Prediction of Extreme & Fatigue Response of Flexible Pipe

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Presentation to cover the following points:

• Set the context for current work
  – Real Life and Sureflex JIPs
  – Recent industry findings

• Development in Fatigue Life Modelling

• Extreme Loading on Flexible Pipe
  – Birdcaging, armour wire disorganisation and buckling

• Conclusions
Acknowledge the work of my MCS Kenny colleagues:

- Annette Carty-Mole
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- John Smyth
- Rafael Fumis
SureFlex JIP Deliverables

The JIP produced two deliverables (End 2010):

• State of the Art Report on Flexible Pipe Integrity
  – Gathered data on flexible pipe population statistics, damage, degradation and failure mechanisms worldwide
  – Reviewed current integrity management practice
  – Reviewed developments in monitoring and inspection methods for flexible pipe

• Guidance Note on Monitoring Methods and Integrity Assurance for Flexible Pipe
  – Life cycle flexible pipe integrity assurance
  – Sources of flexible pipe degradation, damage and failure
  – Guidance on Inspection and Monitoring Techniques

• [www.ukoilandgasuk.co.uk](http://www.ukoilandgasuk.co.uk)
  – Click on “Publications”
  – Code: OP010; Category: Operations; Keyword: Flexible Pipe
  – Cost: £50 for Members O&GUK, £100 for Non-Members
SureFlex Findings: Water Depth vs Internal Diameter

Operating Flexible Risers, Water Depth vs. ID

Experience that Delivers
SureFlex Findings: Pressure vs Internal Diameter
SureFlex Findings:
Failure / Damage Statistics

Flexible Pipe Failure/Damage Mechanisms

- 2002 UKCS and Norway only
- 2010 Worldwide

Failure / Damage Mechanism:
- others:
  - Smooth bore collapses
  - Pigging Damage
  - Upheaval Buckling
  - Excess Torsion
  - Excess Tension
  - Sheath cracking
  - Armourwire failure
Main recommendations from SureFlex are:

- Create a joined-up approach to S-N curve definition for corrosion fatigue and improve our methodology for corrosion fatigue assessment.
- Put more focus on and significantly improve our practice on annulus vent system design, commissioning and maintenance.
- Establish an industry consensus on failure mechanisms involved in tensile armour birdcaging and lateral buckling through discussion and information sharing between relevant stakeholders.
- Establish a mechanism for annual update of the “Guidance Note” document:
  - “Procedure – Industry Practice – Guidance Note” format is well established
  - Inspection and monitoring techniques are developing quickly now in response to demand
    - Need to capture latest industry experience and practice
Flexible Riser Fatigue: Real Life JIP
Completed 2006

• Objective
  – Establish an independent, consistent and transparent fatigue analysis methodology for flexible pipes

• JIP participants
  – Operators
    • BP, ExxonMobil, ChevronTexaco, Statoil, Petrobras, Shell, ConocoPhillips, Woodside
  – Flexible Pipe Suppliers
    • Flexi France, Wellstream, NKT

• Real Life achieved:
  – Robust Global Analysis Methodology (Effectively)
  – Provided insight into Global to local transposition
    • Time domain rainflow counting of wire stress
  – Produced a set of industry guidelines
    • Consistency and transparency
    • Implementation into API / ISO
  – Highlighting the importance of Hysteresis
Flexible Pipe Bending - Hysteresis

- **Stick-Slip Bending**
  - Tensile Armour initially sticks on reverse bending
  - Slip is **inline** with and transverse to lay-direction
  - Hysteretic fatigue stress

![Graph showing stress-strain relationship](image-url)

- **Regular Stress Cycle**
Wire Equations of Equilibrium
Layercom Methodology

\[
\frac{d\sigma_{11}}{ds} t + \sigma_{12,\text{tot}} = 0 \quad \text{Tangential}
\]

\[
\sigma_{11} t \kappa_n - \sigma_{22,\text{diff}} = 0 \quad \text{Surface Normal}
\]

\[
- \sigma_{11} t \kappa_t + \sigma_{32,\text{tot}} = 0 \quad \text{Transverse}
\]

- Method of Solution
  - Incremental curvature determines incremental non-slip axial stress
  - Incremental non-slip axial stress determines incremental tangential shear, normal interface and transverse shear stresses
  - Check Coulomb law and gradually relax stresses while retaining equilibrium
  - Wire curvatures from loxodromic / geodesic equations
Friction-Induced Stress
Layercom Methodology

- Structural Model for Friction – Irregular Loading

Pipe Bending Curvature

Wire Stress

Hysteresis Loop
3D (out-of-plane) Irregular Seas

Layercom Methodology

3D Pipe Bending in Irregular Seas
Hs = 2m, Tp = 13s, 15deg off-bow
Global Tension (left) and Curvature (right) Responses

Experience that Delivers
3D (out-of-plane) Irregular Seas

Layercom Methodology

3D Pipe Bending in Irregular Seas
Hs = 2m, Tp = 13s, 15deg off-bow

Armour Total Stress at 8 Equally Spaced Positions on the Cross Section

Experience that Delivers
• Single tensile armour wire in isolation

• Wire constrained between cylindrical surfaces
  – Apply curvature to cylindrical surfaces

• Compare FE results with:
  – Theoretical wire-curvature models
  – Analytical Tools
    • Layercom
Wire Deformation Path under Bending – Fatigue Stress

Applied end rotation (both ends)

View 1

View 2

Original Wire Position

Frictionless Contact

neutral

Axis

Resultant Axial Displacement of Wire - Principle Wire Stress for Fatigue Calculation
• Theoretical models for wire curvature change for a given pipe curvature

• Normal and Transverse Components of curvature change
• Theoretical models for wire curvature change for a given pipe curvature

• Normal and Transverse Components of curvature change
• Theoretical models for wire curvature change for a given pipe curvature

• Normal and Transverse Components of curvature change
  – Witz & Tan
  – Saevik
  – MCSK Loxodrome
Transverse Delta-Curvature Comparison

![Graph showing transverse curvature comparison with angular position for different methods: MCS Loxodrome, Saevik, Witz & Tan, and Abaqus/Standard.](image)
Normal Delta-Curvature Comparison

Angular Position [degrees]

Normal Curvature [1/m]

-0.01 -0.005 0 0.005 0.01

0 50 100 150 200 250 300 350 400

MCS Loxodrome
Saevik
Witz & Tan
Abaqus/Standard

Experience that Delivers
Verification – Single Wire Sliding Model Set-up

- Wire plus Inner and outer cylindrical slivers
- Curvature enforced by displacing cylinders in pipe curvature

Applied displacement at each node (both cylinders)

Tensile Armour Wire
Each Layer Modelled Explicitly –
Contact, Friction, Lock-in

Experience that Delivers
Flexible Pipe Fatigue

Ongoing Industry Efforts

• Continue to improve analysis models
• Set standard methodology for armour wire testing and S-N curve development
  – Marintek JIP
  – Step towards transparency
• Manufacturers further evaluating annulus environment
• Most likely we are conservative in our fatigue predictions
  – Recent OTC Brazil 2011 paper by Charlesworth, D’All, et al
    › Performed fatigue testing of armour wires in bend stiffener region
    › After 10 year operation West of Shetlands, armour wires in near pristine condition, with very little fatigue damage
**Birdcaging**

- Radial buckling mode of the tensile wires
  - High compression loads
  - Bending
  - Reverse End Cap
  - Local deformation of individual wires about wire ‘weaker’ axis
Armour Wire Disorganisation & FE Models
Armour Wire Disorganisation

Experience that Delivers
Good comparison with experimental results:

**Finite Element Model**
Key Conclusions are:

- Considerable step-up in capability to model the complex cross-section of flexible pipe

- This has contributed to improved prediction of:
  - Flexible riser fatigue life
  - Armour wire disorganisation
  - Birdcaging
  - Latter two points important for deepwater application (Sureflex JIP)

- Need continued efforts across industry to rationalise fatigue life predictions with a consistent, transparent approach

- Finite Element Analysis work is being validated against test data
Umbilical / Flexible Suite of Models
Thank you

Any questions?