Risers – Flexible Pipes and Umbilicals

Local Structural Analysis

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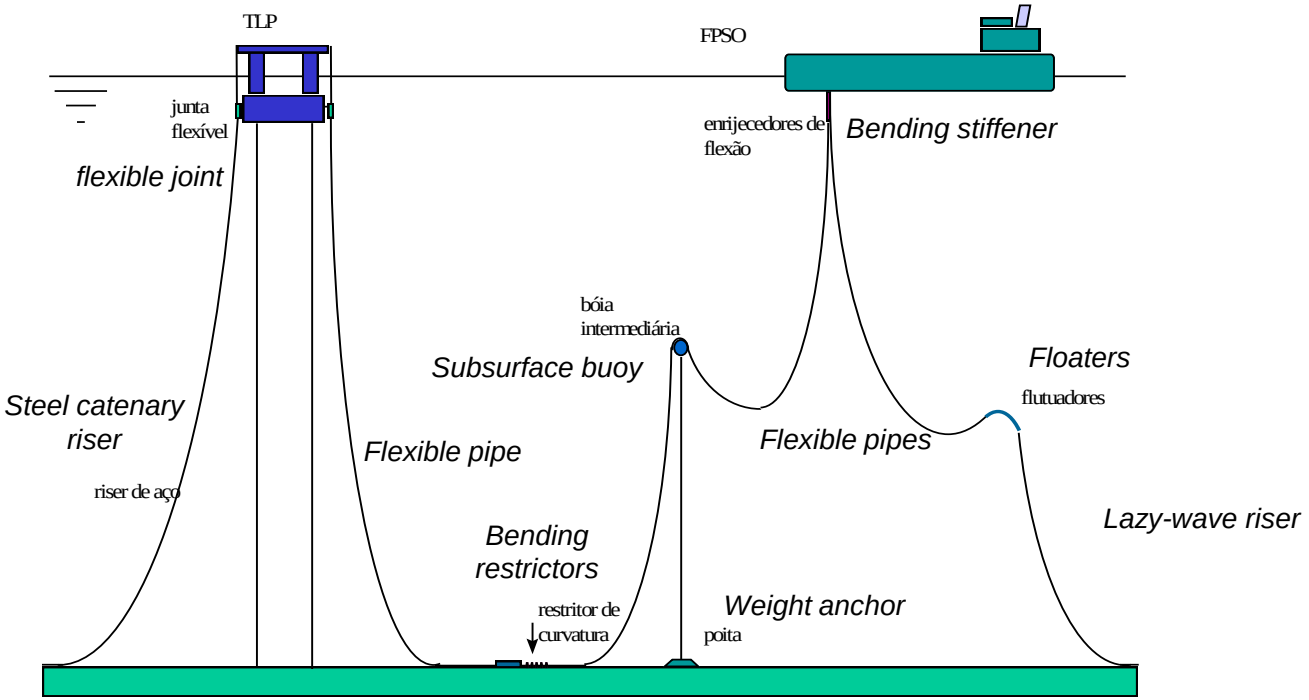
Risers

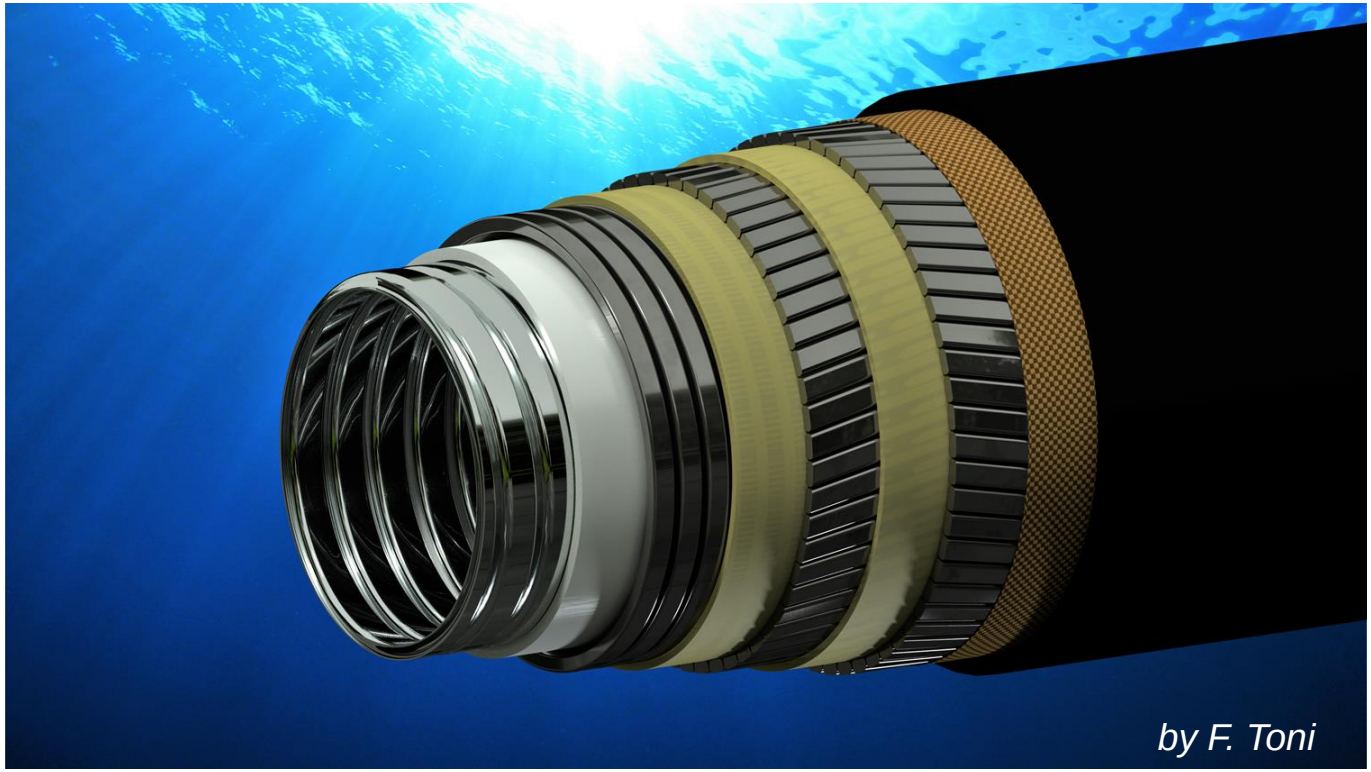


- ***Umbilical cables***: control signals, electrical power, fluid injection to the submarine equipment at the well head.

- ***Flexible pipes:*** conveying oil, gas, from the well head to the production floating system or to another storage and offloading vessel after processing.

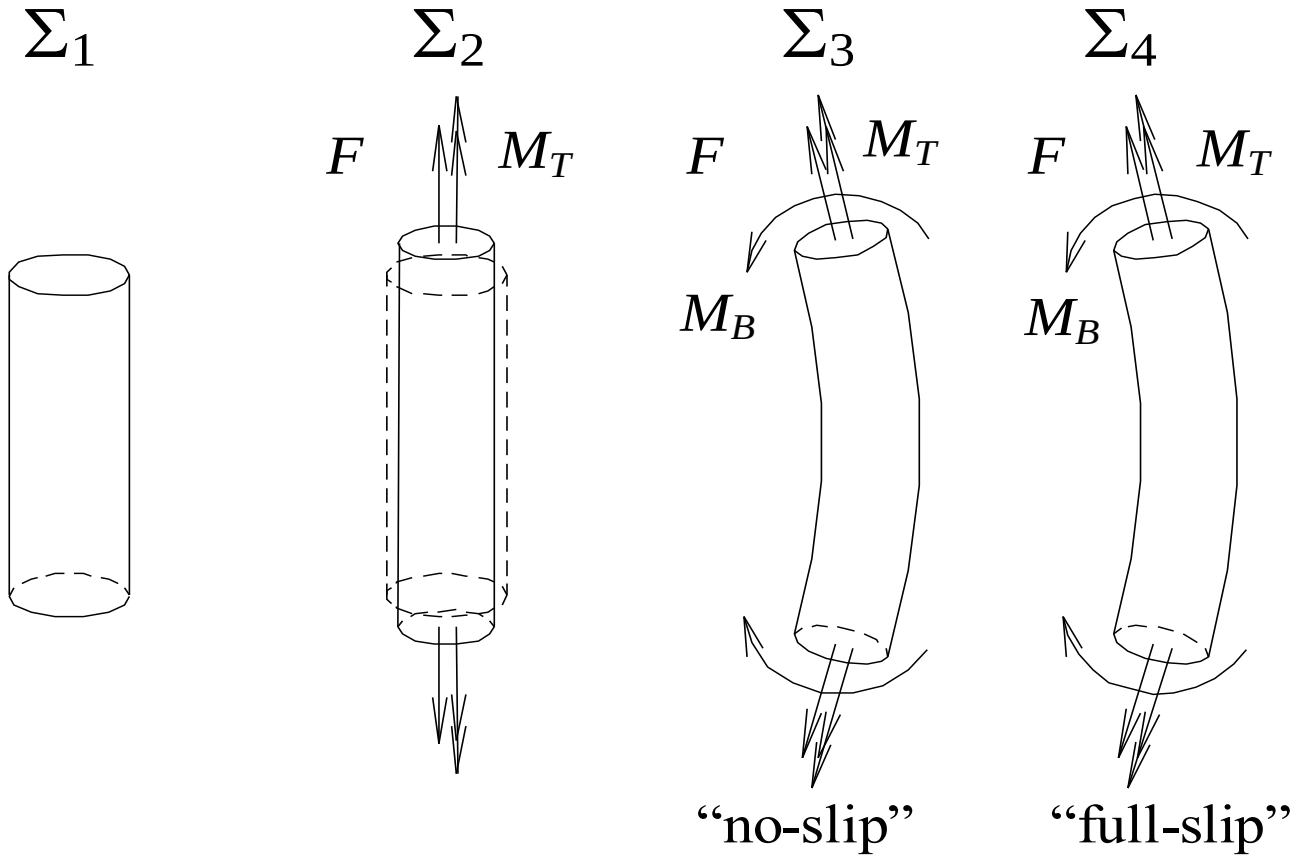
Umbilicals

Flexible Pipes

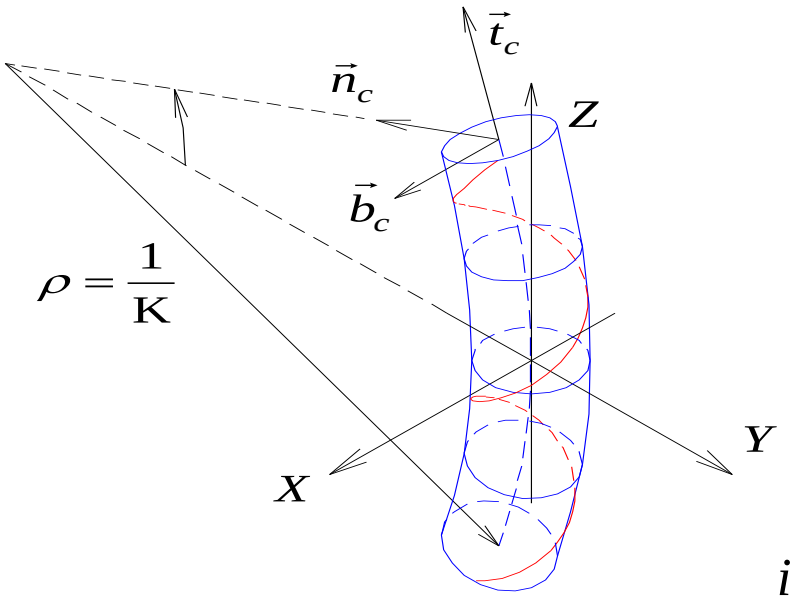


Cylindrical Layers
and
Central Core (umbilicals)

Deformed Configurations
Ramos Jr, R., 2001 (Anexo C)



Efforts on cylindrical layers



Tension: F_i

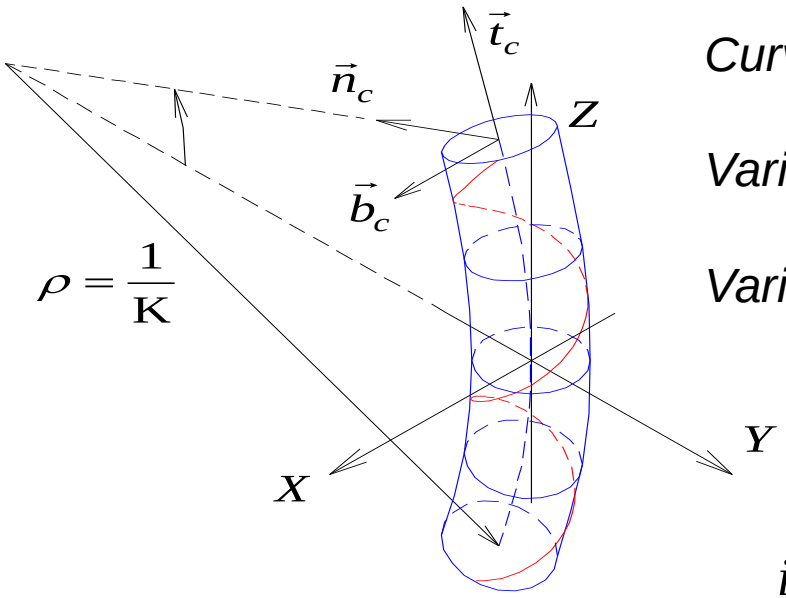
Torsion: $M_{t,i}$

Bending: $M_{f,i}$

Inter-layer pressure: $p_{c,i}$ and $p_{c,i-1}$

i: layer

Deformed Cylindrical Layer



Elongation: $\Delta L / L$

Rotation around the central axis: $\Delta\varphi / L$

Curvature imposed to the central axis: K

Variation of the mean layer radius: ΔR_i

Variation of the layer thickness: Δt_i

i: layer

Thickness variation

$$\frac{\Delta t_i}{t_i} = -\nu_i . \frac{\Delta L}{L} - \left(1 - \frac{1}{2}\frac{t_i}{R_i}\right) . \left[\frac{1}{2}(1-\nu_i^2) + \nu_i(1+\nu_i)\frac{R_i}{t_i}\right] . \frac{\left(p_{c,i-1} + \mu_{in} . p_{in}\right)}{E_i} -$$

$$-\left(1 + \frac{1}{2}\frac{t_i}{R_i}\right) . \left[\frac{1}{2}(1-\nu_i^2) - \nu_i(1+\nu_i)\frac{R_i}{t_i}\right] . \frac{\left(p_{c,i} + \mu_o . p_o\right)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Theory of elasticity: thick wall pressure vessels

i: layer

Thickness variation

$$\frac{\Delta t_i}{t_i} = -\nu_i . \frac{\Delta L}{L} - \left[\nu_i (1+\nu_i) \frac{R_i}{t_i} \right] \frac{\left(p_{c,i-1} - p_{c,i} + \mu_{in} . p_{in} - \mu_o . p_o \right)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Shell theory: thin wall pressure vesses

i: layer

Mean radius variation

$$\frac{\Delta R_i}{R_i} = -\nu_i \cdot \frac{\Delta L}{L} + \left(1 - \frac{1}{2}\frac{t_i}{R_i}\right) \cdot \left[(1-\nu_i^2)\frac{R_i}{t_i} + \frac{1}{2}\nu_i(1+\nu_i)\right] \cdot \frac{\left(p_{c,i-1} + \mu_{in} \cdot p_{in}\right)}{E_i} -$$
$$-\left(1 + \frac{1}{2}\frac{t_i}{R_i}\right) \cdot \left[(1-\nu_i^2)\frac{R_i}{t_i} - \frac{1}{2}\nu_i(1+\nu_i)\right] \cdot \frac{\left(p_{c,i} + \mu_o \cdot p_o\right)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Theory of elasticity: thick wall pressure vessels

i: layer

Mean radius variation

$$\frac{\Delta R_i}{R_i} = -\nu_i . \frac{\Delta L}{L} + \left[(1-\nu_i^2) \frac{R_i}{t_i} \right] \frac{\left(p_{c,i-1} - p_{c,i} + \mu_{in} . p_{in} - \mu_o . p_o \right)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Shell theory: thin wall pressure vesses

i: layer

Normal force supported by the cylindrical layer

$$\frac{F_i}{E_i A_i} = \frac{\Delta L}{L} + \frac{1}{2}\left(1 - \frac{1}{2}\frac{t_i}{R_i}\right).\nu_i\left(2\frac{R_i}{t_i} - 1\right)\frac{.(p_{c,i-1} + \mu_{in}.p_{in})}{E_i} - \\ - \frac{1}{2}\left(1 + \frac{1}{2}\frac{t_i}{R_i}\right).\nu_i\left(2\frac{R_i}{t_i} + 1\right)\frac{(p_{c,i} + \mu_o.p_o)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Theory of elasticity: thick wall pressure vessels

i: layer

Normal force supported by the cylindrical layer

$$\frac{F_i}{E_i A_i} = \frac{\Delta L}{L} + \nu_i \frac{R_i}{t_i} \frac{(p_{c,i-1} - p_{c,i} + \mu_{in}.p_{in} - \mu_o.p_o)}{E_i}$$

μ_{in}: “flag”: ‘1’ if a central tube or ‘0’ if not.

μ_o: “flag”: ‘1’ if the last cylindrical layer, or ‘0’ if not.

Shell theory: thin wall pressure vesses

i: layer

Torsion and Bending Moments supported by the cylindrical layer

$$M_{t,i} = (GJ_p)_i . \frac{\Delta\varphi}{L}$$

$$M_{f,i} = (EI)_i . K$$

Linear Theory of rods

i: layer

Radius variation of a solid core and efforts

$$\frac{\Delta R_i}{R_i} = -\nu_i . \frac{\Delta L}{L} - (1+\nu_i).(1-2\nu_i).\frac{p_{c,i}}{E_{i_{eq}}}$$

$$\frac{F_i}{E_{i_{eq}} \pi R_i^{\,2}} = \frac{\Delta L}{L} - 2\nu_i \frac{p_{c,i}}{E_{i\,eq}}$$

$$E_{i_{eq}} = \frac{T}{\pi R_i^{\,2}} \varepsilon$$

$$M_{t,i} = (GJ_p)_{i_{eq}} . \frac{\Delta\varphi}{L}$$

$$M_{f,i} = (EI)_{i_{eq}} .K$$

Linear Theory of rods

i: layer

Umbilicals

Equilibrium Equations
Stiffness Parameters

Cylindrical Elements. Central Core.

Incognitae

Incognitae	Symbol	Number
Contact pressure or gap between layers i and i+1	p_{ci} or g_i	$n+m-1$
Axial load supprted by layer i	Fi	$n+m$
Twist moment supported by layer i	M_{ti}	$n+m$
Bending moment supported by layer i	M_{fi}	$n+m$
Mean radius variation, layer i	ΔR_i	$n+m$
Tichness variatiation of layer i (*)	Δt_i	$n+m$
Laying angle variation (helical layer i)	α_i	n
Axial elongation	$\Delta L/L$	1
Twist per unit length	$\Delta\varphi/L$	1
Bending curvature	K	1
Total		$7n+6m+2$

(*) Except if the first layer is na umbilical central core.

Equilibrium equations – all layers

$$\sum_{i=1}^{n+m} F_i = F$$

$$\sum_{i=1}^{n+m} M_{t,i} = M_t$$

$$\sum_{i=1}^{n+m} M_{f,i} = M_f$$

Algebraic equation system composed by ***thirteen groups***, solvable numerically to obtain :

- *7n + 6m + 1 incognitae if the first layer is an electrical cable core*
- *7n + 6m + 2 incognitae if the first layer is a pipe or equivalente pipe*

n: number of helical layers;

m: number of cylindrical layers.

Bending stiffness for an umbilical

$$M_f = (EI)_{eq}.\mathrm{K}$$

$$\boxed{(EI)_{eq} = \sum_{i=1}^{m} E_i I_i + \sum_{i=1}^{n} n_i \cos\alpha_i \left[G_i I_{t,i} + \frac{3}{2}\left(E_i I_{y,i} - G_i I_{t,i}\right)\cos^2\alpha_i \right]}$$

Full slipping

$$\boxed{(EI)_{eq} = \sum_{i=1}^{m} E_i I_i + \sum_{i=1}^{n} n_i \cos\alpha_i \left[\frac{1}{2}(EA)_i.R_i^{\,2} \cos^3\alpha_i + G_i I_{t,i} + \frac{3}{2}\left(E_i I_{y,i} - G_i I_{t,i}\right)\cos^2\alpha_i \right]}$$

No slipping

Stiffness matrix for a umbilical

$$\begin{bmatrix} F \\ M_t/R \\ M_f/R \end{bmatrix} = \begin{bmatrix} c_{hh} & c_{h\varphi} & 0 \\ c_{\varphi h} & c_{\varphi\varphi} & 0 \\ 0 & 0 & c_{\kappa\kappa} \end{bmatrix} \begin{bmatrix} \varepsilon_h \\ \varepsilon_\varphi \\ \kappa \end{bmatrix}$$

Depends on loading!

$$\varepsilon_h = \frac{\Delta L}{L}; \varepsilon_\varphi = \frac{\Delta\varphi R}{L}; \kappa = KR$$

$$c_{hh} = (EA)_{eq}; c_{\varphi\varphi} = \frac{(GJ)_{eq}}{R^2}; c_{\kappa\kappa} = \frac{(EI)_{eq}}{R^2}$$

Stiffness parameters of an umbilical cable – tension and torsion

For each loading condition (say, A and B, not linearly dependent), numerical values of the cable elongation and twist are determinedas part of the system solution.

$$(F;M_t)_A \Rightarrow (\varepsilon_h;\varepsilon_\varphi)_A$$

$$(F;M_t)_B \Rightarrow (\varepsilon_h;\varepsilon_\varphi)_B$$

Stiffness parameters of an umbilical cable – tension and torsion

Coefficients c_{hh} and $c_{h\varphi}$ are determined by solving the equations:

$$\begin{bmatrix} \varepsilon_{hA} & \varepsilon_{\varphi A} \\ \varepsilon_{hB} & \varepsilon_{\varphi B} \end{bmatrix} \cdot \begin{bmatrix} c_{hh} \\ c_{h\varphi} \end{bmatrix} = \begin{bmatrix} F_A \\ F_B \end{bmatrix}$$

Depend on loading!

Analogously for $c_{\varphi h}$ and $c_{\varphi\varphi}$:

$$\begin{bmatrix} \varepsilon_{hA} & \varepsilon_{\varphi A} \\ \varepsilon_{hB} & \varepsilon_{\varphi B} \end{bmatrix} \cdot \begin{bmatrix} c_{\varphi h} \\ c_{\varphi\varphi} \end{bmatrix} = \begin{bmatrix} M_{tA} \\ M_{tB} \end{bmatrix}$$

Stiffness parameters for a umbilical subjected to axial tension, bending and torsion with tubes pressurization, **without** *slippage between layers*

$$\begin{bmatrix} F \\ M_t/R \\ M_f/R \\ p_p R^2 \\ \dots \\ p_q R^2 \end{bmatrix} = \begin{bmatrix} c_{hh} & c_{h\varphi} & c_{h\kappa} \\ c_{\varphi h} & c_{\varphi\varphi} & c_{\varphi\kappa} \\ c_{\kappa h} & c_{\kappa\varphi} & c_{\kappa\kappa} \\ c_{ph} & c_{p\varphi} & c_{p\kappa} \\ \dots & \dots & \dots \\ c_{qh} & c_{q\varphi} & c_{q\kappa} \end{bmatrix} \begin{bmatrix} \varepsilon_h \\ \varepsilon_\varphi \\ \kappa \end{bmatrix}$$

"Stiffness matrix" depends on loading; solution not a trivial task!

$$\varepsilon_h = \frac{\Delta L}{L}; \varepsilon_\varphi = \frac{\Delta\varphi R}{L}; \kappa = KR$$

$$c_{hh} = (EA)_{eq}; c_{\varphi\varphi} = \frac{(GJ)_{eq}}{R^2}; c_{\kappa\kappa} = \frac{(EI)_{eq}}{R^2}$$

Stiffness parameters for a umbilical to axial tension, bending and torsion with tubes pressurization, **with** *slippage between layers*

$$\begin{bmatrix} F \\ M_t/R \\ M_f/R \\ p_p R^2 \\ \dots \\ p_q R^2 \end{bmatrix} = \begin{bmatrix} c_{hh} & c_{h\varphi} & 0 \\ c_{\varphi h} & c_{\varphi\varphi} & 0 \\ c_{\kappa h} & c_{\kappa\varphi} & c_{\kappa\kappa} \\ c_{ph} & c_{p\varphi} & 0 \\ \dots & \dots & \dots \\ c_{qh} & c_{q\varphi} & 0 \end{bmatrix} \begin{bmatrix} \varepsilon_h \\ \varepsilon_\varphi \\ \kappa \end{bmatrix}$$

$$\varepsilon_h = \frac{\Delta L}{L}; \varepsilon_\varphi = \frac{\Delta\varphi R}{L}; \kappa = KR$$

$$c_{hh} = (EA)_{eq}; c_{\varphi\varphi} = \frac{(GJ)_{eq}}{R^2}; c_{\kappa\kappa} = \frac{(EI)_{eq}}{R^2}$$

Case study:

Analytical Model vs Experiments

(*Ref: OMAE2010-20895*)

Steel Tube Umbilical testing in instrumented bench:

Experimental arrangement description

Stress results in the steel tubes

Comparisons to the mathematical model (OMAE2010-20892)

Umbilical Description

Non-armoured STU

1 central steel tube ID 38.1mm WT 3.0mm polyethylene coating t = 1.0mm;

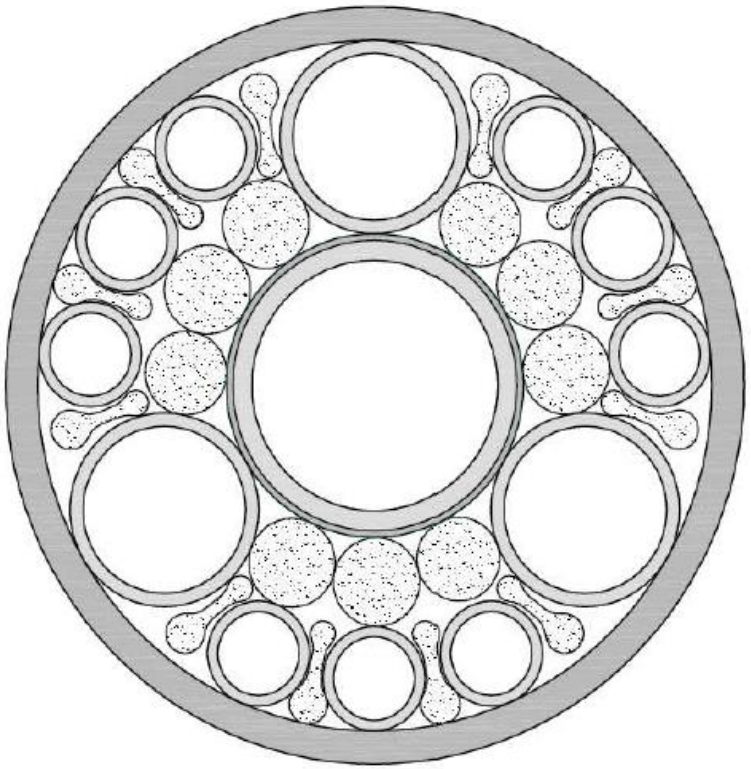
3 steel tubes ID 25.4mm, WT 2.0mm;

9 steel tubes ID 12.7mm, WT 2.6mm;

low-density polyethylene fillers (suitable arrangement of the steel tubes and avoid direct contact between them);

high-density polyethylene outer sheath

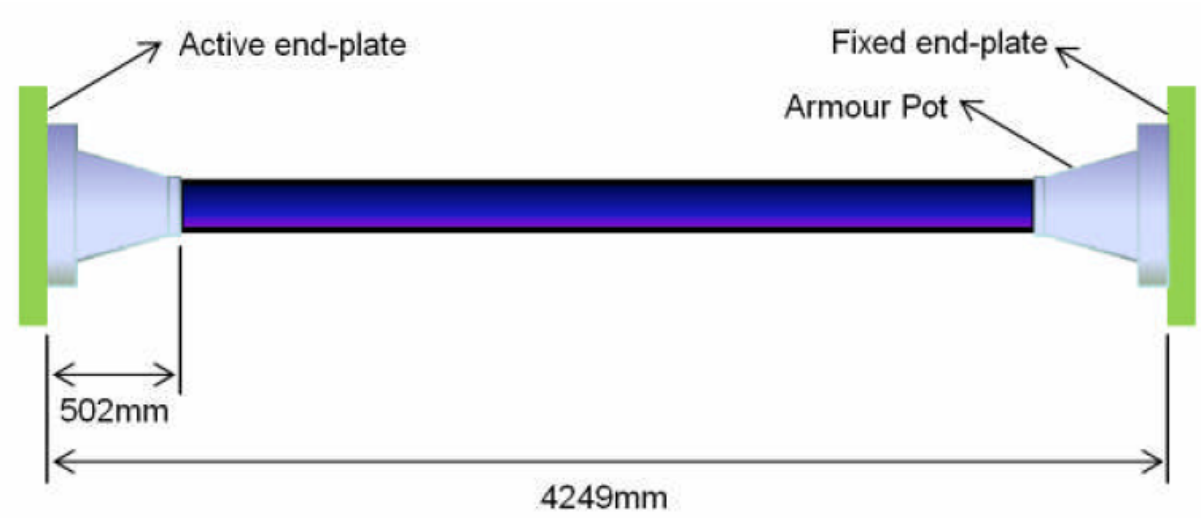
Heterogeneous layer type “B”



Experimental Arrangement – Test Bench

Test bench:

- Total 4249mm sample;
- Free umbilical length 3245mm;
- Steel tubes can be pressurized
- One fixed end plate, one active end plate
  - Tension
  - Bending



Experimental Arrangement – Test Bench

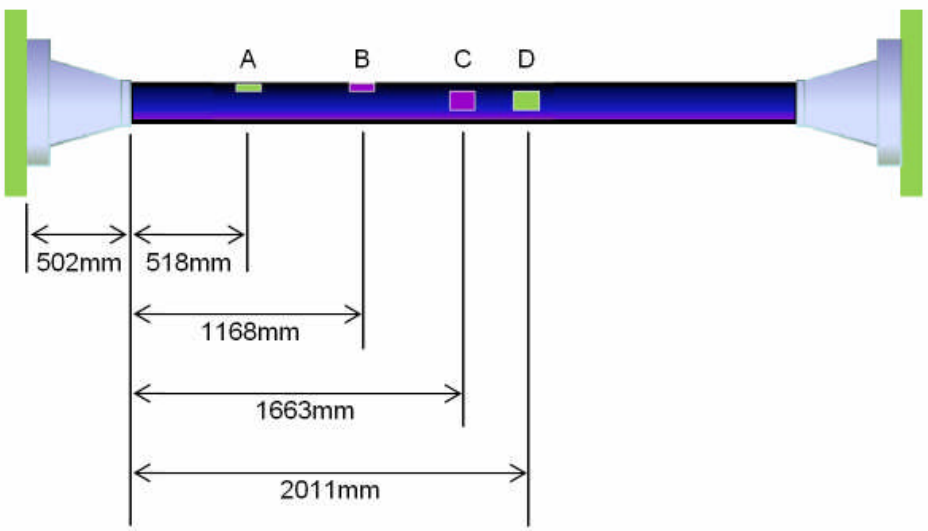
Fixed end-plate

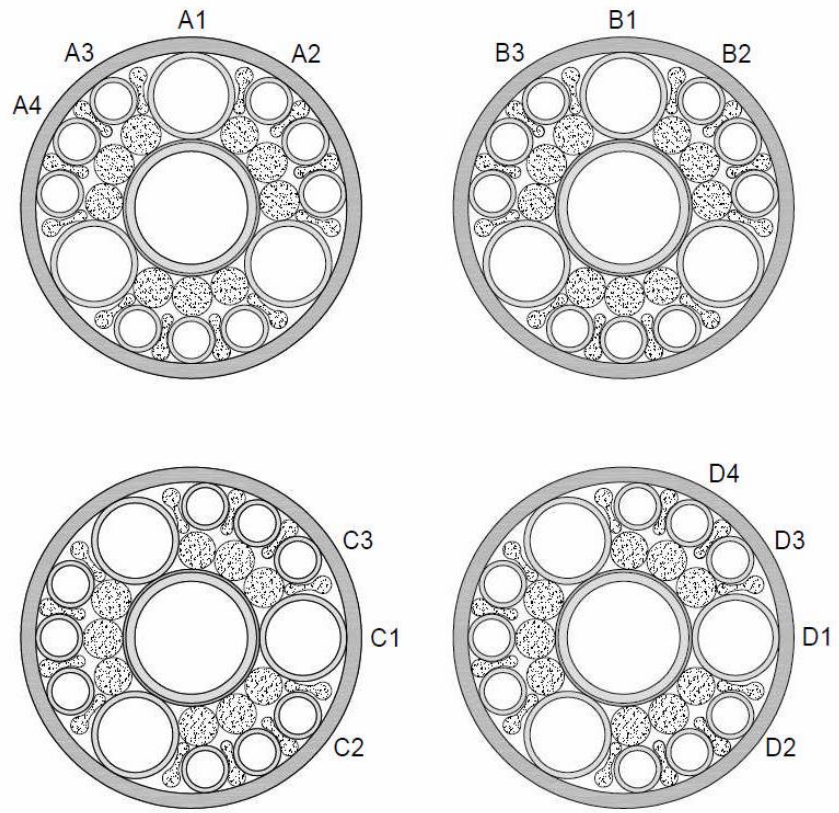
Active end-plate

Experimental Arrangement –Instrumentation

- Several strain gauges were attached at certain points along the umbilical length.

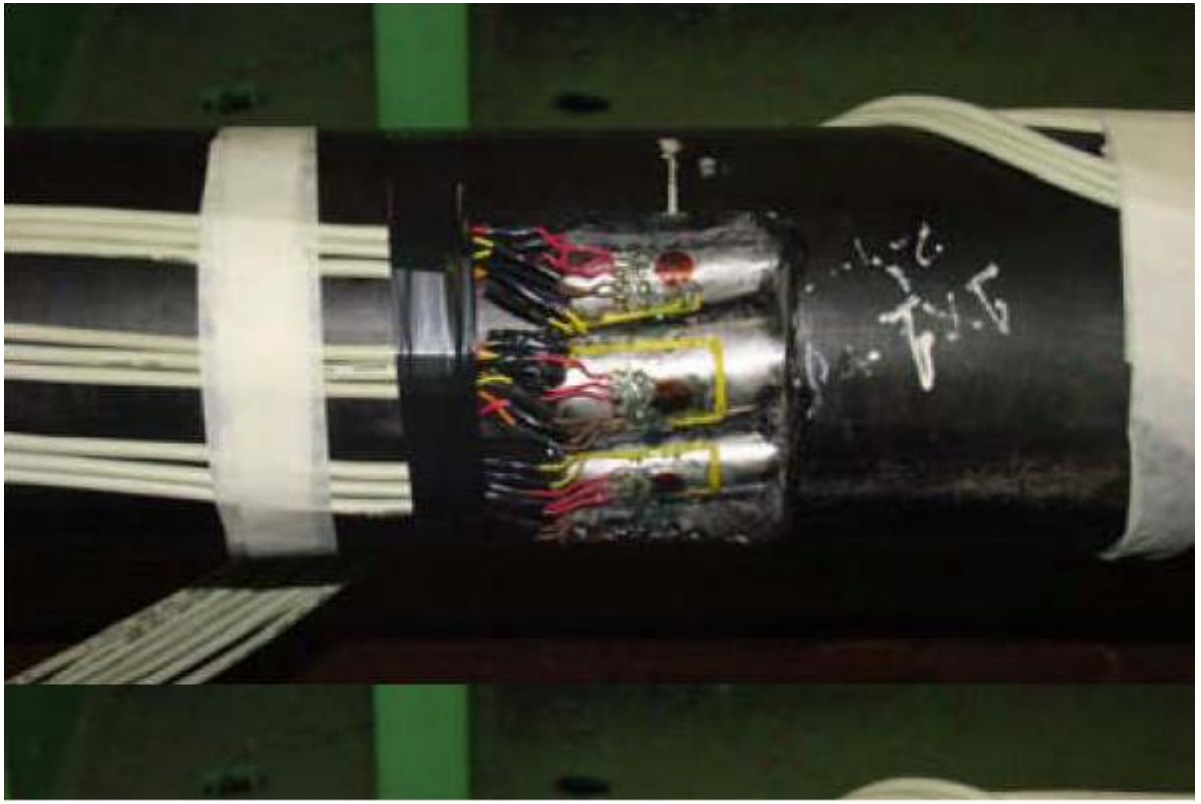
- In these points, windows were opened on the external sheath to allow access to the tubes.





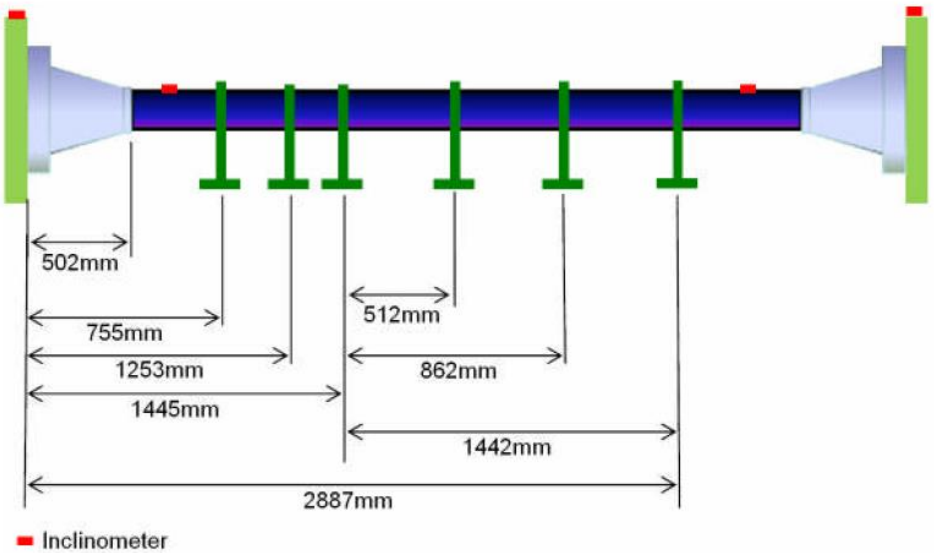
Experimental Arrangement –Instrumentation

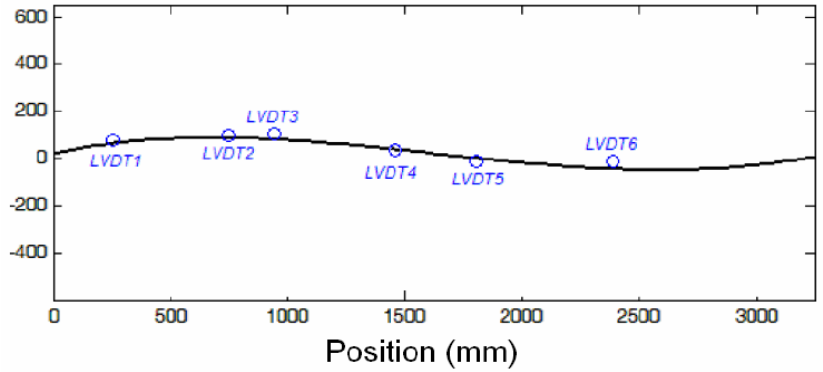
Instrumented window detail:



Experimental Arrangement –Instrumentation

- Curvature assessed through LVDTs placed along the umbilical length.
- Curve fit with third-order polynomial.





Experimental Results
Comparison to Mathematical Model

The stresses presented here were calculated from measurements of tubes A1 and A2.

They belong to window A, which presents larger curvature due to their position, for which larger bending stresses are expected.

The presented data refer to axial stress, since this is the main component on the external surface of the tube.

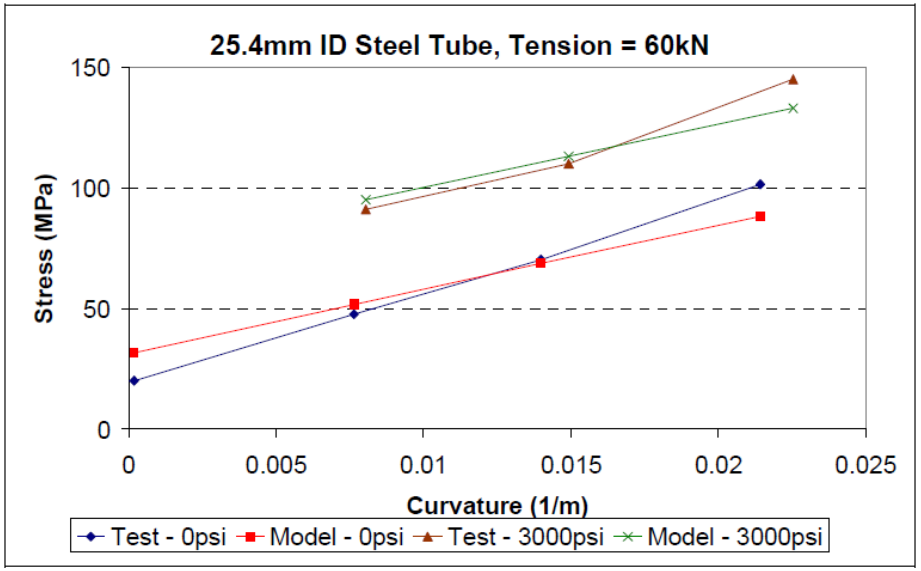
A representative subset of the complete test matrix was selected to illustrate the results encountered in the comparisons.

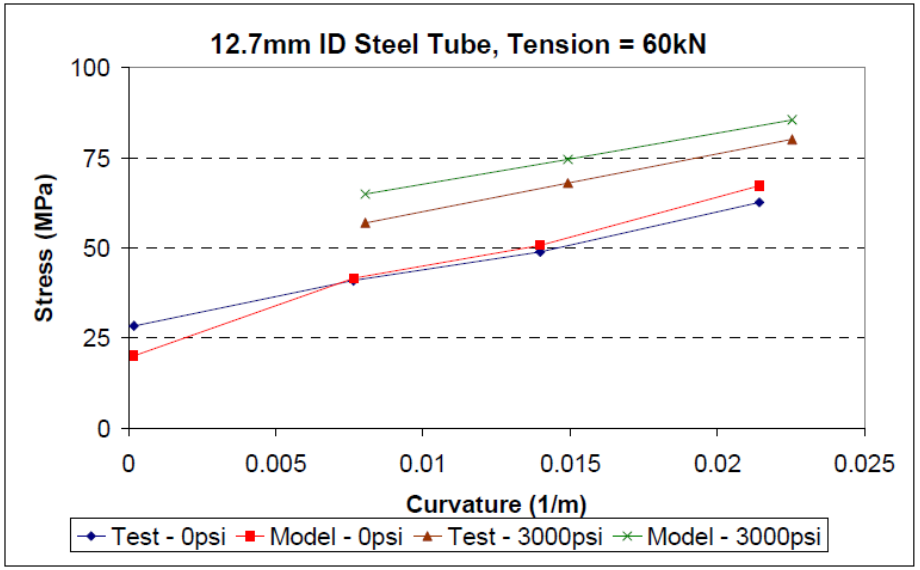
Load	Tension (kN)	Pressure (psi)	End Angle (deg)	Curvature * (1/m)
Minimum	10.0	0	-1.5	0
Maximum	90.0	3000	+1.5	0.023

*Due to end rotation.

Experimental Results
Comparison to Mathematical Model

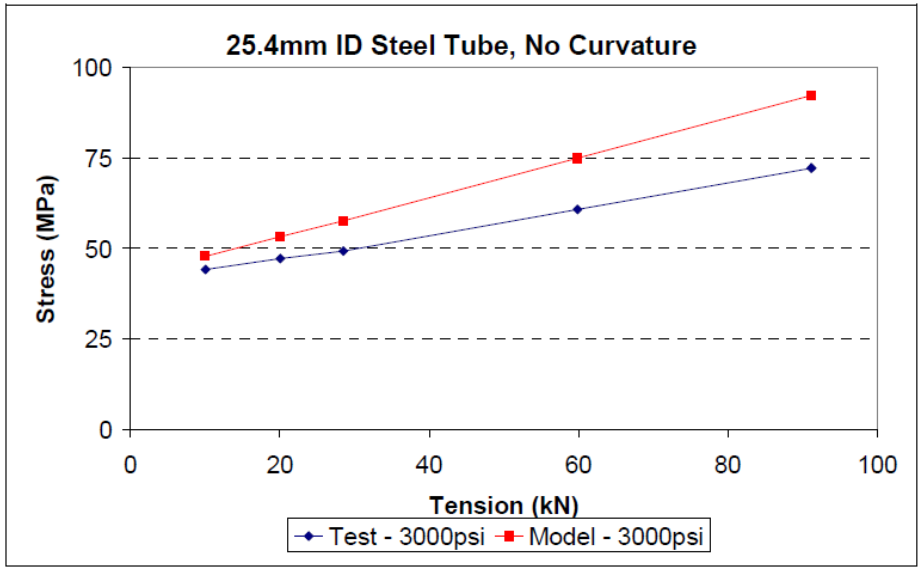
Stresses for varying curvature, tension 60kN

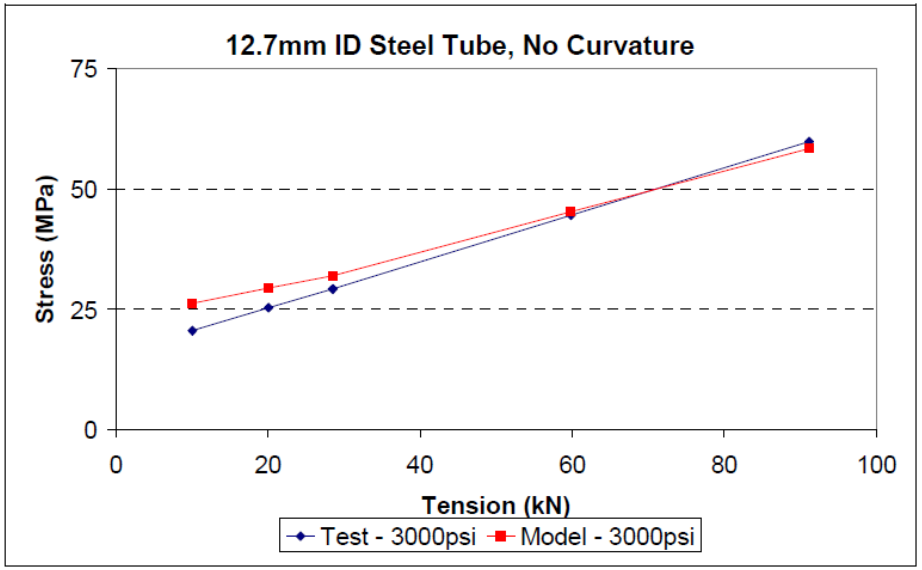




Experimental Results
Comparison to Mathematical Model

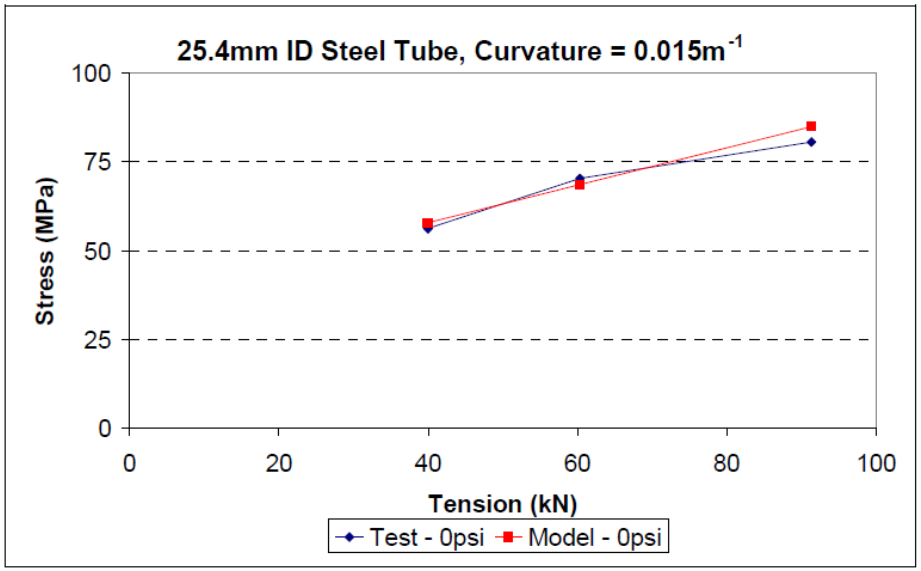
Stresses for varying tension, no curvature

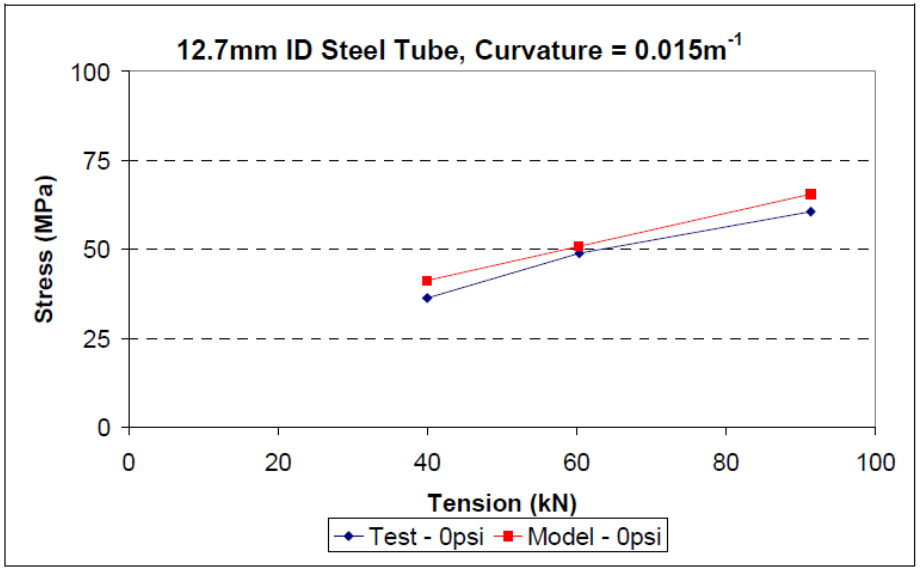




Experimental Results
Comparison to Mathematical Model

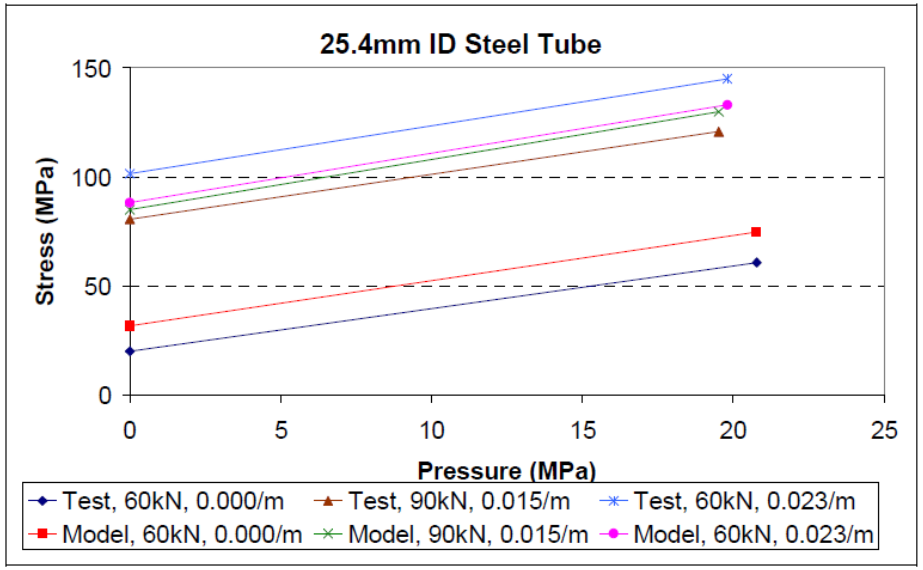
Stresses for varying tension, curvature 0.015m^{-1}

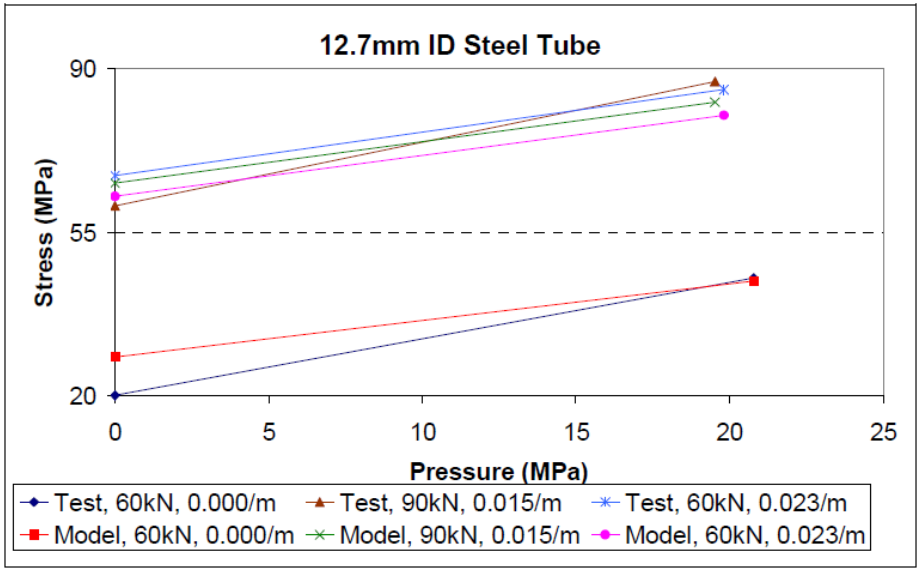




Experimental Results
Comparison to Mathematical Model

Stresses for varying pressure





Experimental Results
Comparison to Mathematical Model

The comparison of experimental data to model results indicates that the model can capture both qualitative and quantitative response aspects within the tested range.

Differences between experimental data and model results are within an acceptable level

- Uncertainties and deviations that are intrinsic to any experiment
- Hypotheses and simplifications included in the mathematical model

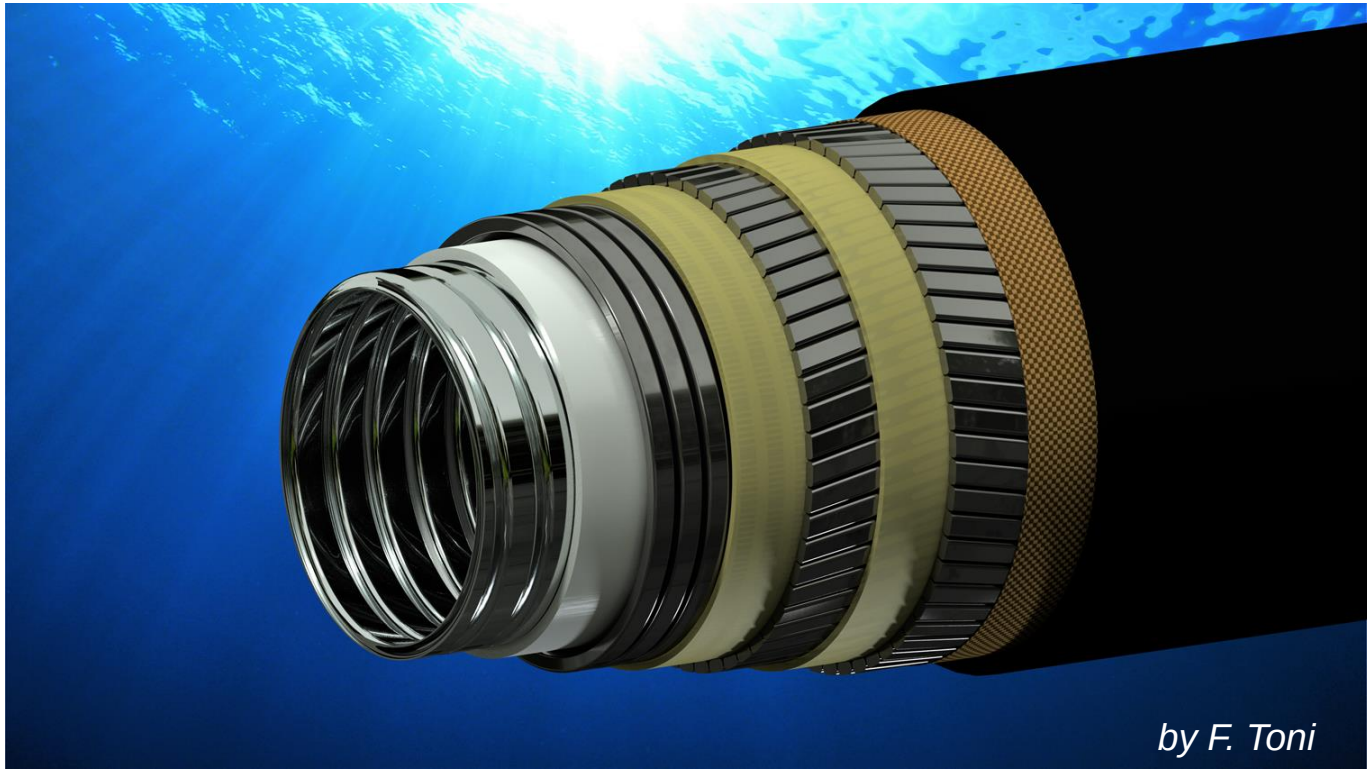
Summary

- Equilibrium and constitutive equations were stated for cylindrical layers and ‘solid’ cores.
- Equilibrium equations stated for umbilical cables with homogeneous layers (all elements in a given layer of the same type).
- Stiffness parameters were formulated.
- Experimental assesment made.

Flexible Pipes

Equilibrium Equations
Axisymmetric loads
Stiffness Parameters

Flexible Pipes



Recall equilibrium equations for helical layers

$$F_i = n_i.(EA)_i.\left[(\cos^3\alpha_i).\frac{\Delta L}{L_1} + (R_i.\sin\alpha_i.\cos^2\alpha_i).\frac{\Delta\varphi}{L_1} + (\sin^2\alpha_i.\cos\alpha_i).\frac{\Delta R_i}{R_i}\right]$$

$$M_{t,i} = \frac{n_i}{R_i}.\left[(GI_t)_i.\cos\alpha_i.\cos(2\alpha_i) + (EI_y)_i.sen\alpha_i.sen(2\alpha_i)\right]\Delta\alpha_i + \left[n_i(EA)_i R_i sen\alpha_i \cos^2\alpha_i\right]\frac{\Delta L}{L} + \left[n_i(EA)_i R_i^2.\cos\alpha_i.sen^2\alpha_i\right]\frac{\Delta\varphi}{L} +$$

$$+ n_i sen\alpha_i\left[(EA)_i sen^2\alpha_i - \frac{(GI_t)_i\cos^2\alpha_i}{R_i^2} - \frac{(EI_y)_i sen^2\alpha_i}{R_i^2}\right].\Delta R_i$$

$$(p_{c,i} - p_{c,i-1}).b_i = -\left[\frac{E_i A_i \sin^2\alpha_i\cos^2\alpha_i}{\mathrm{R_i}}\right]\frac{\Delta L}{L_1} - \left[E_i A_i \sin^3\alpha_i\cos\alpha_i\right]\frac{\Delta\varphi}{L_1} - \left[\frac{E_i A_i \sin^4\alpha_i}{R_i^2}\right]\Delta R_i$$

$$\Delta t_i = -\frac{t_i}{2E_i}.\left(p_{c,i} + p_{c,i-1}\right) - \left(\nu_i t_i \cos^2\alpha_i\right).\frac{\Delta L}{L_1} - \left(\nu_i t_i \mathrm{R_i}\sin\alpha_i\cos\alpha_i\right).\frac{\Delta\varphi}{L_1} - \left(\frac{\nu_i t_i \sin^2\alpha_i}{\mathrm{R_i}}\right)\Delta R_i$$

$$\Delta\alpha_i = \cos^2\alpha_1.R_1\frac{\Delta\varphi}{L_1} + \sin\alpha_1.\cos\alpha_1.\left(\frac{\Delta R}{R_1} - \frac{\Delta L}{L_1}\right)$$

(5*n* algebraic equations for the helical layers)

Compatibility equations and equibrium on the cross section

$$\Delta R_{i+1} = \Delta R_i + \frac{1}{2}(\Delta t_{i+1} + \Delta t_i) + g_i$$

(n+m-1) eqs.

$$\left.\begin{aligned} \sum_{i=1}^{n+m} F_i &= F \\ \sum_{i=1}^{n+m} M_{t,i} &= M_t \end{aligned}\right\}$$

2 eqs.

(*n+m+1* additional equations)

Summing up:

- 4 m equations for the plastic layers;
- 5n equations for the helical layers;
- n+m+1 additional equations (geometric compatibility and equilibriumcompatibilidade e equilíbrio)

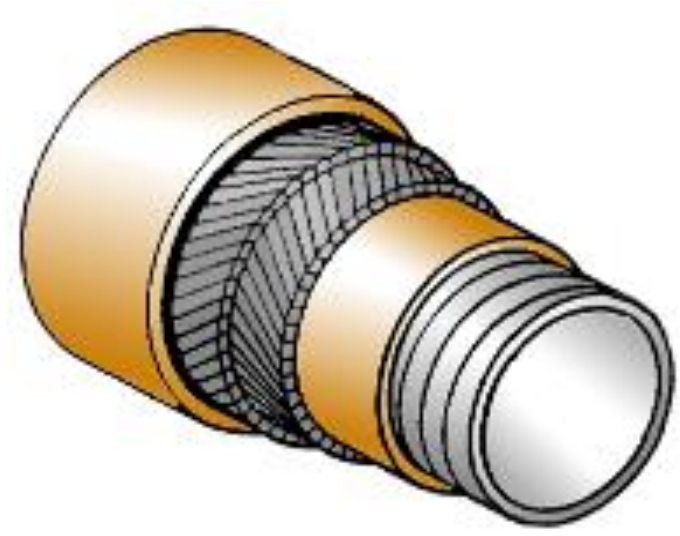
Total: 6n + 5m + 1 equations

Stiffness Matrix for a flexible pipe

$$\begin{Bmatrix} F \\ M_T \\ F_{ip,p} \\ F_{op,p} \end{Bmatrix} = \begin{bmatrix} k_{11,p} & k_{12,p} & k_{13,p} & k_{14,p} \\ k_{21,p} & k_{22,p} & k_{23,p} & k_{24,p} \\ k_{31,p} & k_{32,p} & k_{33,p} & k_{34,p} \\ k_{41,p} & k_{42,p} & k_{43,p} & k_{44,p} \end{bmatrix} \cdot \begin{Bmatrix} \dfrac{\Delta L}{L_0} \\ \dfrac{\Delta \varphi}{L_0} \\ \Delta R_{i,p} \\ \Delta R_{o,p} \end{Bmatrix}$$

Case study:
Analytical Model vs Experiments

(*Ramos Jr, et al. 2015*)

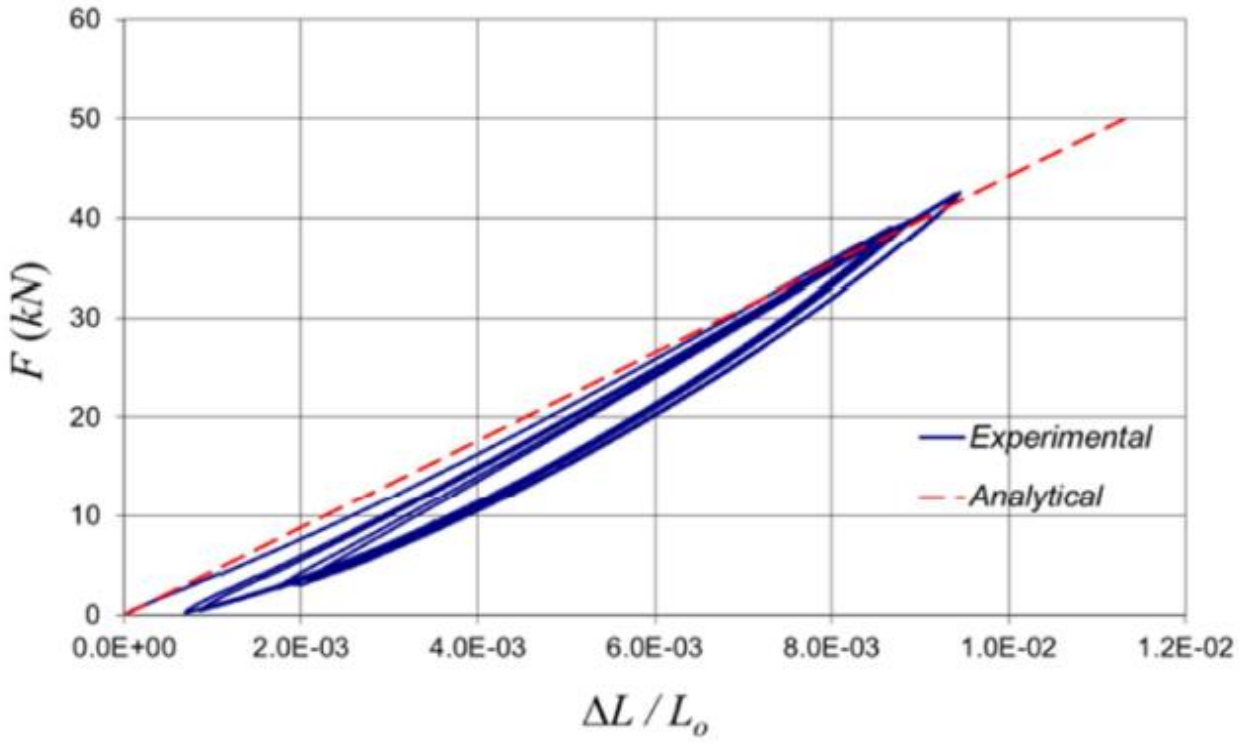


Flexible Pipe:
2.5”, 5 structural layers

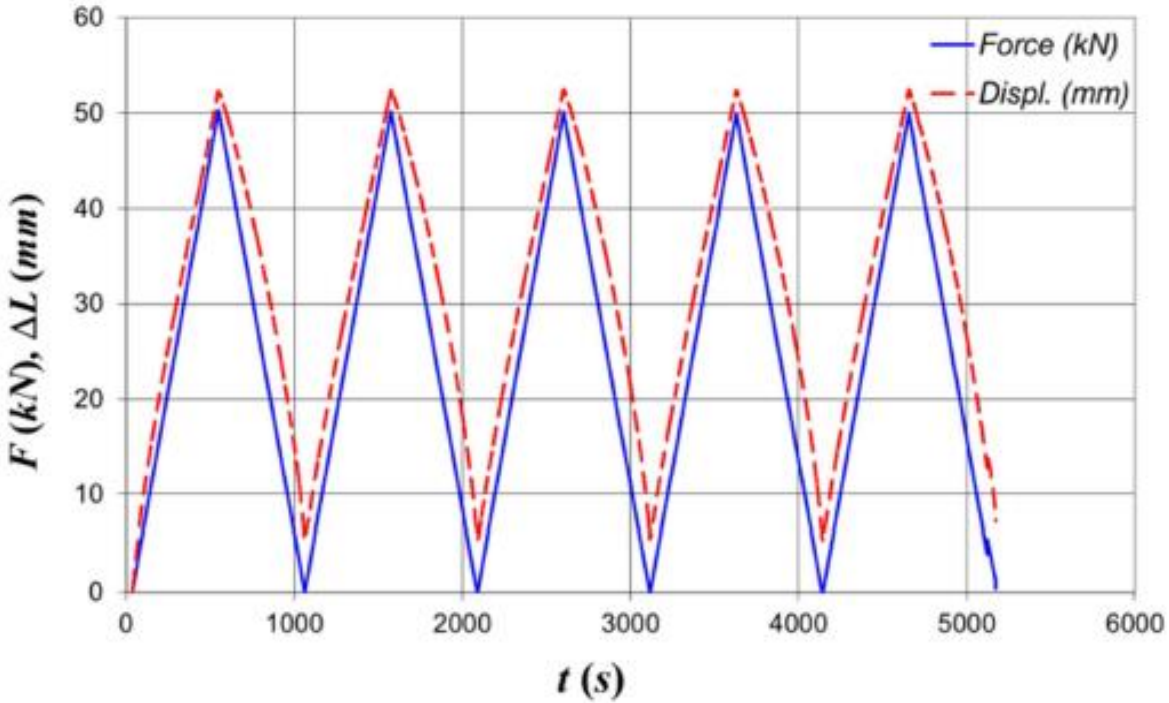
Layer	Proprieties
1	E_1 = 190 GPa, ν_1= 0.3, $R_{i,1}$= 33.37mm, $R_{o,1}$ = 35mm, n_1 = 1, α_1 = 85.8°, t_1 = 1.63mm, b_1 = 12mm, A_1 = 19.56 mm^2
2	E_2 = 280 MPa, ν_2= 0.4, $R_{i,2}$= 35mm, $R_{o,2}$ = 41mm, t_2 = 6 mm, A_2 = 1432.57 mm^2, J_2 = 2.082×10^6 mm^4
3	E_3 = 207 GPa, ν_3= 0.3, $R_{i,3}$= 41mm, $R_{o,3}$ = 43mm, n_3 = 29, α_3 = 55.5°, t_3 = 2mm, b_3 = 5mm, A_3 = 10.0 mm^2
4	E_4 = 207 GPa, ν_4= 0.3, $R_{i,4}$= 43 mm, $R_{o,4}$ = 45 mm, n_4 = 29, α_4 = -55.5°, t_4 = 2 mm, b_4 = 5 mm, A_4 = 10.0 mm^2
5	E_5 = 320 MPa, ν_5= 0.4, $R_{i,5}$= 45mm, $R_{o,5}$ = 50mm, t_5 = 5 mm, A_5 = 1492.26 mm^2, J_5 = 3.376×10^6 mm^4

Experimental set up at IPT laboratory

Tensioning test



Tensioning test



Flexible Pipe Stiffness Matrix (IS):

K_{ij}	j = 1	j = 2	j = 3	j = 4
i = 1	1.443E+7	-3.137E+4	1.295E+8	5.122E+8
i = 2	-3.137E+4	8.632E+4	3.761E+6	-3.431E+4
i = 3	1.295E+8	3.761E+6	6.017E+10	-8.228E+9
i = 4	5.122E+8	-3.431E+4	-8.228E+9	2.998E+10

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