University of Liège
Faculty of Applied Sciences

Crashworthiness of offshore wind turbine jackets based on the continuous element method

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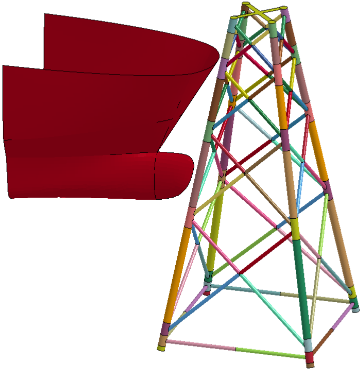
September 7, 2018

Agenda

- Introduction
- Structural behaviour
- Developments
  - ▷ Models
  - ▷ Local crushing
  - ▷ Global deformation
  - ▷ Punching
  - ▷ Base deformation
- General algorithm
  - ▷ Description
  - ▷ Validation
- Conclusions

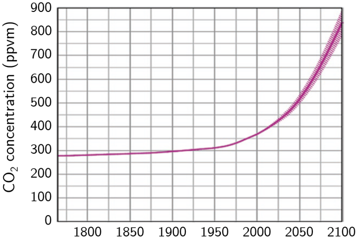


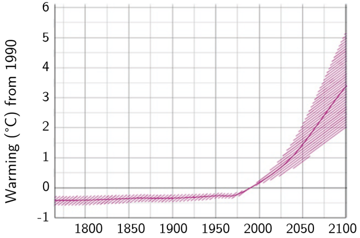
Introduction

Energetic context

- Global warming
- Depletion of fossil resources

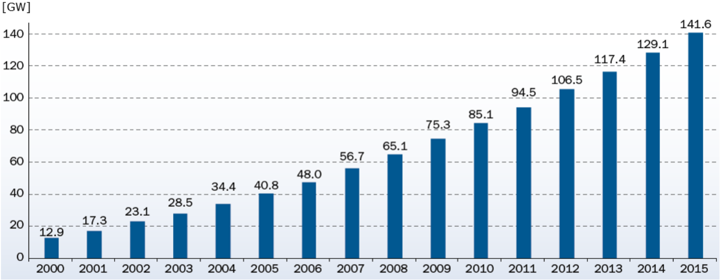
⇒ Need of renewable energies





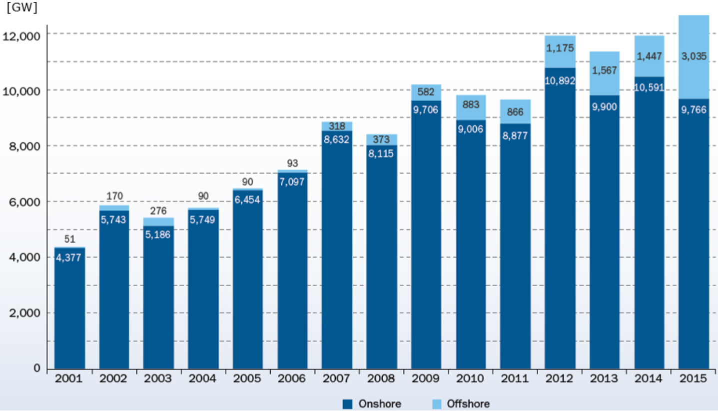
F Princiotta. 2011.

EU cumulative wind capacity



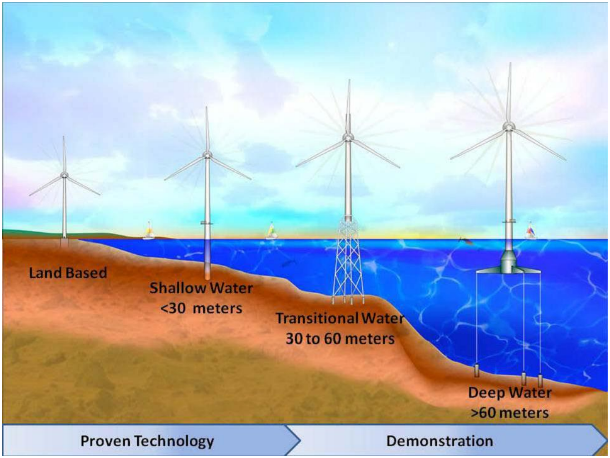
EWEA. *Wind in power - 2015 European Statistics*. 2016.

EU on- and offshore wind power installed yearly



EWEA. *Wind in power - 2015 European Statistics*. 2016.

Offshore wind turbine foundations



www.bard.edu

Offshore wind turbine jackets

www.offshorewind.biz

Ship collisions on offshore structures

Collision risk assessment

- 100s of scenarios
- Nowadays: FE method
  - ▷ Accurate but time-demanding
  - ▷ Need for strong expertise
  - ▷ $\Rightarrow$ not suitable for a pre-design stage

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Need a faster and simpler method

Steps to develop the method

1. Structural behaviour
   - Identification of governing parameters
   - Listing of deformation modes

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2. Resistance for each deformation mode
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1. Structural behaviour
   - Identification of governing parameters
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2. Resistance for each deformation mode
   - Assumption on deformation pattern
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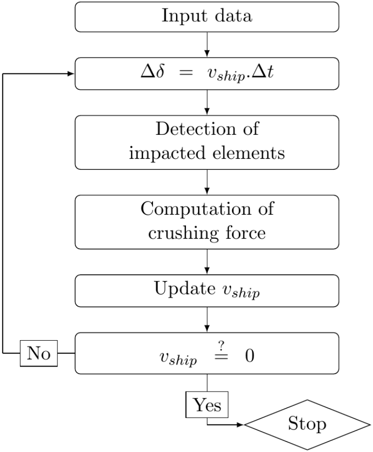
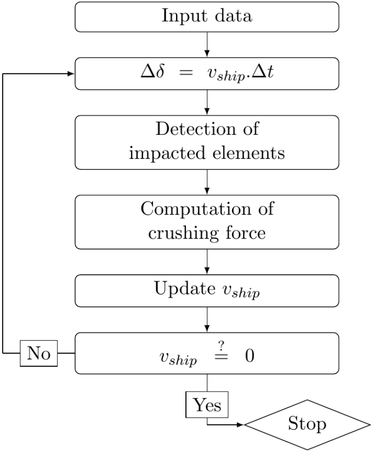
   - Validation
3. Total resistance of the jacket
   - Combination of the deformation modes
   - Modelling all the collision scenarios
   - Validation

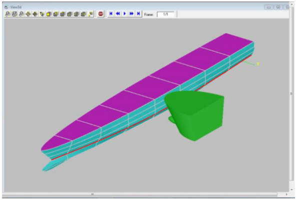
General methodology

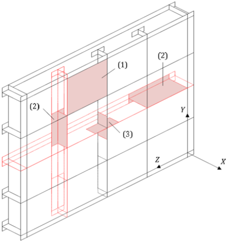


SHARP interface / Dr. L Buldgen's PhD thesis

General methodology



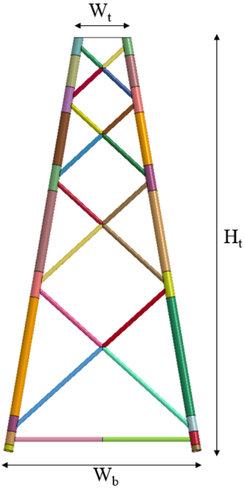




SHARP interface / Dr. L Buldgen's PhD thesis

Structural behaviour

Collided OWT jacket

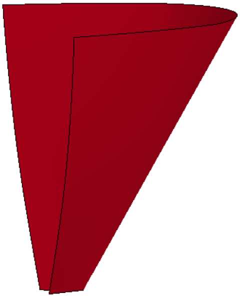


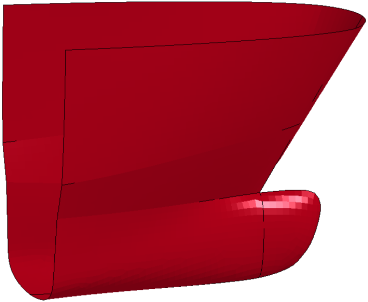
	Unit	Value
H_t	m	55
W_b	m	25
W_t	m	6.4

	Unit	Leg	Brace
D_e/t	–	26	13

Striking ships

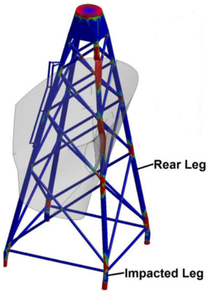
- Modelled as rigid

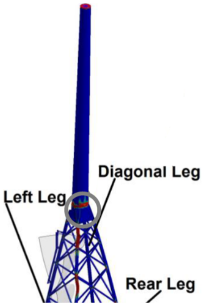


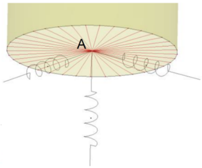


Parameters governing the crashworthiness

Gravity	Turbine - tower	Soil stiffness





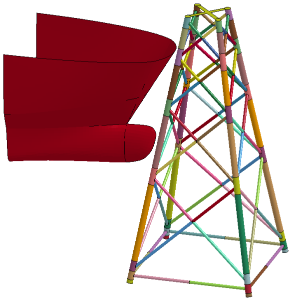


No effect	No effect	No effect

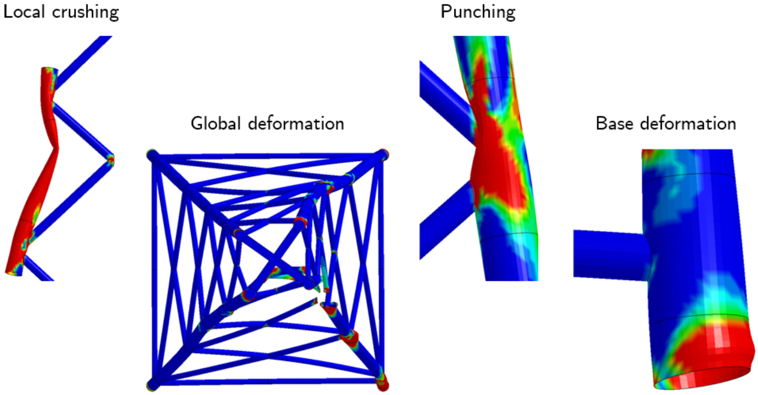
H Le Sourne, A Barrera, and JB Maliakel. 2015.

Collision modelling

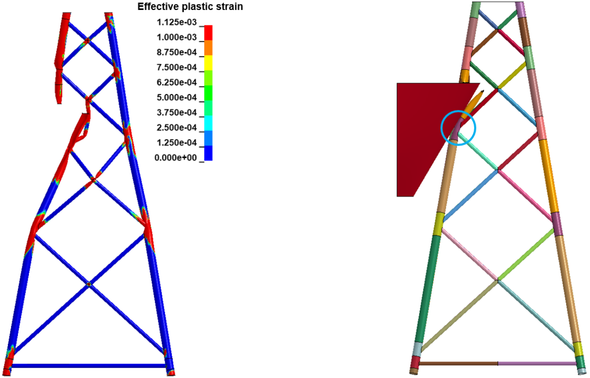
- Gravity not included
- Tower and turbine not modelled
- Four legs clamped at foundation level



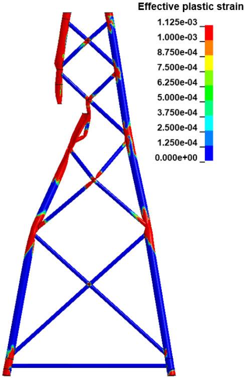
Identification of deformation modes

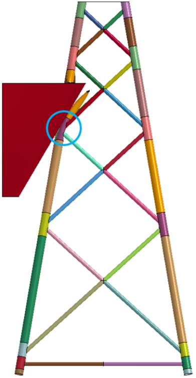


Effect of material failure modelling



Effect of material failure modelling



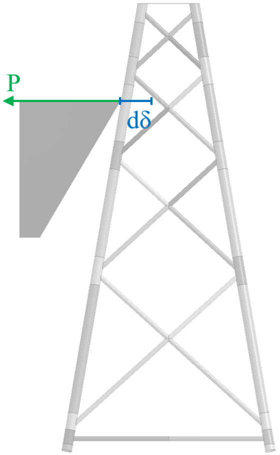


⇒ Material failure not modelled

Developments

Analytical and finite element models

Upper-bound theorem with plastic limit analysis



- Theorem:

$$\dot{E}_{ext} = \dot{E}_{int}$$

$$\Downarrow$$

$$P\dot{\delta} = \dot{E}_{int}$$

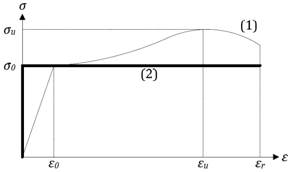
$$= \int_V \sigma \dot{\varepsilon} dV$$

Internal energy rate

- Deformation pattern
- Strain rate

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial \dot{U}_i}{\partial X_j} + \frac{\partial \dot{U}_j}{\partial X_i} + \frac{\partial \dot{U}_k}{\partial X_i}\frac{\partial U_k}{\partial X_i} + \frac{\partial U_k}{\partial X_i}\frac{\partial \dot{U}_k}{\partial X_i}\right)$$

- Material law



Internal energy rate

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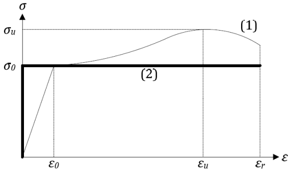
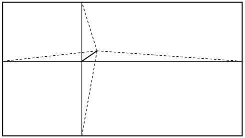
$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial \dot{U}_i}{\partial X_j} + \frac{\partial \dot{U}_j}{\partial X_i} + \frac{\partial \dot{U}_k}{\partial X_i}\frac{\partial U_k}{\partial X_j} + \frac{\partial U_k}{\partial X_i}\frac{\partial \dot{U}_k}{\partial X_j}\right)$$



- Material law

- Plate subjected to lateral load:

$$\dot{E}_{int} = \frac{2}{\sqrt{3}}\sigma_0 t_p \int_A \sqrt{\dot{\varepsilon}_{XX}^2 + \dot{\varepsilon}_{YY}^2 + \dot{\varepsilon}_{XY}^2 + \dot{\varepsilon}_{XX}\dot{\varepsilon}_{YY}}\, dA$$



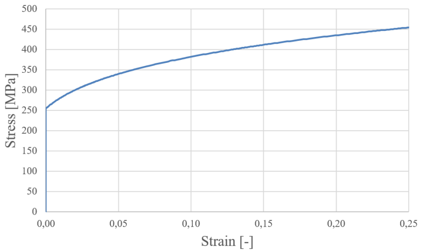
Numerical validation

- Modeller: *PATRAN*

  Solver: *LS-DYNA* explicit

  Post-processor: *LS-PrePost*

- Elastic and power law hardening



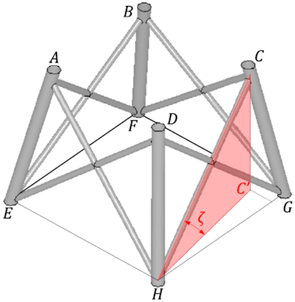
Developments

Local crushing of impacted tubular members

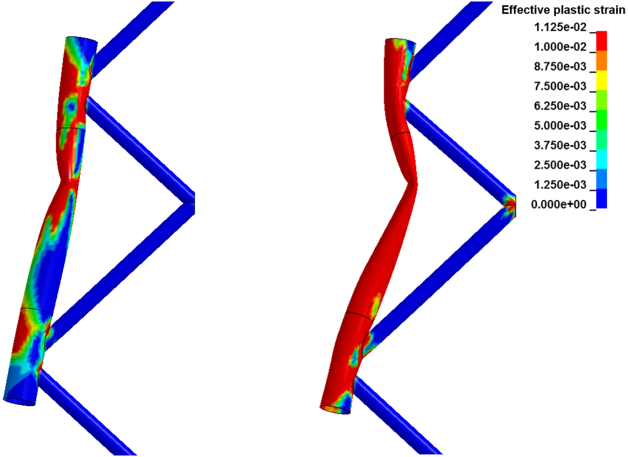
L Buldgen, H Le Sourne and T Pire. Extension of the super-elements method to the analysis of a jacket impacted by a ship. *Marine Structures*, (38):44-71, 2014.

Objectives

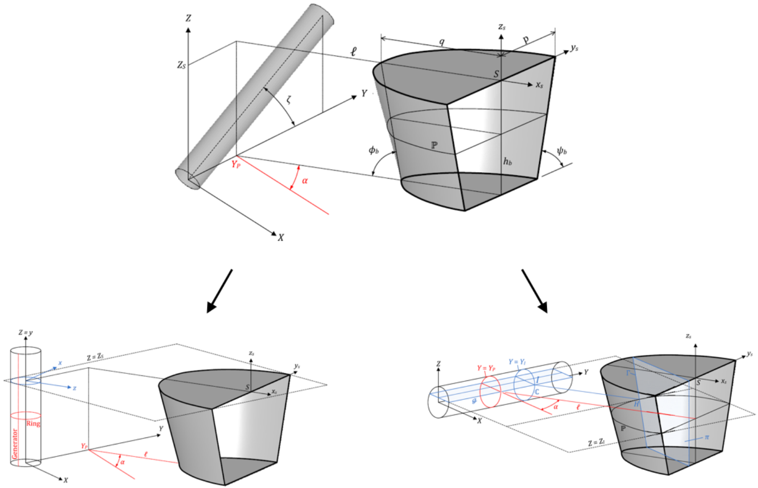
- Compute local crushing of impacted tubular members
- Tubular members
  - independent from each other
  - clamped at both extremities



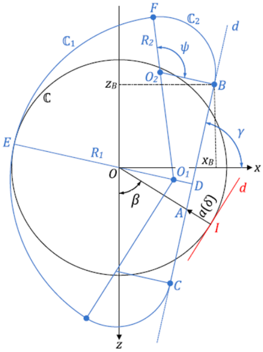
Denting and mechanism

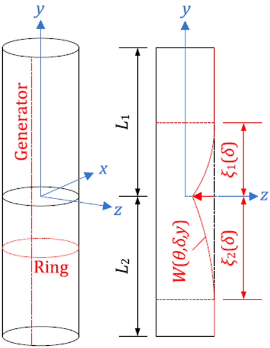


Configuration



Cross-section denting: deformation pattern





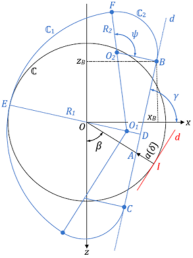
- Rings and generators independent

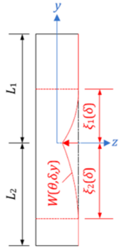
$$\Rightarrow \dot{E} = \dot{E}_r + \dot{E}_g$$

T Wierzbicki and MS Suh. 1988.

Cross-section denting: rings

- Rings have constant length
- For 1 ring:
  - ▷ Moving plastic hinges
  - ▷ Change of curvature
- For all rings:
  - ▷ Integrate on dented part (between ξ_1 and ξ_2)

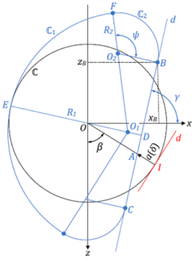


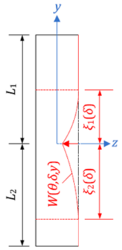


T Wierzbicki and MS Suh. 1988.

Cross-section denting: generators

- $E_{flexural} << E_{axial}$
- For 1 generator:
  - ▷ Axial elongation
- For all generators:
  - ▷ Integrate for all generators ($\beta \in [0; 2\pi]$)





T Wierzbicki and MS Suh. 1988.

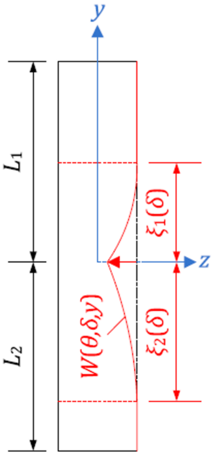
Cross-section denting: dent extension

$$P_l(\delta)\dot{a}(\delta) = \dot{E} = \dot{E}_r + \dot{E}_g$$

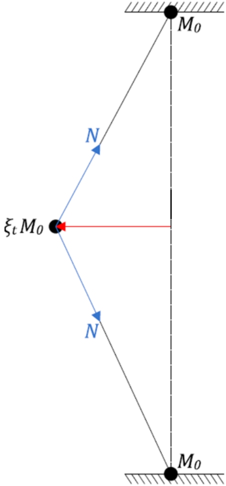
- Upper-bound theorem

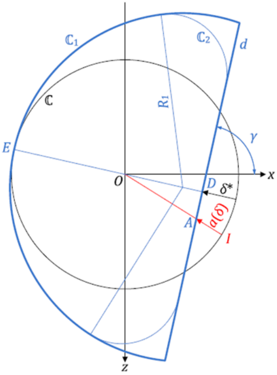
  $\Rightarrow$ minimise crushing force

$$\frac{\partial P_l}{\partial \xi_1} = 0 \quad ; \quad \frac{\partial P_l}{\partial \xi_2} = 0$$

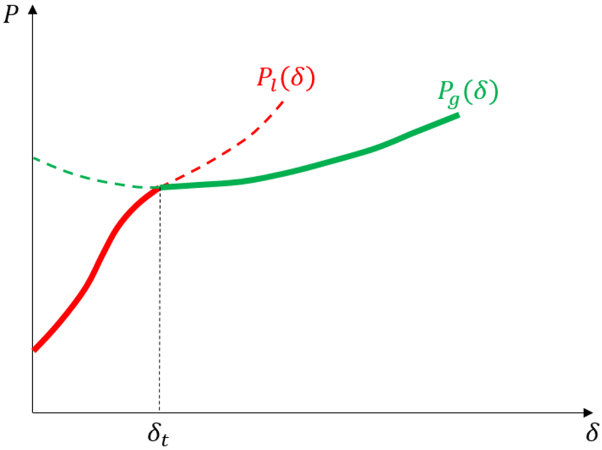


Plastic mechanism



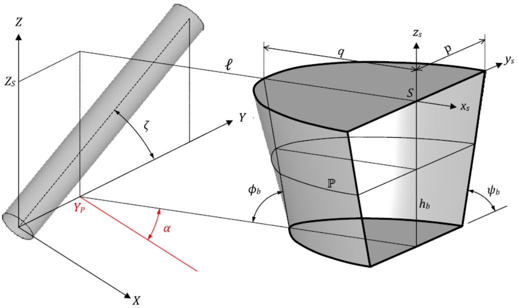


Switch between denting and mechanism

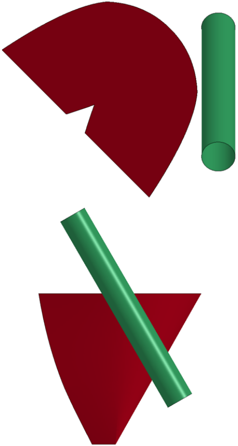


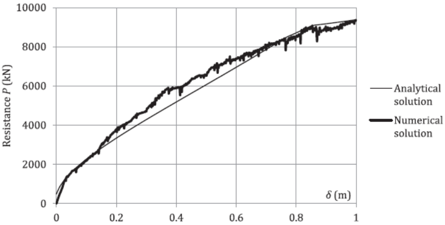
Horizontal and oblique tubular members

- Same methodology for horizontal tubular members
- Linear interpolation for oblique tubular members



Numerical validation





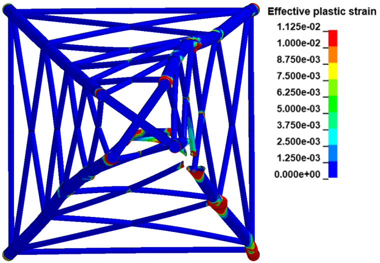
Developments

Global deformation of the whole jacket

H Le Sourne, T Pire, JR Hsieh and P Rigo. New analytical developments to study local and global deformations of an offshore wind turbine jacket impacted by a ship. In *Proceedings of the ICCGS 2016, University of Ulsan, Korea*. 2016.

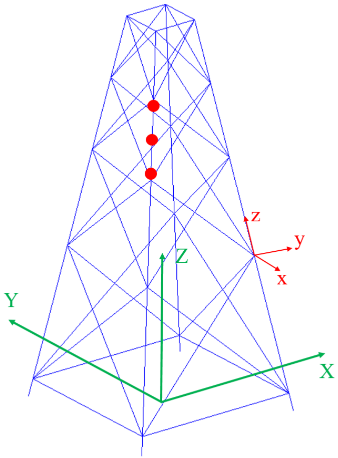
Objectives

- Compute the deformation of the whole jacket
- Interaction between all the tubular members



Approach

- Similar to FE
- 1 tubular member
  $\rightarrow$ 1 $3D$ beam element
- Specificities:
  - ▷ Second-order effects
  - ▷ Plastic hinges at 3 locations
  - ▷ Displacement control



Algorithm

- Elementary stiffness matrices $\underline{\underline{k}}$
  - Fully elastic
  - Plastic hinges at 3 locations
- Assembly

$$\underline{\underline{K}} = \sum_{assembly} \underline{\underline{R}}^T \underline{\underline{k}}\ \underline{\underline{R}}$$

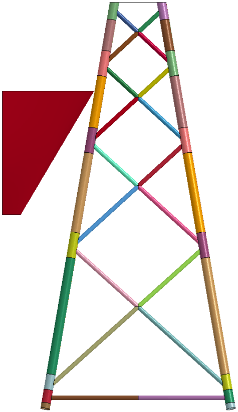
- Displacement control
- Iterative resolution

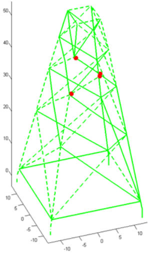
$$\Delta \underline{u} = \underline{\underline{K}}^{-1} \Delta \underline{\hat{F}}$$

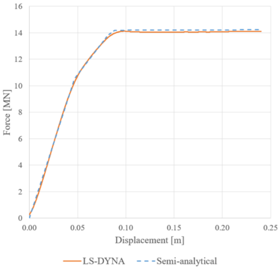
- Internal forces

$$\Delta \underline{s} = \underline{\underline{k}}\ \underline{\underline{R}} \Delta \underline{u}$$

Numerical validation







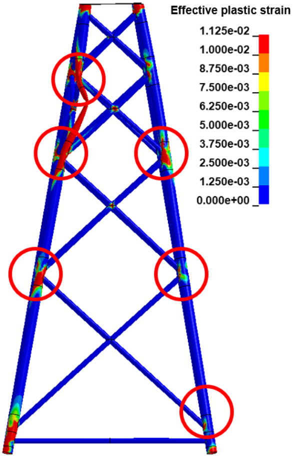
Developments

Punching of legs by compressed braces

T Pire, JR Hsieh, H Le Sourne and P Rigo. Quick assessment of the punching resistance of an offshore wind turbine jacket impacted by a ship. In *Proceedings of the ICSOS 2018, University of Chalmers, Sweden*. 2018.

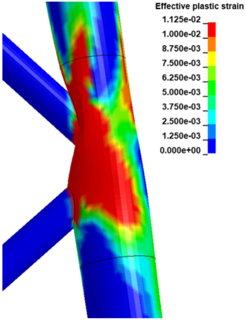
Objectives

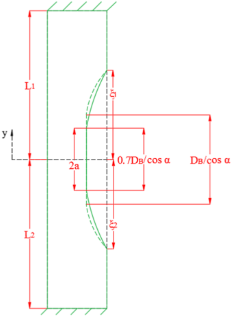
- Compute punching
  - ▷ at 1 connection
  - ▷ for the whole jacket



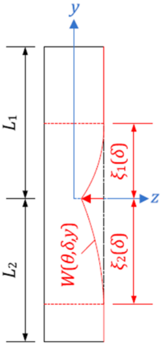
Punching at one connection: deformation pattern

- Similar to local crushing





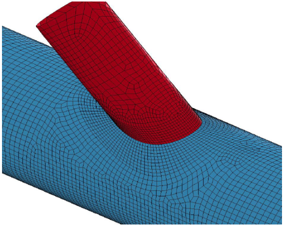
Punching

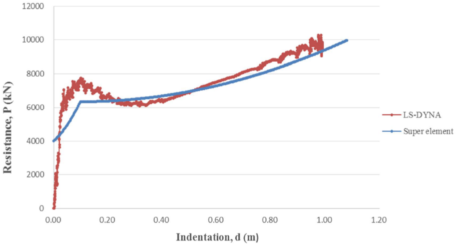


Crushing

JR Hsieh. 2016.

Punching at one connection: validation

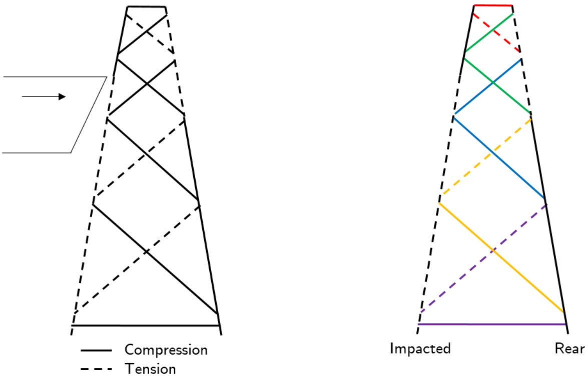




JR Hsieh. 2016.

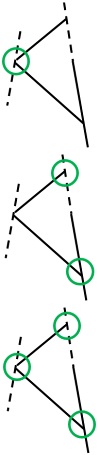
Punching in one plane: identification

- Compression - tension
- Links between legs

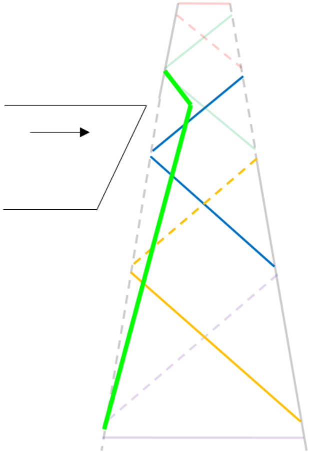


Punching in one plane: deformation

- Level activation

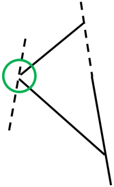


- Punching penetration

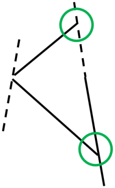


Punching in one plane: force

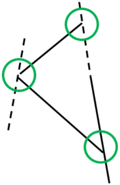
- At one level:



$$P = P_{imp.}$$



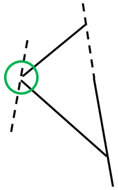
$$P = P_{rear} = P_{r1} + P_{r2}$$



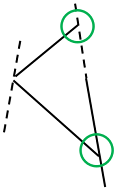
$$P = min(P_{imp.}; P_{rear})$$

Punching in one plane: force

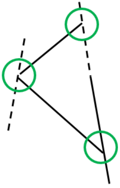
- At one level:



$P = P_{imp.}$



$P = P_{rear} = P_{r1} + P_{r2}$

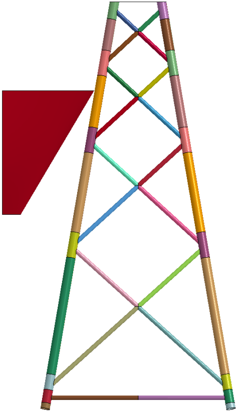


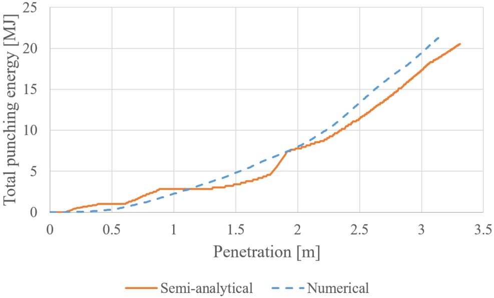
$P = min(P_{imp.}; P_{rear})$

- For the whole plane:

$$\sum P_{level}$$

Numerical validation





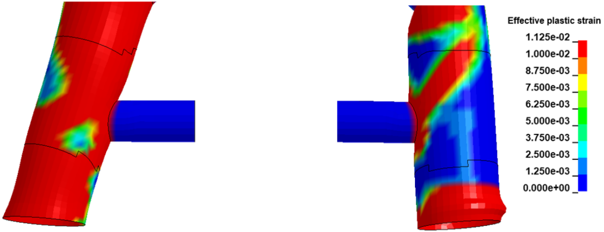
Developments

Deformation at the base of the jacket

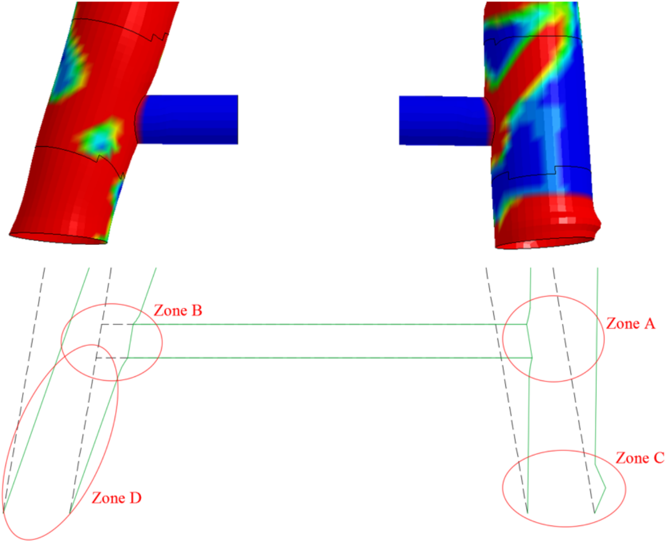
T Pire, H Le Sourne, S Echeverry and P Rigo. Analytical formulations to assess the energy dissipated at the base of an offshore wind turbine jacket impacted by a ship. *Marine Structures*, (59):192-218, 2018.

Objectives

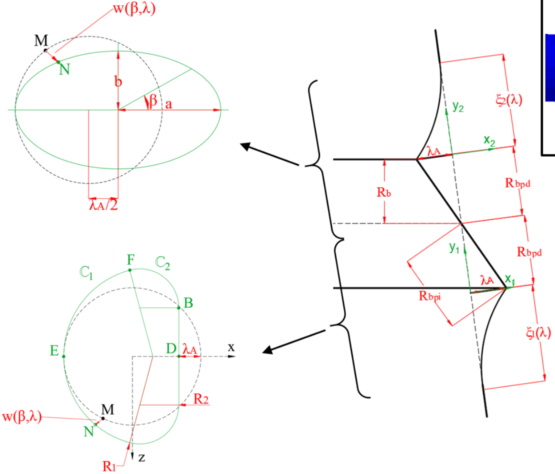
- Compute the deformation near the foundation level
- Includes
  - ▷ Impacted leg
  - ▷ Rear leg
  - ▷ Bottom horizontal brace

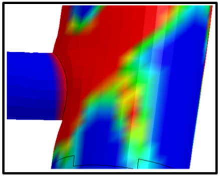


Deformation pattern and zones

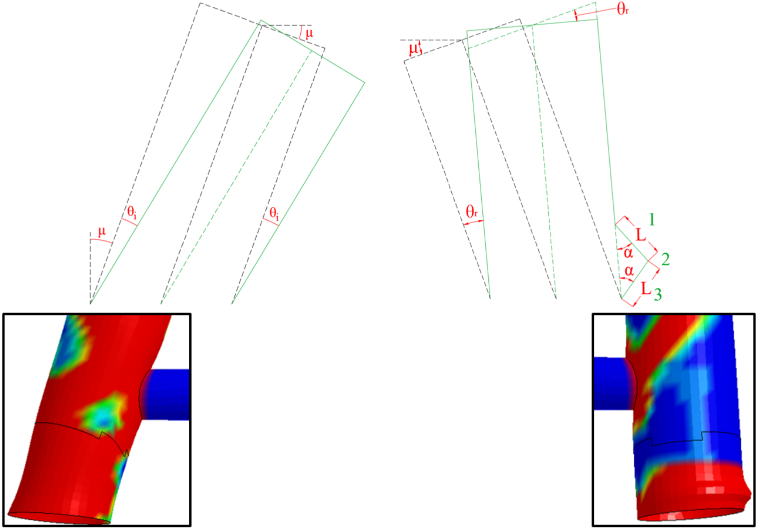


Zones A and B description





Zones C and D description

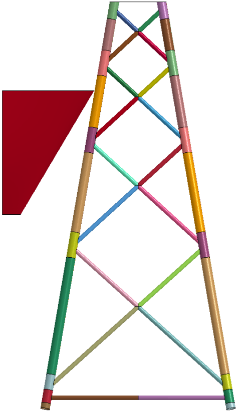


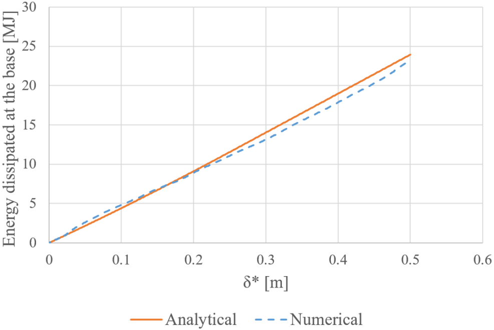
Numerical validation

Crashworthiness of OWT jackets

T. Pire

- Introduction
- Struct. behaviour
- Developments
  - Models
  - Local crushing
  - Global deformation
  - Punching
  - Base deformation
- General algorithm
- Conclusions





General algorithm

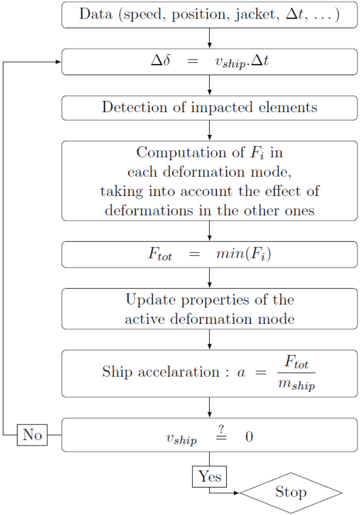
Description

T Pire, H Le Sourne and P Rigo. Presentation of an algorithm to assess the crashworthiness of an offshore wind turbine jacket using analytical formulations, 2016. BERA PhD Day.

Objectives

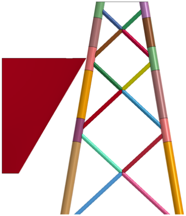
- Study the crashworthiness of the jacket
- Valid whatever the collision scenario
- Combine the four deformation modes

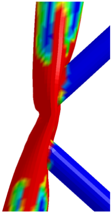
Algorithm


Data (speed, position, jacket, Δt, ...)
$\Delta\delta = v_{ship}.\Delta t$
Detection of impacted elements
Computation of F_i in each deformation mode, taking into account the effect of deformations in the other ones
$F_{tot} = min(F_i)$
Update properties of the active deformation mode
Ship accelaration : $a = \frac{F_{tot}}{m_{ship}}$
$v_{ship} \stackrel{?}{=} 0$
No
Yes
Stop

Implementation

- Impact on a connection: no 3-hinges mechanism
- $\delta_{crush} + \delta_{punch} \leq D_e$
- Axial force in braces computed with *global deformation* mode
- ...

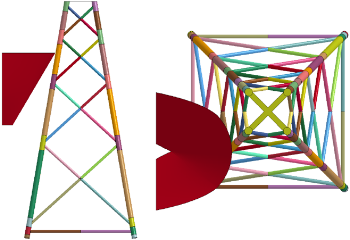


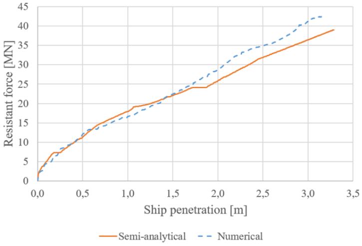


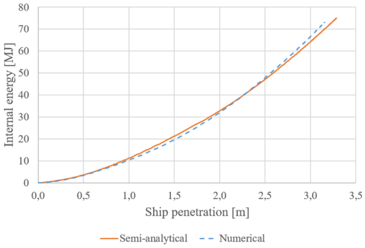
General algorithm

Numerical validation

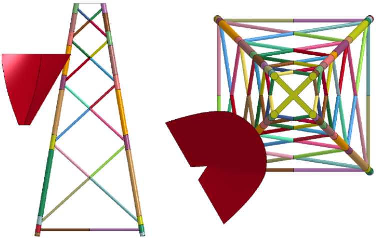
Collision scenario 1

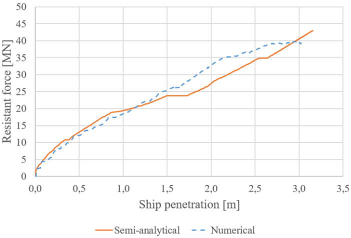


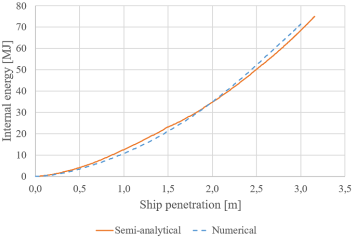




Collision scenario 2







Collision scenario 3

Crashworthiness of OWT jackets

T. Pire

Introduction

Struct. behaviour

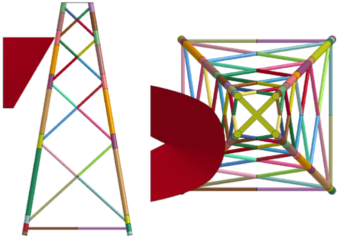
Developments

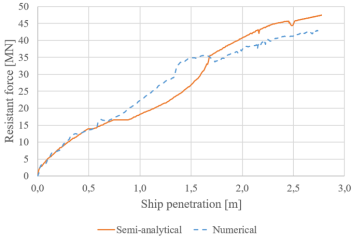
General algorithm

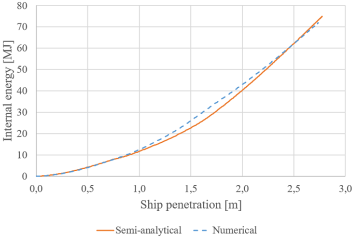
Description

Validation

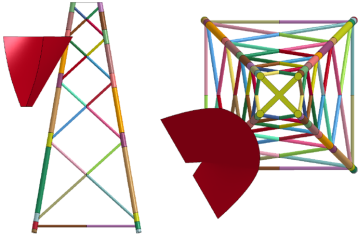
Conclusions

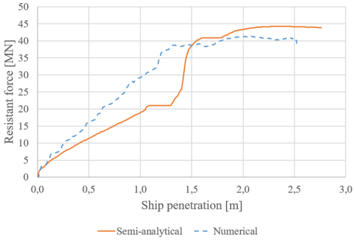


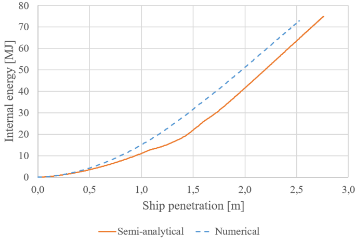




Collision scenario 4







Collision scenario 5

Crashworthiness of OWT jackets

T. Pire

Introduction

Struct. behaviour

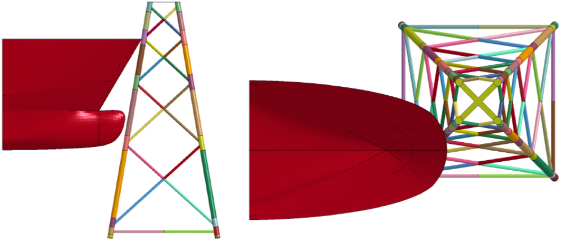
Developments

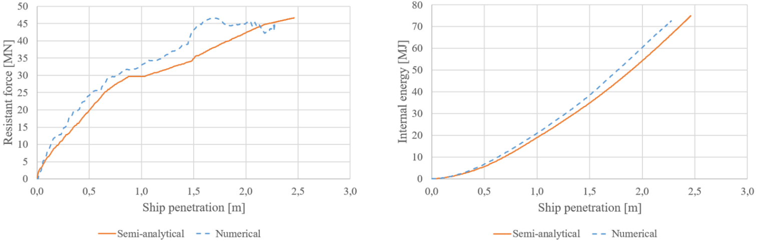
General algorithm

Description

Validation

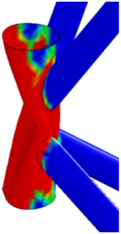
Conclusions

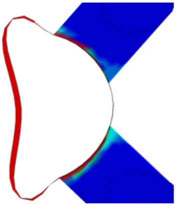




Discussion of the validation

- Good accuracy
  - ▷ Mean discrepancy: 6%
  - ▷ CoV: 8%
- Collision on connection
  - ▷ Crushing and two punching
- Computation time
  - ▷ FE: 10 hours[a]
  - ▷ New: 3 minutes[b]
  - ▷ ⇒ 200 scenarios in 10h



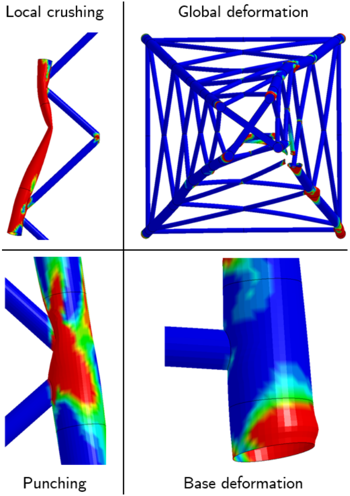


[a] Intel®Xeon®, CPU E5-2630 v2 2.60 *GHz* (2 processors), RAM 64 *Go* (*DDR*3, 1600 *MHz*)

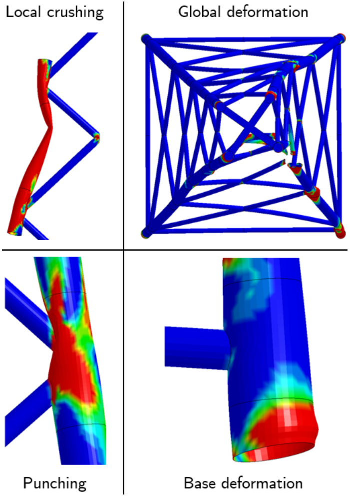
[b] Intel®Core™i3-3217U, CPU 1.80 *GHz*, RAM 8 *Go* (*DDR*3, 800 *MHz*)

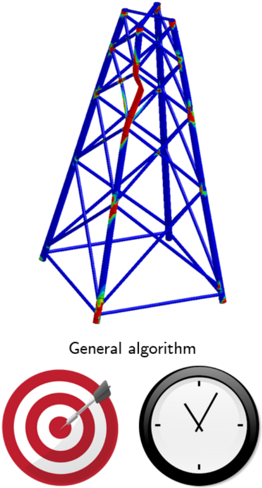
Conclusions

Summary and personal contributions



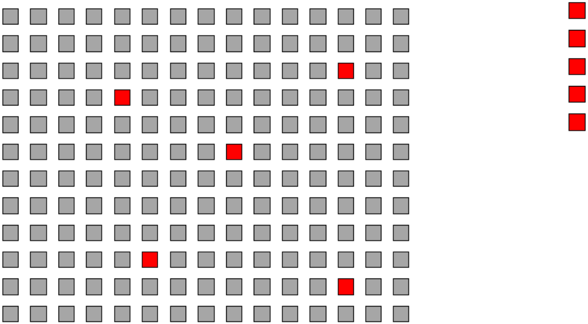
Summary and personal contributions





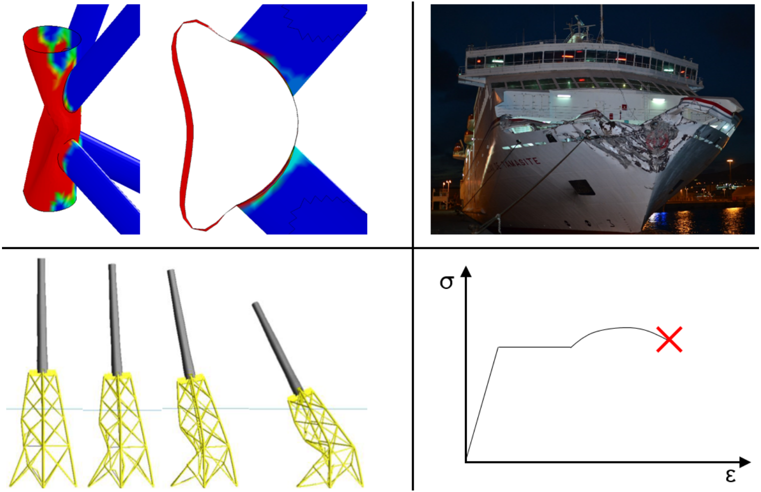
Industrial applications (I)

Pre-design stage	Final design stage
$\rightarrow$ **semi-analytical**	$\rightarrow$ FE



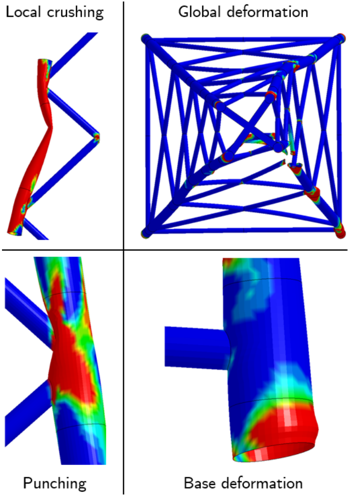
Industrial applications (II)

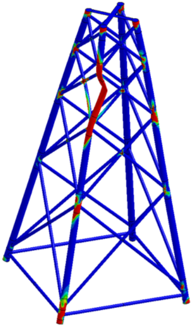
Future work



J Amdahl, and T Holmas. 2011.

Thank you



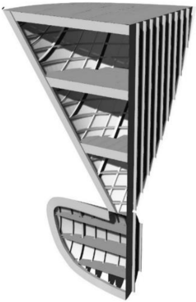


General algorithm

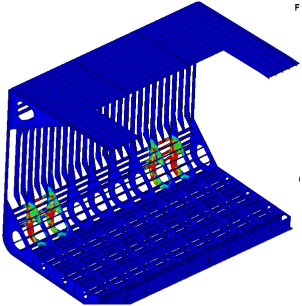
Additional slides

Ship - jacket stiffnesses ratio

- OSV
  - ▷ Jacket → 20%
  - ▷ Ship → 80%

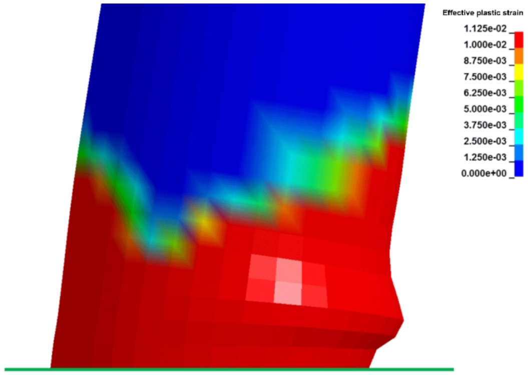


- Ice-class bulk carrier
  - ▷ Jacket → 80%
  - ▷ Ship → 20%



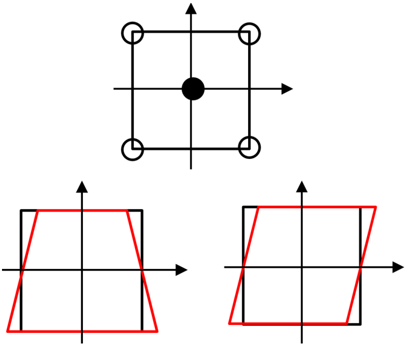
H Le Sourne, A Barrera, and JB Maliakel. 2015.

Soil stiffness effect on base deformation

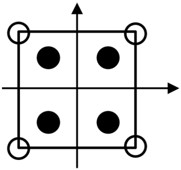


Hourglass deformation modes

- Under-integrated shell element



- Fully integrated shell element

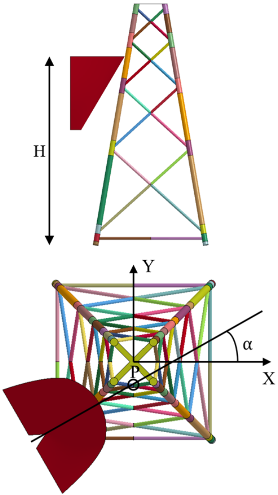


Comparison with USFOS

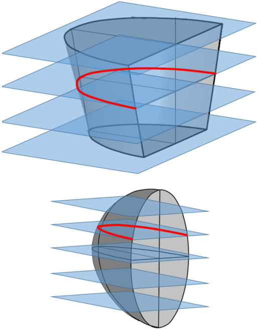
	Thesis	USFOS
Local crushing	✓	○
Global deformation	✓	✓
Punching	✓	✗
Base deformation	✓	✗

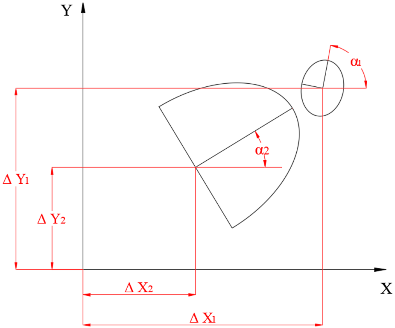
Input data

- Jacket
  - ▷ Geometry
  - ▷ Material properties
- Ship
  - ▷ Geometry (bulbous, non-bulbous. . .)
  - ▷ Mass, velocity
- Impact
  - ▷ Ship trajectory, elevation
- Resolution
  - ▷ Time step

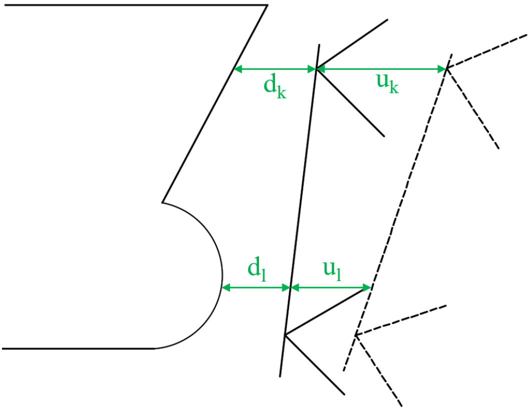


Ship-jacket initial distance





Ship-jacket distance update



Zone B description

Crashworthiness of OWT jackets

T. Pire

Introduction

Struct. behaviour

Developments

General algorithm

Conclusions