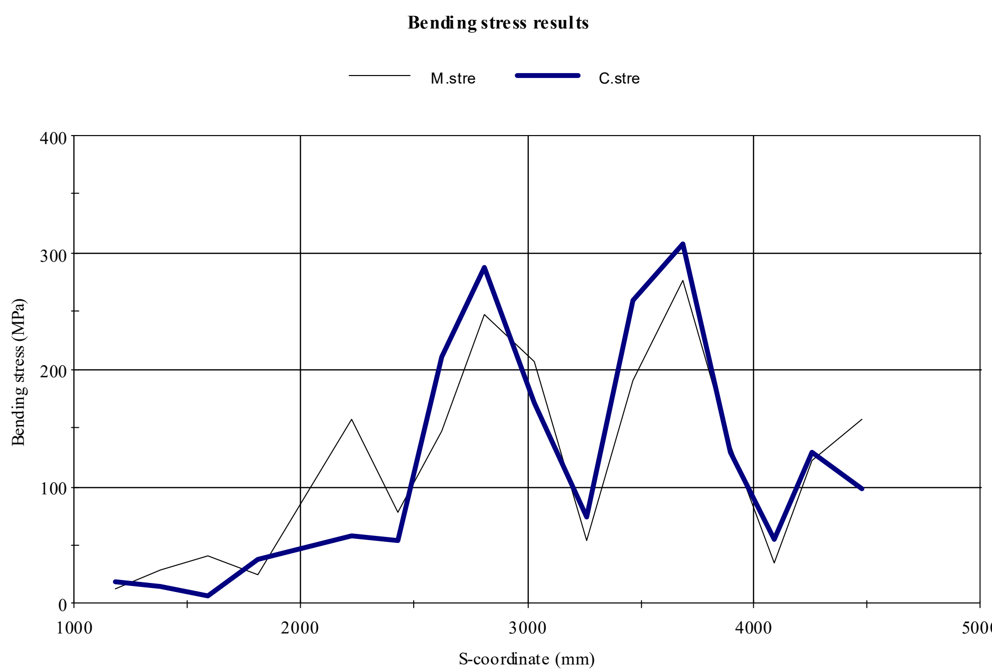
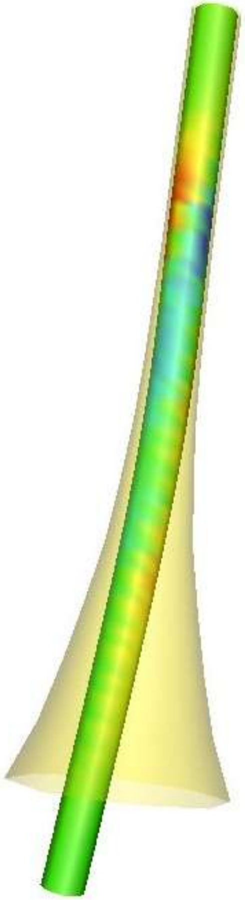
Project experience 2nd strain gauge test in outer tensile armour layer – 15” pipe Jun. - Aug. 1998

- Strain measurements versus Bflex





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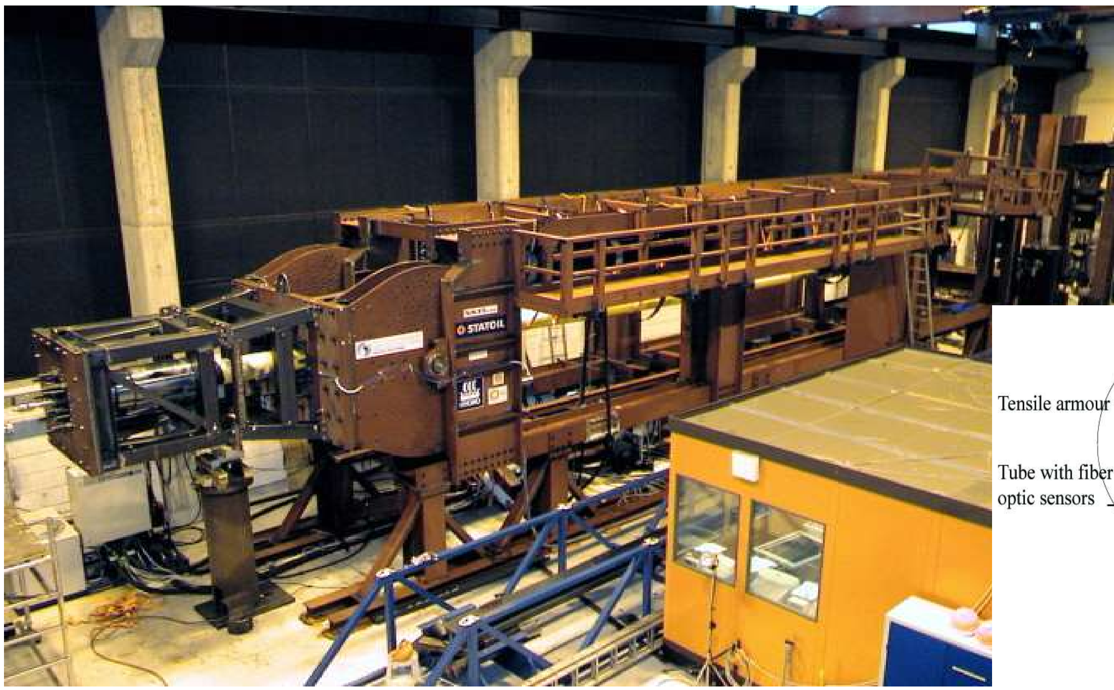
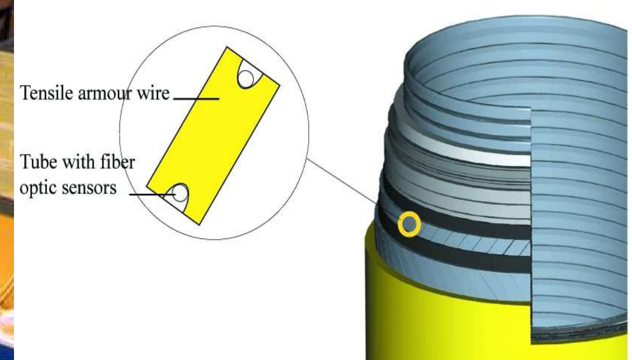
Validation – versus FBG monitoring in inner armour – a Demo 2000 project

- Internal pressure, axial load, bending





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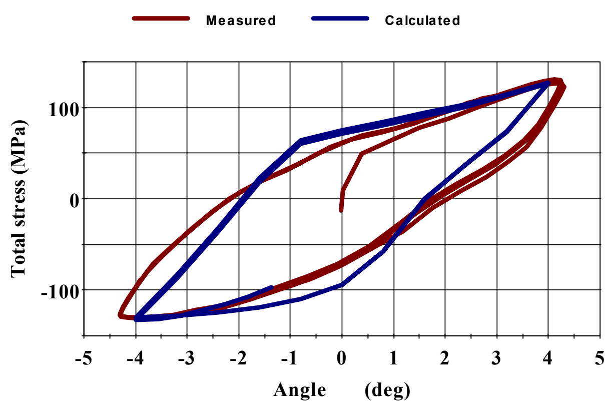
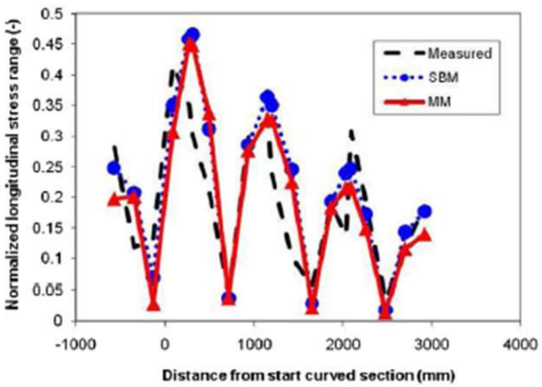
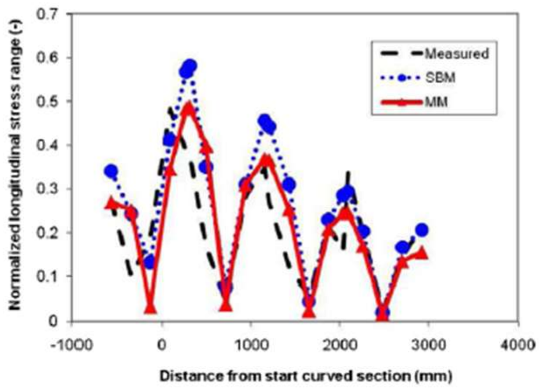
Calibration against Fibre Optic data – Published in OTC 2001, OMAE2002 and in Computers & Strctures 2011

- Calibration of Bflex shear interaction model focusing on the slip parameter u_c
- Both Sandwich beam and moment-curvature formulations were compared

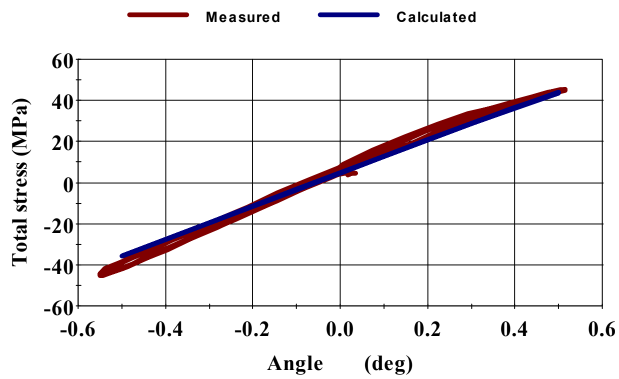




(a) A = 1.5 deg., T = 500 kN, P = 34.0 MPa



(b) A = 2.0 deg., T = 500 kN, P = 34.0 MPa



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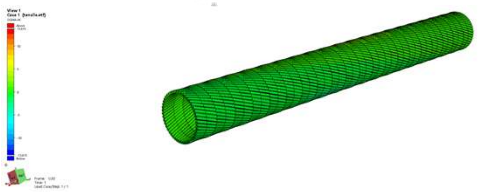
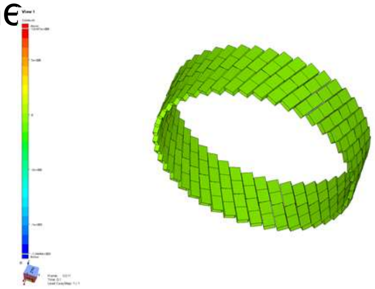
Milestones reached after 2010

- The BFLEX2010 development project sponsored by Equinor starting in 2012
  - Transforming Bflex into a general modelling framework featuring Repeated Unit Cell (RUC) modelling
  - A range of new beam and line contact elements featuring the modelling of arbitrary combinations of tubulars and helices
  - Arbitrary wire slip: both longitudinal and transverse
  - New and more advanced friction models and shear interaction effects by PhD work (Dai)



- The Bflex lateral buckling feature development sponsored by Equinor in 2016
  - New contact element to feature lateral contact between wires in the same layer
  - Verification of the lateral buckling model versus published data by Østergaard – RUC modelling
  - Verifications against other models



- Analytical models for lateral buckling and birdcaging
  - OMAE2012, OMAE2014 and JOMAE – part of Handbook revision 2014
- The development of features supporting power cable modelling

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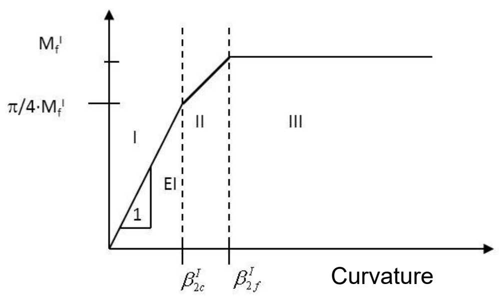
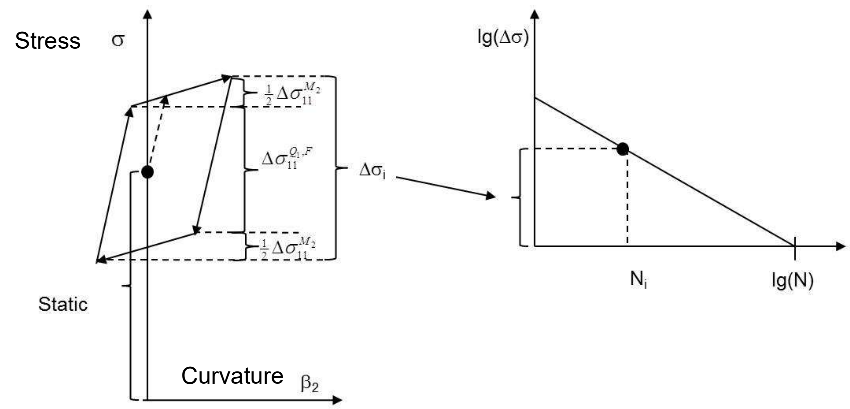
The role of shear interaction

We have:

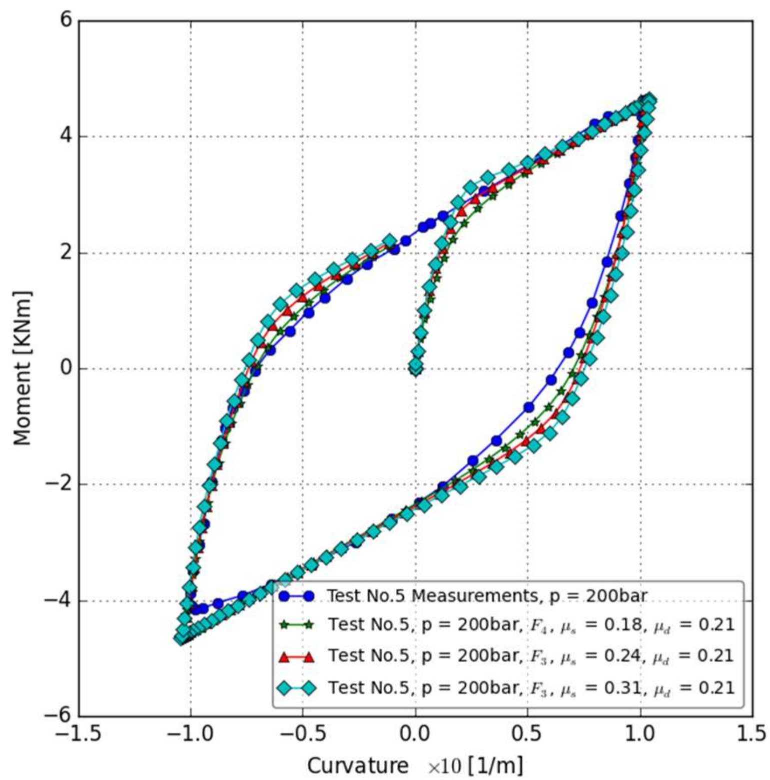
- Moment model for slip curvature versus bending moment with analytical wire axial and bending stresses
- Sandwich beam model for axial slip displacement versus wire axial force and stress. Analytical or numerical local wire bending stresses:





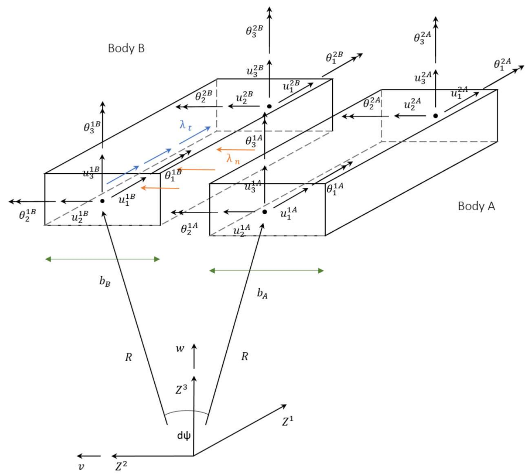
- Slip curvature and displacement can be formulated to include shear interaction by means of the same shear stiffness parameter **k** (Lutchansky, 1969)

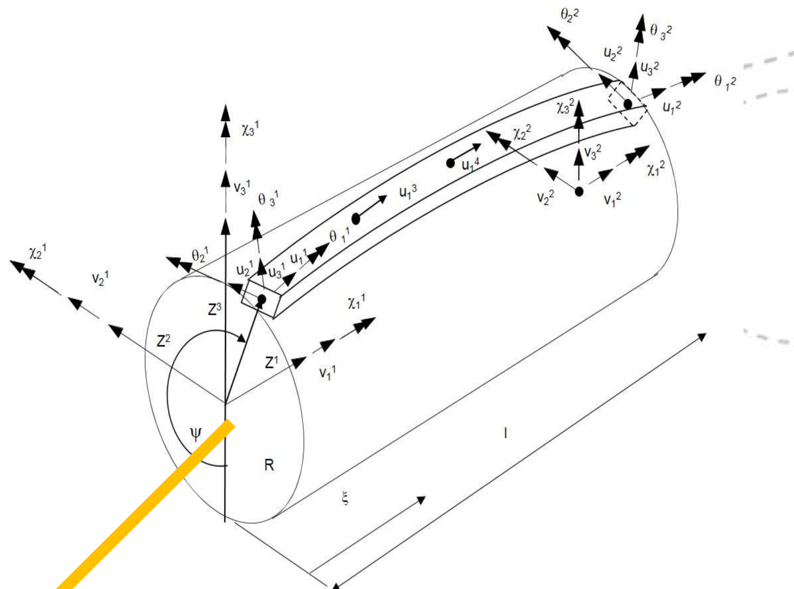
$$\beta_{2c} = [1 + \frac{sin^2\alpha E A_t}{kR^2}]\frac{\mu(q_3^I + q_3^{I+1})}{EA\cos^2\alpha\sin\alpha}$$

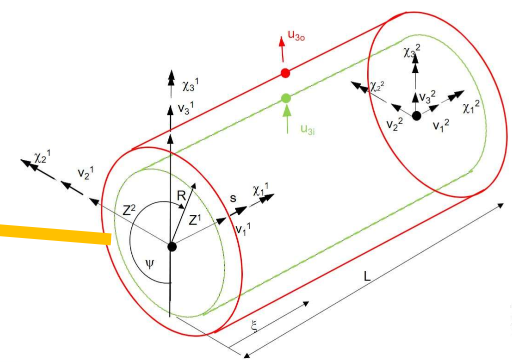


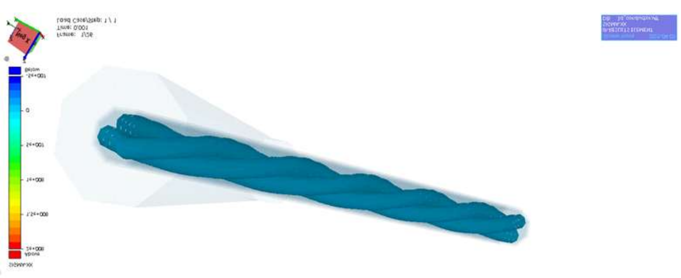
The Bflex program system 2025

- 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 elements allowing for arbitrary slip
  - Several friction formulations
  - Power cable features









Svein Sævik - NTNU, November 2025

Concluding remarks

- This has been a long and very interesting travel!
- I have enjoyed every moment of it!
- I am very grateful to the industry partners that have made the travel possible and to my colleagues in SINTEF Ocean that are providing the daily user support and the implementation of new features!
- I foresee future software developments and the update of the Flexible Pipe Handbook (where also learnings from the Corrosion Fatigue JIP will be integrated), following the needs from the industry, with excitement!

Thank you for your attention!

Some references

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