Efficient and accurate methods for computational simulation of netting structures with mesh resistance to opening

DOCTORAL THESIS

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Ferrol, November 2014

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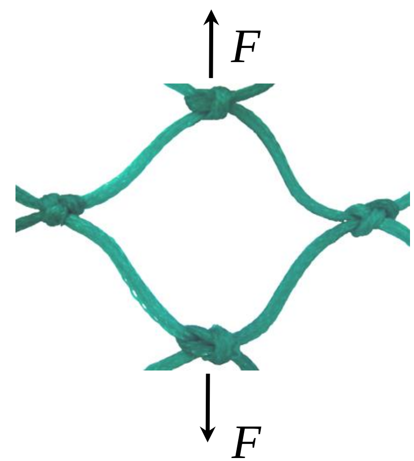
- **Advantages of numerical simulation applied to fishing nets**

- Different conditions can be simulated
- Reduces the dependency on experimental tests (experimental validation is always required)
- Provides information that is difficult to measure (forces in nodes, drag distribution…)

- **Relevance of the resistance to opening**



- It is a key factor in the selective performance of a trawl
- The inclusion of the resistance to opening in the numerical model is necessary to accurately approximate the net shape

Introduction

- **Objective of this thesis:**

> To include the mesh resistance to opening in numerical simulation of net structures

- **Steps:**

Modelling the resistance to opening

1. Develop a twine model including the mesh resistance to opening → Article No. 1
2. Measure the resistance to opening → Article No. 2

Numerical simulation

3. Solve the equations that govern the net structure → Article No. 3
4. Implementation of the twine model → Article No. 4

Outline

Introduction

Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Article No. 2: Quantifying MRO of netting panels

Article No. 3: Calculating the equilibrium shape of netting structures

Article No. 4: Numerical model for netting with MRO

Conclusions

Future work

Unpublished results

Article No. 1

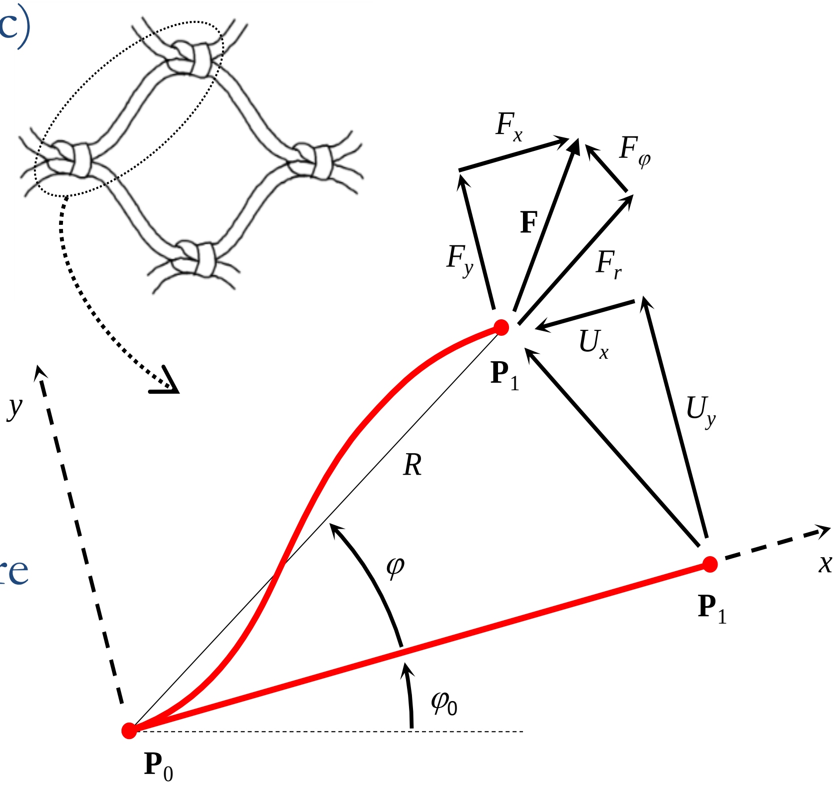
Nonlinear stiffness models of a net twine to describe mesh resistance to opening of flexible net structures

Journal of Engineering for the Maritime Environment

Published online on 9th June 2014

Description of the twine model

- **Literature**
  - O'Neill's analytical solutions (exact, asymptotic)
  - Priour's linear model
- **Assumptions from O'Neill's model**
  - Based on bending stiffness *EI*
  - 2D double-clamped beam
  - x and y coordinates and F_x and F_y forces
  - The insertion angle φ_0 remains fixed
  - Bending moment proportional to the curvature
- **Contributions of the new model**
  - Solution obtained by FEM (ANSYS)
  - Twine extension is considered
  - Polar coordinates R and φ and F_r and F_φ



Dimensional analysis

- **Independent variables**

$$F = F(L, EA, EI, R, \varphi)$$

- **Dimensionless similarity parameters**

$$\Pi_0 = f = F\frac{L^2}{EI} \qquad \Pi_2 = \varphi$$

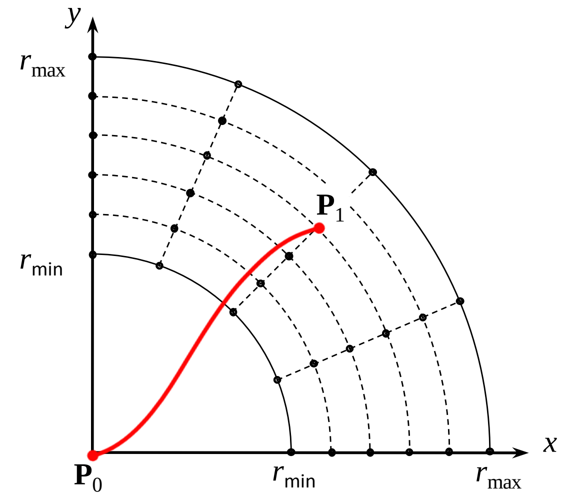
$$\Pi_1 = r = \frac{R}{L} \qquad \Pi_3 = \gamma = L^2\frac{EA}{EI}$$

- **Non-dimensional equation**

$$f = f(r, \varphi, \gamma) \longrightarrow f^{EA_i} = f^{EA_i}(r, \varphi)$$

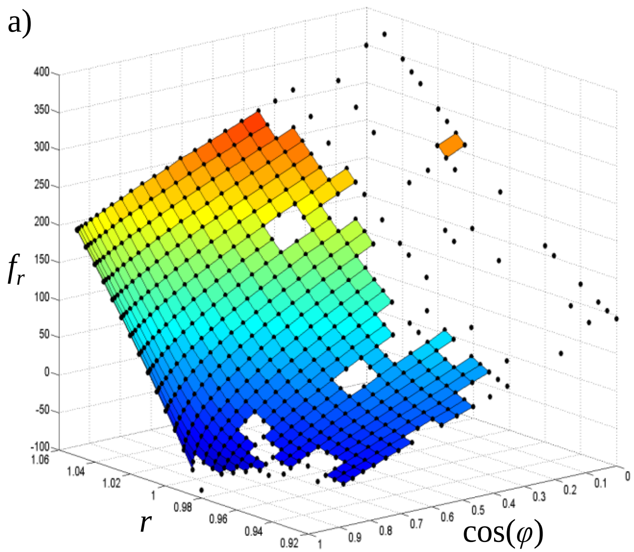
Force-displacement response

- Enforced displacement constraints in polar coordinates
- Geometric nonlinear static analysis to obtain the reaction forces



Grid surface representation of the dimensionless forces in polar coordinates (f_r, f_φ)

a)



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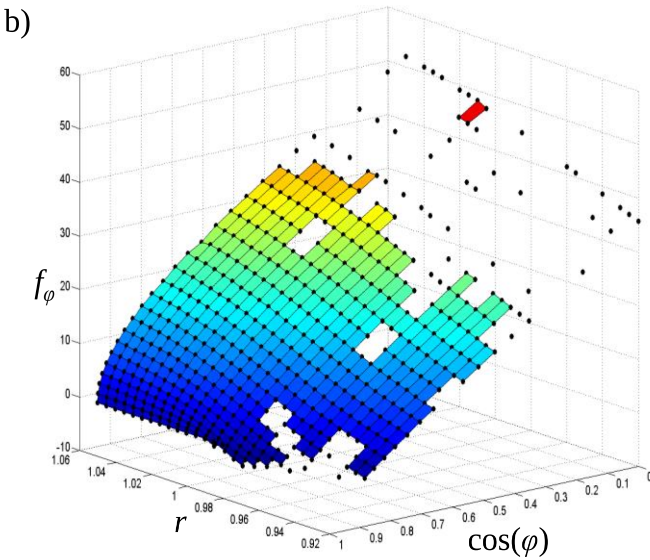


Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Approximate force models

1. Polynomial surface fitting

$$f(r,\cos\varphi)=\sum_{0<i+j<m+n} c_{ij} r^{i} (\cos\varphi)^{j}$$

Force	m	n	R^2
f_r	2	3	0.994
f_φ	1	4	0.985

2. Spline surface fitting of the potential energy

$$v_{ij}(r,\varphi)=\sum_{k=0}^{3}\sum_{l=0}^{3} c_{kl}^{ij}(r-r_i)^k(\varphi-\varphi_j)^l$$

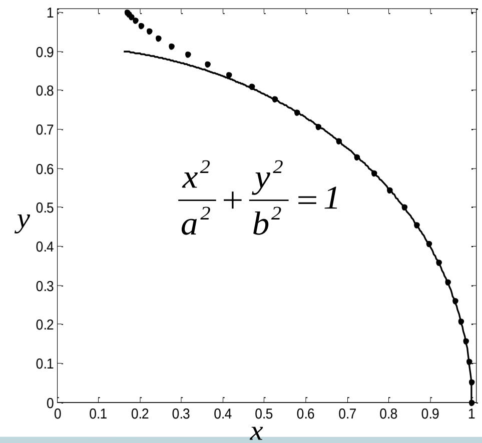
Conservative field →

$$\begin{cases} f_r^{ij}(r,\varphi)=\dfrac{\partial v_{ij}}{\partial r} \\ f_\varphi^{ij}(r,\varphi)=\dfrac{1}{r}\dfrac{\partial v_{ij}}{\partial \varphi} \end{cases}$$

3. Spring-based model

$$f_r(r,\cos\varphi)=EA\left(\frac{L^2}{EI}\right)(r-r_{eq}(\cos\varphi))$$

$f_y >>> f_x$ →

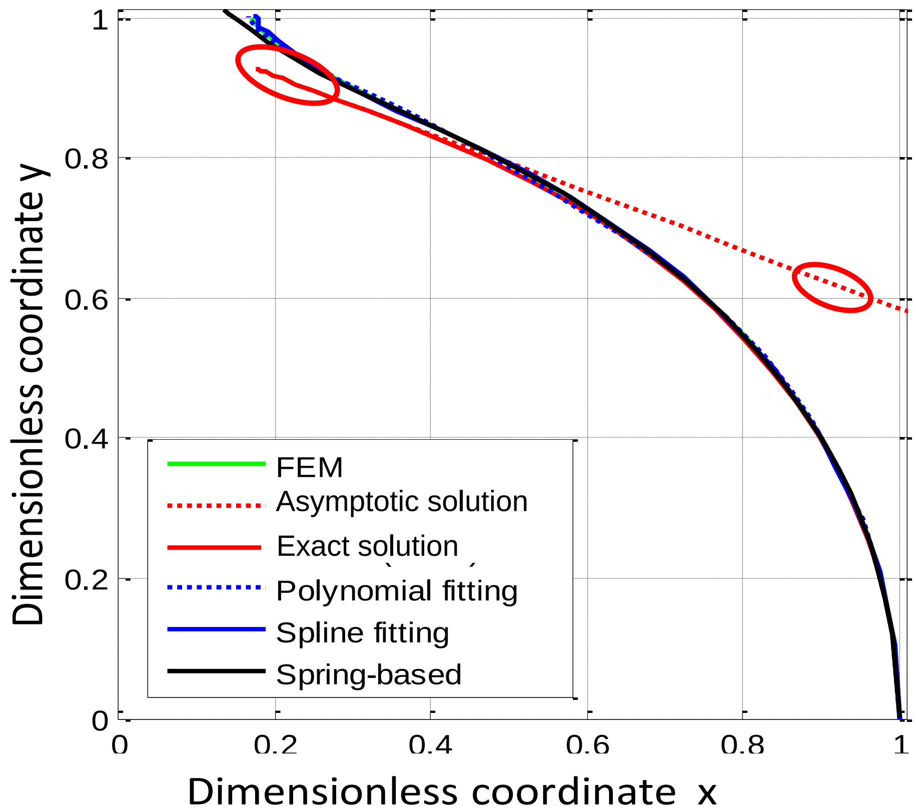


Test problem and results

- **Description:**
  - A twine with fixed φ_0
  - A vertical force ($F_y > 0$) is applied to $\mathbf{P_1}$

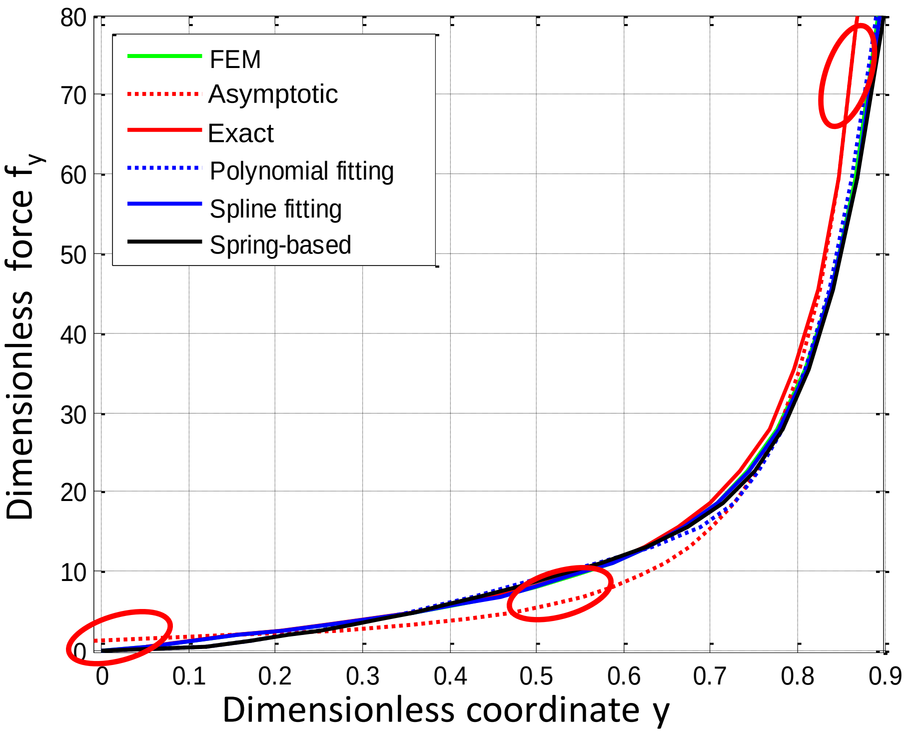
- **Different models are compared**
  - ANSYS solution (FEM)
  - Asymptotic solution
  - Exact solution
  - Model No. 1 Polynomial fitting
  - Model No. 2 Spline fitting
  - Model No. 3 Spring based

- Trajectory of point $\mathbf{P}_1$ as the vertical force increases

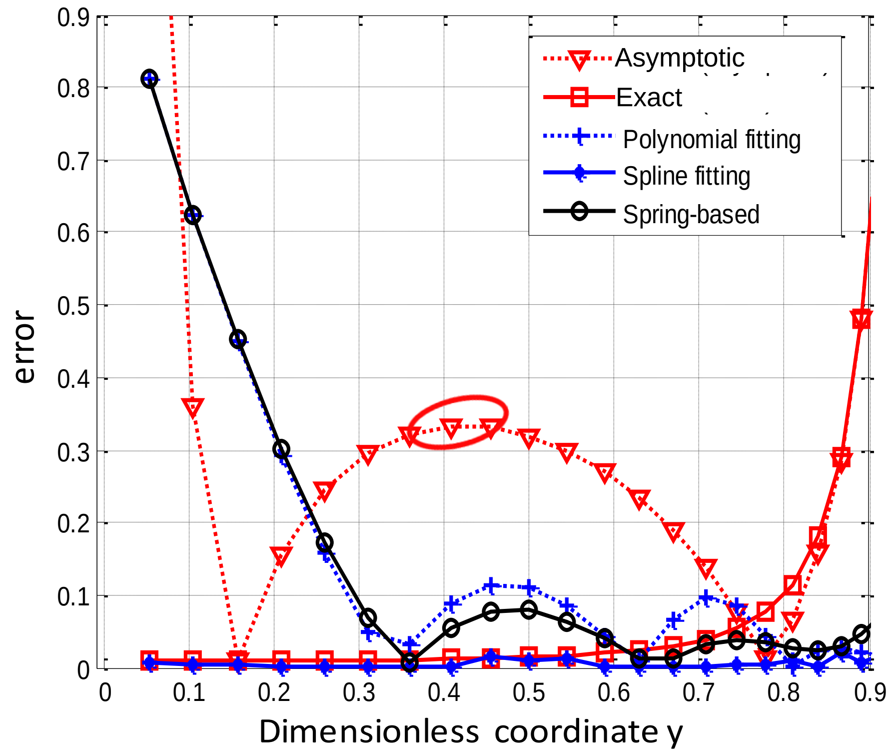


Article No. 1: Nonlinear stiffness models of a twine to describe MRO

- Force-displacement response



- Relative error in force



Summary of the models

Features	Linear model	Exact solution	Asymptotic solution	Proposed models No. 1	Proposed models No. 2	Proposed models No. 3
Takes into account the bending stiffness (EI)	✘	✓	✓	✓	✓	✓
Takes into account twine axial stiffness (EA)	✘	✘	✘	✓	✓	✓
Forces as explicit function of position	✓	✘	✘	✓	✓	✓
Highly accurate	✘	✓	✘	✓	✓	✓
Easy to implement in existing formulations	✓	✘	✘	✓	✘	✓
Conservative force field	✓	✘	✘	✘	✓	✘
Compatible with large axial deformations	✘	✘	✘	✘	✘	✓
Compatible with large transversal forces	✓	✓	✓	✓	✓	✘

Article No. 2

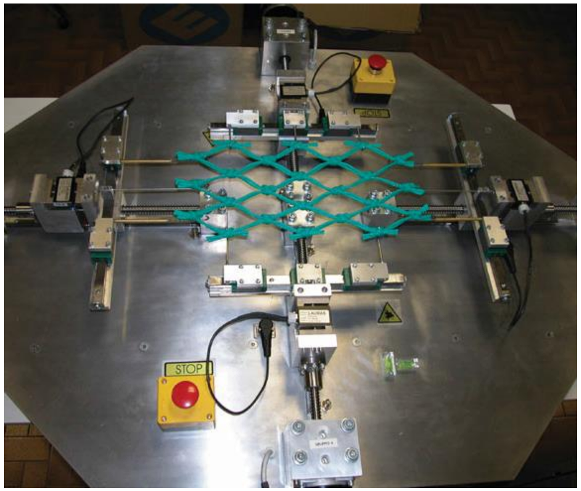
Quantifying mesh resistance to opening of netting panels: experimental method, regression models and parameter estimation strategies

ICES Journal of Marine Science

Published online on 24th July 2014

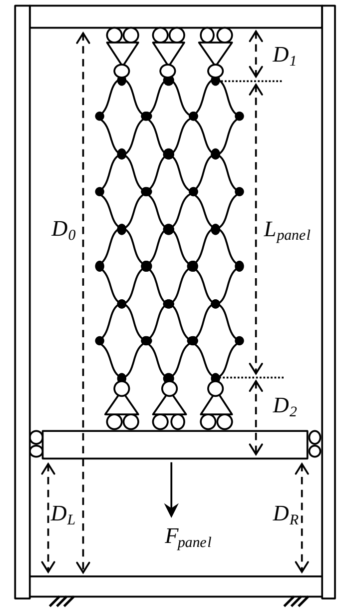
Description of the experimental set-up

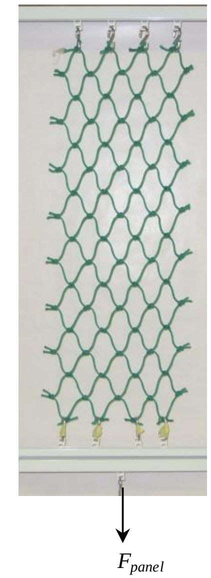
- **Experimental set-up from Sala**



- Expensive measuring instrument
- Imposed normal and transversal displacements
- Asymptotic solution as model
- Fixed constraint estimation strategy
- Disagreement between num. and exp. results

- **Proposed experimental set-up**

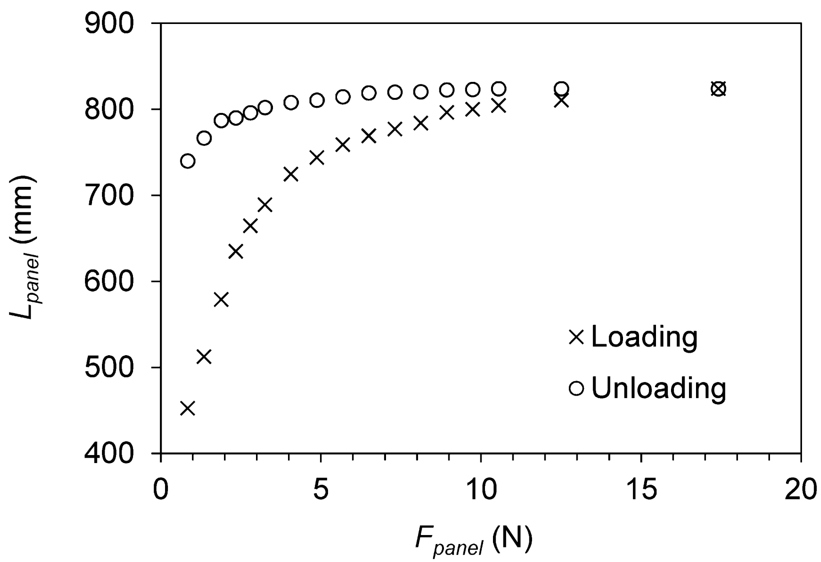




- Simple and inexpensive
- Imposed load in normal direction
- Previous twine models as models
- Different estimation strategies

Methodology

- **Experimental methodology**
  - A normal load is applied and the normal elongation of the panel is measured
  - Different materials were tested
  - Loading and unloading cycle



- **Data analysis**
  - Parameters for the regression: EI , b, L_{twine}, φ_0
  - Theoretical models for MRO:
    - Exact solution
    - Asymptotic solution
    - Polynomial fitting model
    - Spline fitting model
  - 4 parameter estimation strategies

Estimation strategy	Constraint applied on parameter		
	L_{twine}	b	φ_0
1	-	-	-
2	Min/max	Min/max	Min/max
3	Fixed	Fixed	Min/max
4(Sala)	-	-	Fixed

Summary of the results (loading cycle)

<table>
<tr><th></th><th colspan="2">Strategy No. 1</th><th colspan="2">Strategy No.2</th><th colspan="2">Strategy No.3</th><th colspan="2">Strategy No.4 (Sala)</th></tr>
<tr><th></th><th>R^2</th><th>Estimates</th><th>R^2</th><th>Estimates</th><th>R^2</th><th>Estimates</th><th>R^2</th><th>Estimates</th></tr>
<tr><td>Asymptotic solution</td><td colspan="2">-</td><td colspan="2">-</td><td colspan="2">-</td><td>~0.7 for stiff materials</td><td>Only EI Inconsistent results</td></tr>
<tr><td>Exact solution</td><td rowspan="3">>0.995</td><td rowspan="3">Ocassionally out of physical limits or inconsistent</td><td rowspan="3">>0.995</td><td>Small confidence intervals</td><td rowspan="3">>0.990</td><td rowspan="3">Acceptable results reducing the computational effort</td><td rowspan="3">>0.990</td><td rowspan="3">Inconsistent</td></tr>
<tr><td>Polynomial fitting</td><td>Medium confidence intervals</td></tr>
<tr><td>Spline fitting</td><td>Unusually high confidence intervals</td></tr>
</table>

Conclusions

- **Start the analysis with Strategy No. 3**
- **Use Strategy No. 2 if Strategy No. 3 fails**
- **Use the same model to estimate the parameter and to predict the netting behaviour**
- **Limitations of this work**

- Difficulties to fit the unloading cycle
- Does not consider the knot width
- Accurate pre-tension cycles were not applied to the materials

Article No. 3

Assessing the suitability of gradient-based energy minimization methods to calculate the equilibrium shape of netting structures

Computers and structures

Published online on 10th February 2014

Methods to calculate the static equilibrium

- **State of the art**

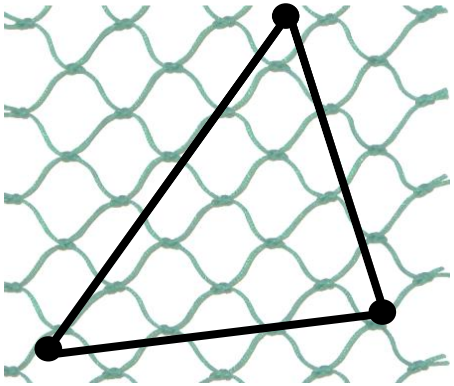
Method	Advantages	Disadvantages
Newton Raphson Iteration (Priour)	- Fast	- Local convergence - Ill-conditioned Jacobian matrix
Dynamic simulation (Lee, Li, Takagi)	- Robust and reliable	- Very slow (hours)
Gradient-based energy minimization method (Le Dret)	- Avoids matrix operations - Not affected by the Jacobian	- Only for conservative forces

- **Objectives of this work**

- Test different gradient-based energy minimization methods
- Include non-conservative forces in the analysis
- Compare Newton iteration and energy minimization methods

Numerical model

- **Formulation developed by Priour**
  - Direct formulation of finite element method
  - Netting is discretized with triangular elements
  - Ropes and cables are discretized with bar elements



- **Applied forces**
  - Elastic forces in finite elements
  - Weight and buoyancy
  - Hydrodynamic drag (Fluid-structure interaction is not considered)
  - Contact with the seabed

- **Equilibrium equations**

$$\mathbf{F}(\mathbf{q}) = \mathbf{f}^{twine} + \mathbf{f}^{hydro} + \mathbf{f}^{weight} + \mathbf{f}^{buoyancy} + \mathbf{f}^{contact} \rightarrow \mathbf{F}(\mathbf{q}_{equilibrium}) = 0$$

Newton Raphson iteration

$$\mathbf{F}(\mathbf{q}) = 0$$

$$\mathbf{d}_i = -\mathbf{J}^{-1}(\mathbf{q}_i)\,\mathbf{F}(\mathbf{q}_i)$$ Calculate search direction **d** with the Jacobian **J**

$$\mathbf{q}_{i+1} = \mathbf{q}_i + \lambda \mathbf{d}_i$$ Perform step with step length λ

- **Two approaches to achieve a globally convergent algorithm**

1) Line search

$$\left|\mathbf{F}\left(\mathbf{q}_i + \lambda_j \mathbf{d}_i\right)\right| < (1-\alpha)\left|\mathbf{F}\left(\mathbf{q}_i\right)\right|$$

- Calculate the step length λ with a line search and the Armijo rule

2) Step limit

$$\lambda_i = \begin{cases} \lambda_{\max} / \max(\mathbf{d}_i) & \text{if } \max(\mathbf{d}_i) > \lambda_{\max} \\ 1 & \text{otherwise} \end{cases}$$

- Limit the step length λ to a fraction of the characteristic length (1%)
- Also used in method 1 when the line search stagnates (often)

Gradient-based energy minimization methods

- **Find the equilibrium position by minimizing the total energy *v***

$$\min_{\mathbf{q}} v(\mathbf{q}) = E_p - W_{nc}$$

E_p: total potential energy of the system

W_{nc}: work done by non-conservative forces

- **The gradient of *v* is the opposite of the force vector**

$$\mathbf{g} = \nabla v(\mathbf{q}) = -\mathbf{F}(\mathbf{q})$$

- **Tested 10 gradient-based methods → only 3 methods succeed:**

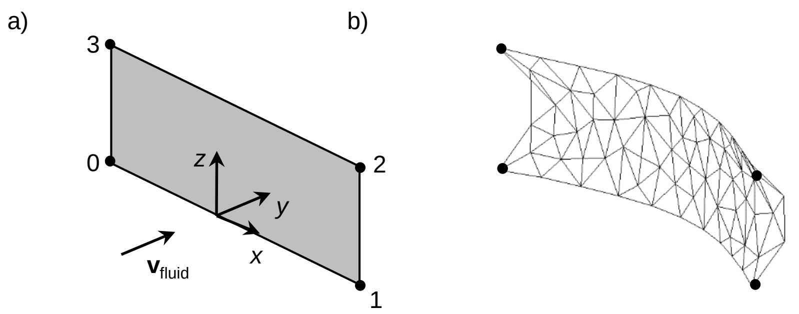
- Nonlinear conjugated gradient
- Limited memory BFGS (LBFGS)
- Newton-CG Trust region

- **After comparing the 3 methods, LBFGS is the best suited to find the equilibrium of netting structures**

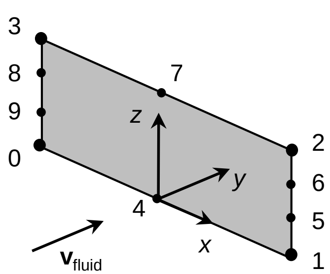
List of benchmark problems

- **A set of benchmark problems is defined (400 variables)**
- **Reference solution obtained via dynamic simulation**

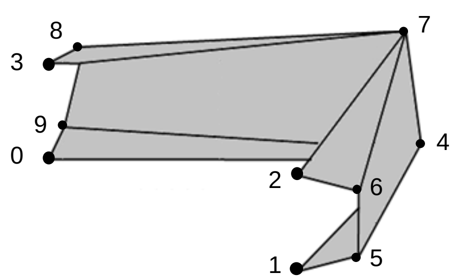
Test 1



Test 2A

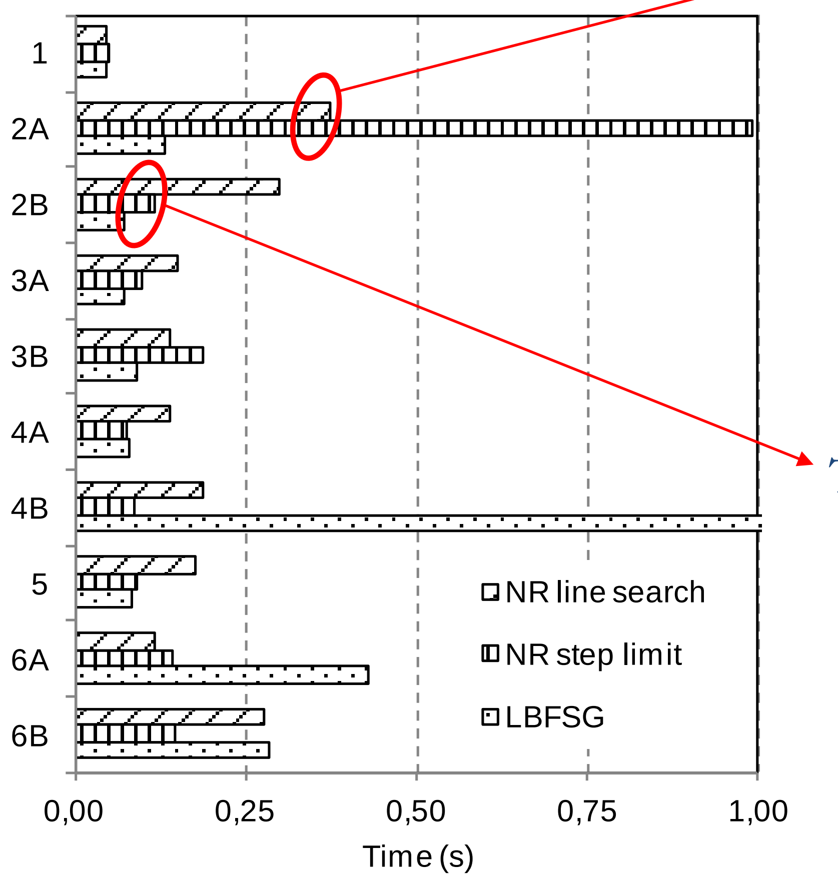


Test 2B

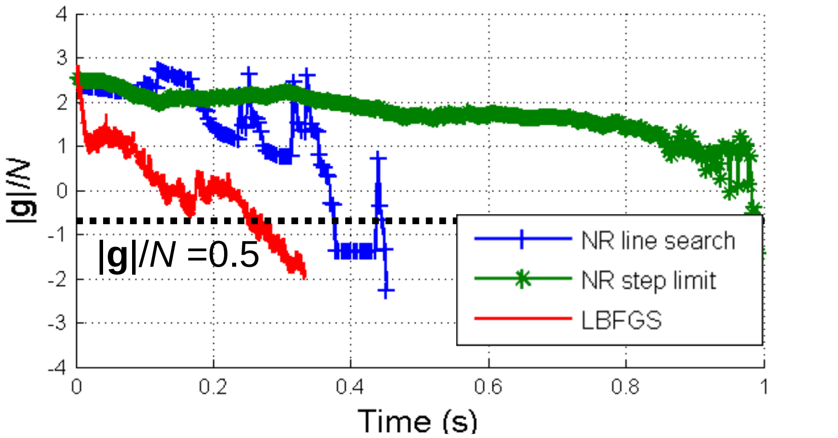


Feature	**Test case**									
	1	2A	2B	3A	3B	4A	4B	5	6A	6B
Large displacements	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
High initial stress	-	✓	-	-	-	-	-	-	-	-
Far initial position	-	✓	-	-	-	-	-	-	✓	-
Netting with low compression stiffness	-	-	-	✓	-	✓	✓	✓	✓	✓
Netting with very low compression stiffness	-	-	-	-	✓	✓	✓	✓	✓	✓
Cable	-	-	-	-	-	✓	✓	-	✓	✓
Cables, high stiffness	-	-	-	-	-	-	✓	-	-	-
Ground contact	-	-	-	-	-	-	-	✓	✓	✓
Panel parallel to flow	-	-	-	-	-	-	-	-	✓	✓

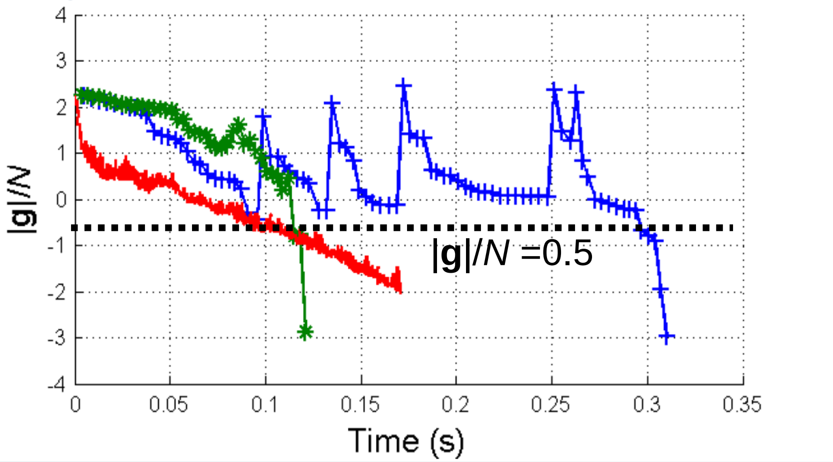
LBFGS versus Newton-Raphson: General trend



Test 2A: Large deformations. Far initial position

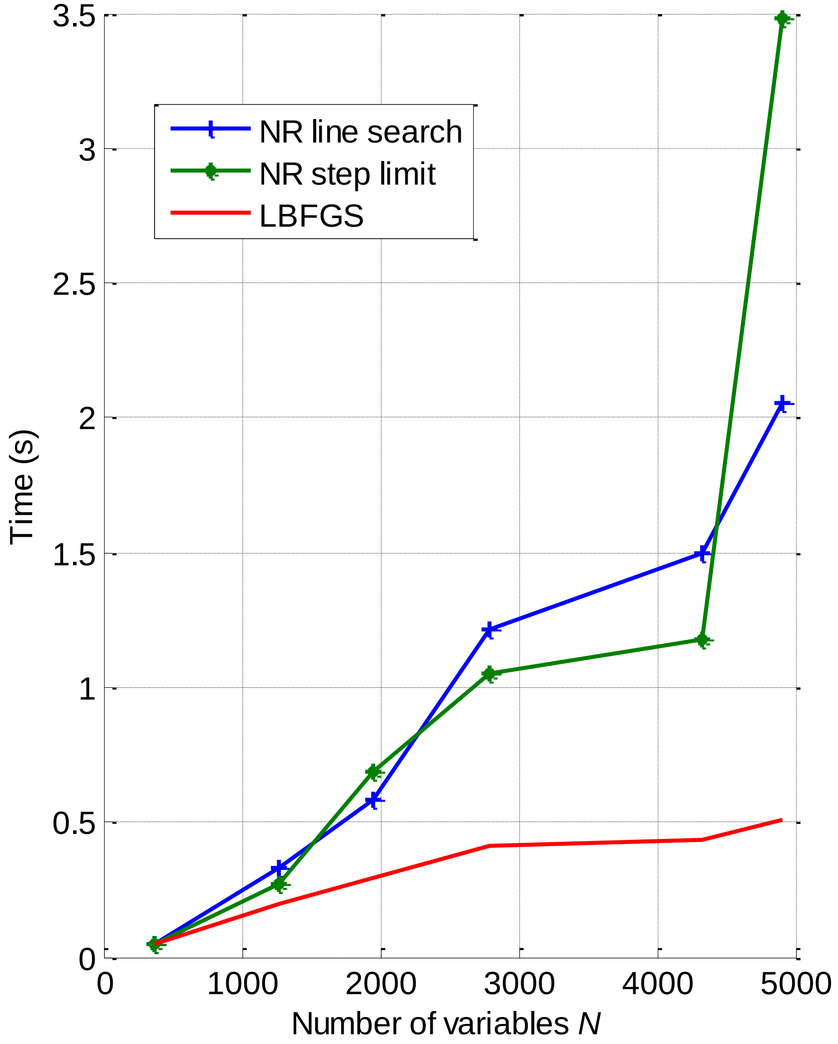


Test 2B: Large deformations. Close initial position



Effect of the problem size

- **Solved Test1**
  - Problem size: 363 – 5000 variables
- **The advantage of LBFGS over NR increases with the problem size**
  - It avoids matrix factorization
  - ×4 times faster (5000 variables)
- **The performance of NR is irregular**
  - Chances of getting tangled mesh configurations during the iteration increase with the number of finite elements used to model the netting



Summary of the results

Features	Newton-Raphson	LBFGS
Robust	✘	✓
Easier to program	✘	✓
Faster in achieving medium precision solution	✘	✓
Faster in achieving high precision solution	✓	✘
Faster with the problem size	✘	✓

Newton-Raphson and LBFGS are complementary methods

- The use of each method depends on the application
- Both methods can be combined to solve problems

Article No. 4

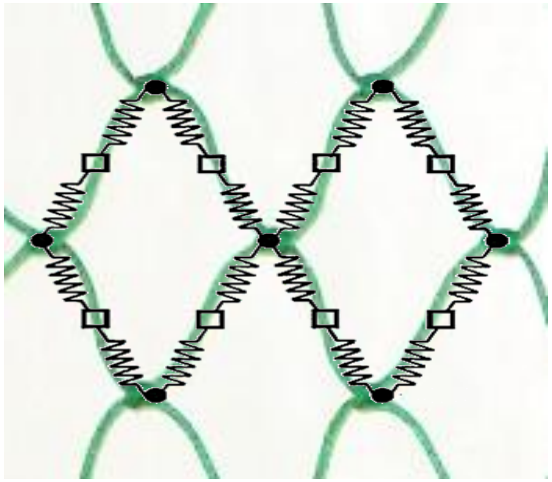
An efficient and accurate model for netting structures with resistance to opening

Submitted to the *International Journal of Solids and Structures* on 25th April 2014

Article No. 4: Numerical model for netting with MRO

Description of the model

- **Lumped mass formulation (Takagi, Lee, Li)**
  - Point mass (knots) interconnected by springs
  - Intermediate nodes are usually required
  - The knot size is not considered



- **Objectives of this work**
  - Incorporate the **polynomial fitting twine model** in the lumped mass formulation
  - Include the knot size
  - Compare results from simulation with experimental measurements
  - Compare the new model with the traditional lumped mass formulation

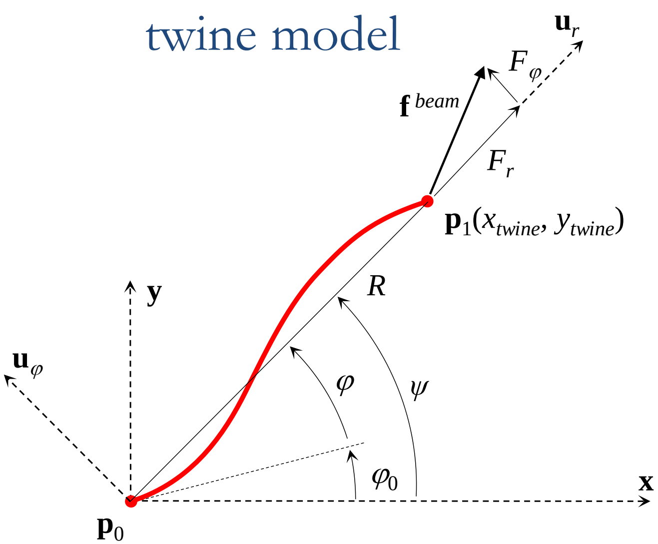
Numerical model for a twine

- **Twine model for large axial deformations**

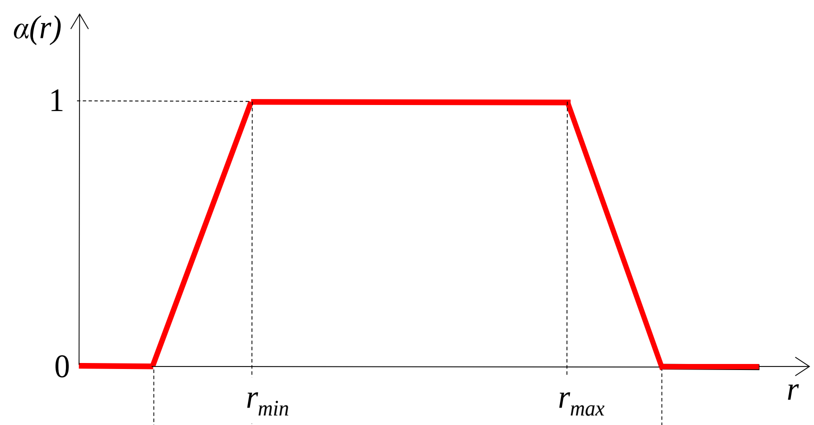
$$\mathbf{f}^{twine}(r,\varphi)=\alpha\mathbf{f}^{beam}+(1-\alpha)\mathbf{f}^{spring}$$

$$\mathbf{f}^{beam}=(F_r^{beam},F_\varphi^{beam})$$

Polynomial fitting twine model



Blending function



$$\mathbf{f}^{spring}=(F_r^{spring},0)$$

$$F_r^{spring}(r)=EA(r-1)$$

Spring for large axial deformation

Article No. 4: Numerical model for netting with MRO

Numerical model for a mesh

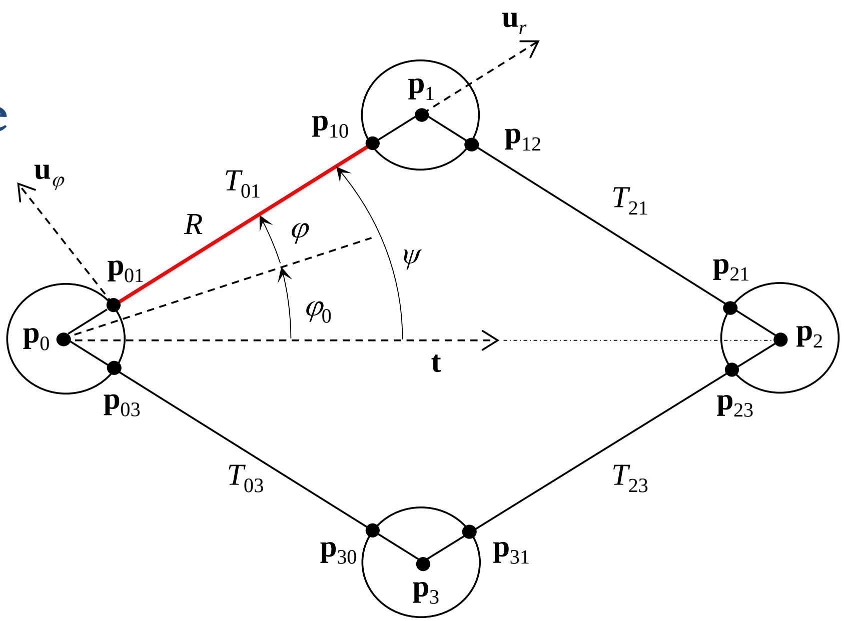
- **A local frame is defined for each twine**

$$\{\mathbf{u}_r, \mathbf{u}_\varphi, \mathbf{u}_z\}$$

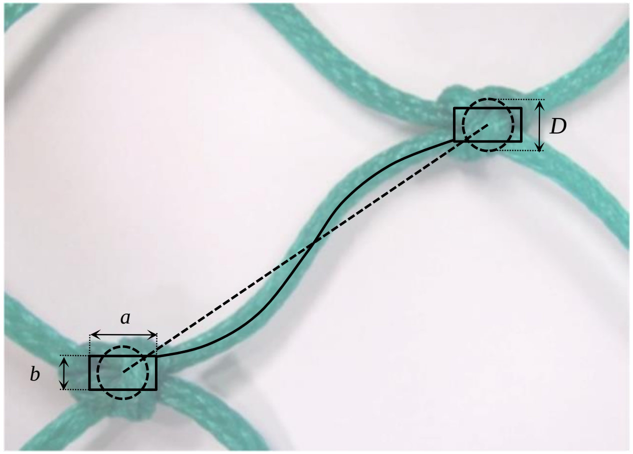
$$\mathbf{u}_r = (\mathbf{p}_1 - \mathbf{p}_0)/|\mathbf{p}_1 - \mathbf{p}_0|$$

$$\mathbf{u}_z = \mathbf{t} \times \mathbf{u}_r$$

$$\mathbf{u}_\varphi = \mathbf{u}_r \times \mathbf{u}_z$$

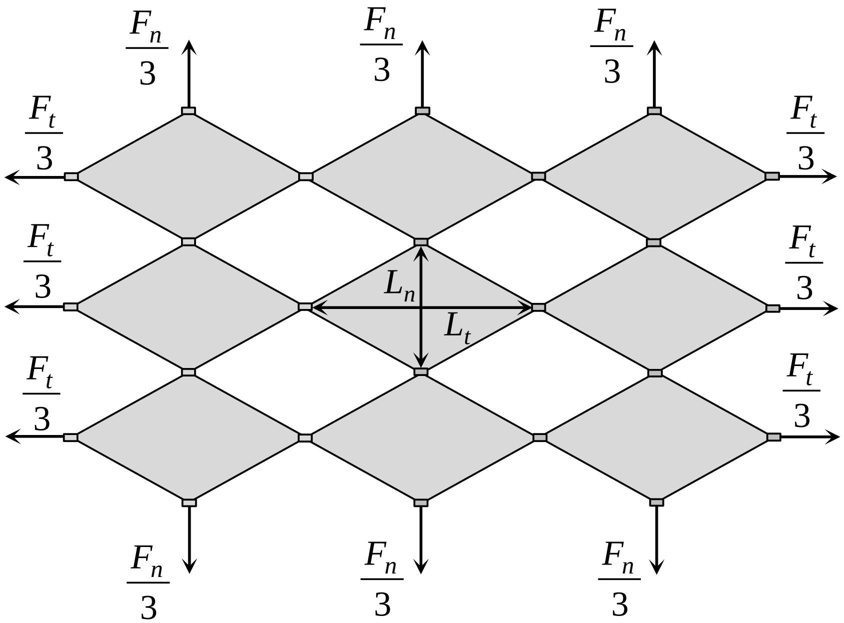


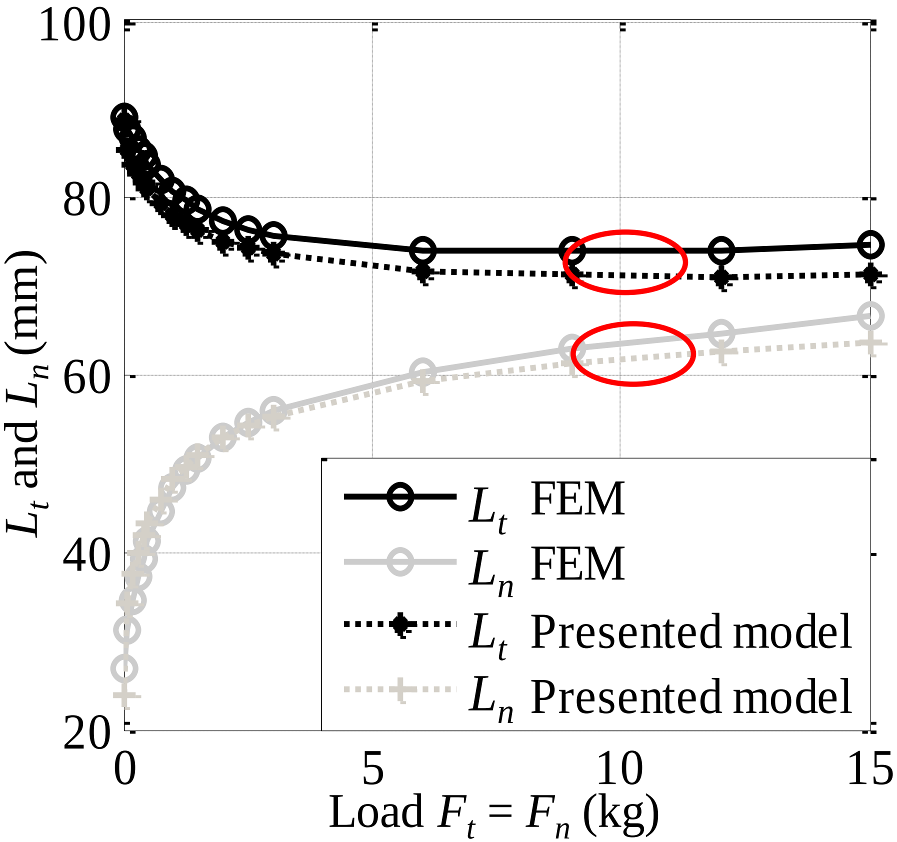
- **Spherical knot shape**
  - The diameter is the average between the effective knot width *a* and height *b*



Numerical validation

- Comparison of the proposed model with FEM solution
- A net panel is stretched in normal and transversal direction



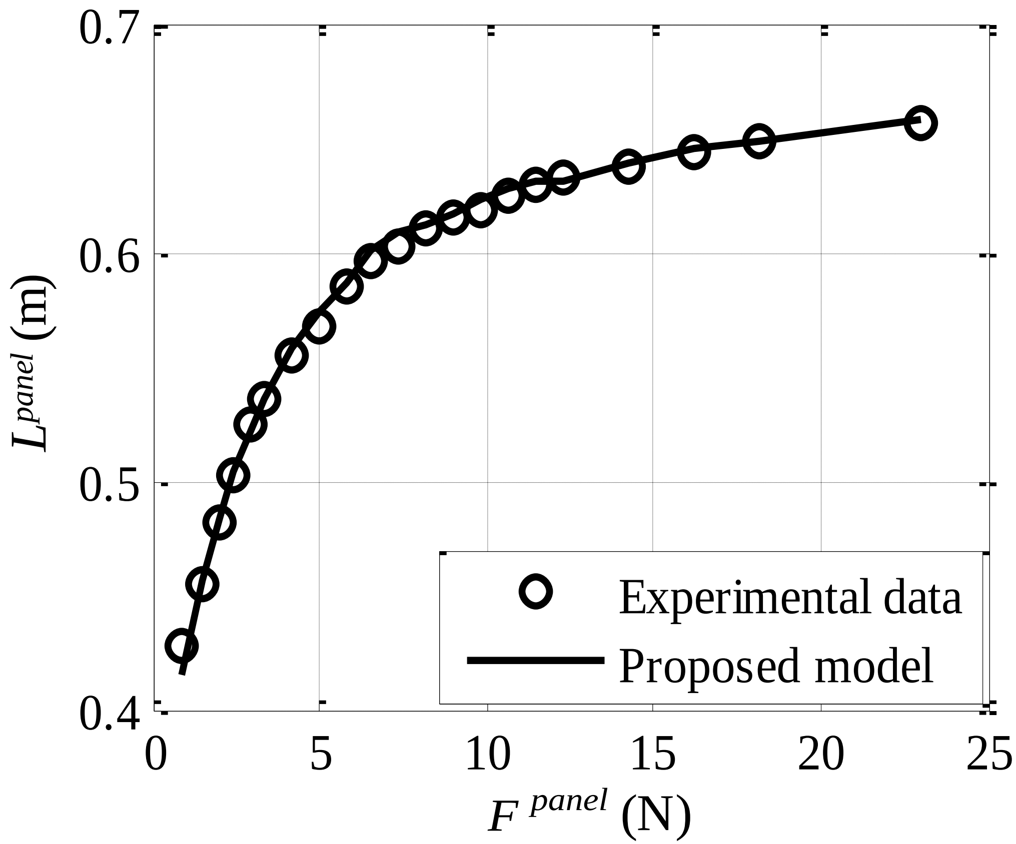


Experimental validation

- **Reproduce the experiment from Article No. 2 for one sample panel**

- **Assumptions to validate**
  - Lumped mass approximation
  - Spherical knots

- **Results from fitting**
  - $\boldsymbol{R^2 = 0.997}$
  - $EI = 74.9 \pm 8.7\%$ Nmm^2
  - $L_{twine} = 41.5 \pm 2.6\%$ mm
  - $D = 2.1 \pm 0.7\%$ mm
  - $\varphi_0 = 22.7 \pm 0.4\%$ rad

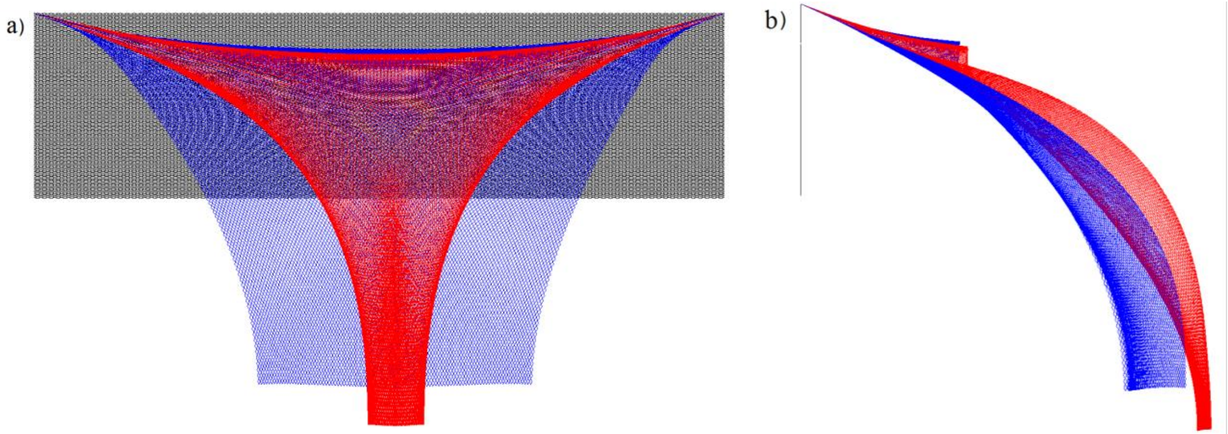


Analysis of the computational efficiency

- **Compare the proposed model with a classical spring model**

- 100×100 mesh panel = 61812 variables
- Vertical force is applied to the bottom edge
- The panel is exposed to a constant water current normal to the panel

	Presented model	**Classical linear spring model**
Numerical meshes	10000	10000
Total solution time (s)	305.5	162.4
Force evaluation calls	10933	10804
Time per call(ms)	27.9	15.0
Time per call per mesh(μs)	2.79	1.50



Summary of the results

Features	**Lumped mass + springs**	**Lumped mass + polynomial fitting twine model**
Takes into account the bending stiffness (*EI*)	✗	✓
Takes into account twine axial stiffness (*EA*)	✓	✓
Compatible with large deformations	✓	✓
Easy to program	✓	✗
Conservative field	✓	✗
Avoids intermediarte nodes	✗	✓
Includes the knot size	✗	✓

Both models have a similar computational overhead

Outline

Introduction

Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Article No. 2: Quantifying MRO of netting panels

Article No. 3: Calculating the equilibrium shape of netting structures

Article No. 4: Numerical model for netting with MRO

Conclusions

Future work

Unpublished results

Conclusions

- **The proposed twine models have been demonstrated to be accurate, efficient, and easy to program**
- **The experimental procedure to measure the MRO is easy and accurate**
- **The LBFGS method has been proved to be efficient and accurate in the calculation of the equilibrium shape in problems with large number of variables**
- **The presented models and methods have been successfully applied to simulate netting structures: the twine model has been implemented, the LBFGS method has been used to solve the equilibrium equations and the experiment has been numerically reproduced**

Outline

Future work

- Validate the present work with fishing trawls
- Apply parallelization techniques to improve efficiency
- Analyse the effect of how the loading history and plastic deformation affect the MRO
- Apply the presented models and methods to computer-aided design of trawls → topology optimization of trawls
  → testing the selective performance of cod-end

Outline

Introduction

Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Article No. 2: Quantifying MRO of netting panels

Article No. 3: Calculating the equilibrium shape of netting structures

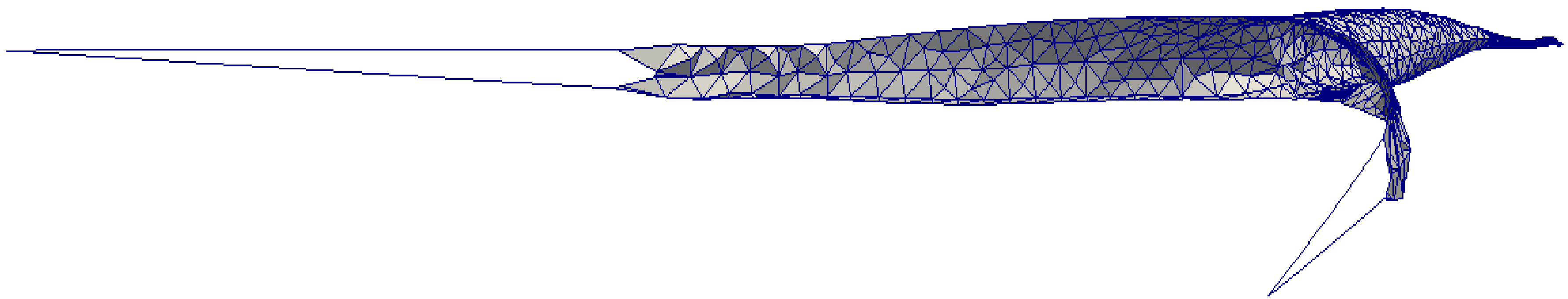
Article No. 4: Numerical model for netting with MRO

Conclusions

Future work

Unpublished results

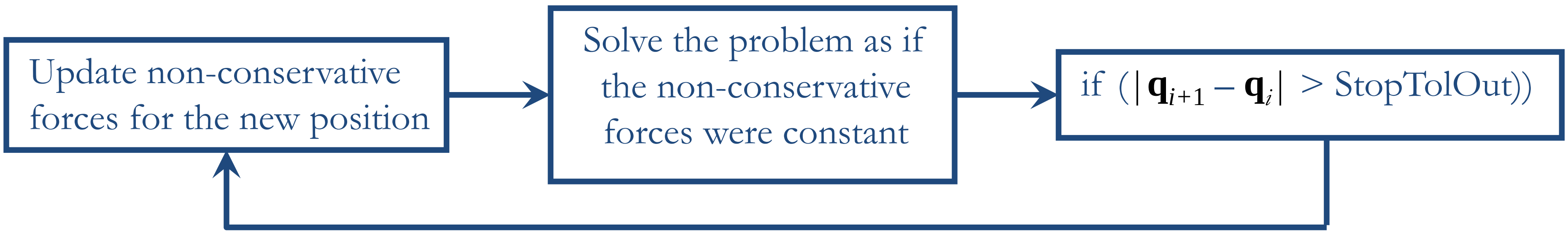
Use LBFGS method to calculate complete trawls

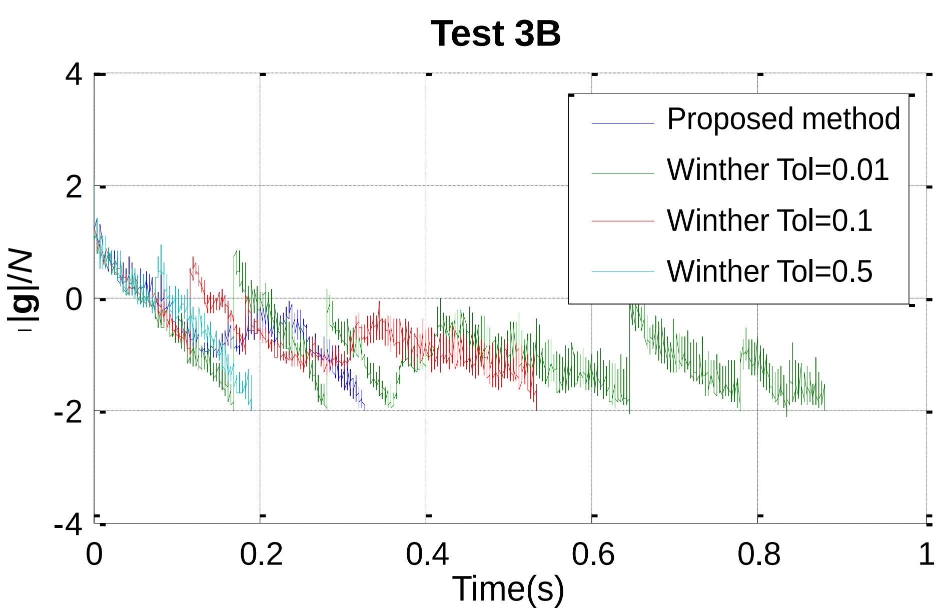


Initial position

- **Total computation time LBFGS: ~6s for 3978 variables and |g|/*N* = 0.5**
- **Unable to compare LBFGS and Newton Raphson methods**
- **Numerical models for the catch and doors are not included**

Approximated non-conservative energy vs Winther's method



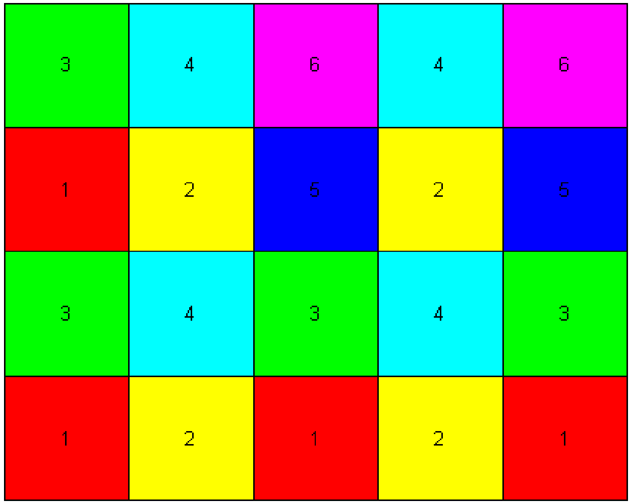


Parallelization of the evaluation of forces for all the triangular elements of the netting structure

- **Problem: unprotected shared memory with different threads**
- **Solutions (4000 variables)**

	Time per evaluation (ms)
No paralelization	3.6
Greedy coloring	1.9
Write the shared memory out of the parallelization loop	0.9

Greedy coloring for
6 colors and 4 threads



- **In fishing nets it reduces the computational overhead in a 50%**

Efficient and accurate methods for computational simulation of netting structures with mesh resistance to opening

DOCTORAL THESIS

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Ferrol, November 2014