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

Timothee Pire

September 7, 2018
Agenda

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

- Global warming
- Depletion of fossil resources

$\Rightarrow$ Need of renewable energies
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EU cumulative wind capacity

EU on- and offshore wind power installed yearly

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Offshore wind turbine foundations

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Ship collisions on offshore structures

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Collision risk assessment

- 100s of scenarios

- Nowadays: FE method
  - Accurate but time-demanding
  - Need for strong expertise
  - ⇒ not suitable for a pre-design stage
Collision risk assessment

100s of scenarios

Nowadays: FE method

- Accurate but time-demanding
- Need for strong expertise
- ⇒ not suitable for a pre-design stage

Need a faster and simpler method
Steps to develop the method

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1. Identification of governing parameters
2. Listing of deformation modes

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Steps to develop the method

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

2. **Resistance for each deformation mode**
   - Assumption on deformation pattern
   - Development of formulations
   - Validation

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Steps to develop the method

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

2. Resistance for each deformation mode
   - Assumption on deformation pattern
   - Development of formulations
   - Validation

3. Total resistance of the jacket
   - Combination of the deformation modes
   - Modelling all the collision scenarios
   - Validation
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General methodology

Input data

\[ \Delta \delta = v_{ship} \cdot \Delta t \]

Detection of impacted elements

Computation of crushing force

Update \( v_{ship} \)

\[ v_{ship} \neq 0 \]

No

Yes

Stop

SHARP interface / Dr. L Buldgen's PhD thesis
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- Input data
  \[ \Delta \delta = v_{ship} \Delta t \]
- Detection of impacted elements
- Computation of crushing force
- Update \( v_{ship} \)
- \( v_{ship} \neq 0 \) → No
- \( v_{ship} = 0 \) → Yes
- Stop

SHARP interface / Dr. L Buldgen’s PhD thesis
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Collided OWT jacket

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>$H_t$</td>
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<tr>
<td>$W_b$</td>
<td>m</td>
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<tr>
<td>$W_t$</td>
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<table>
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<th>Brace</th>
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<td>26</td>
<td>13</td>
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</table>
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Modelled as rigid
### Parameters governing the crashworthiness

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gravity</th>
<th>Turbine - tower</th>
<th>Soil stiffness</th>
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<td>No effect</td>
<td>No effect</td>
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<td>Turbine - tower</td>
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<td>No effect</td>
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<tr>
<td>Soil stiffness</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
</tr>
</tbody>
</table>

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H Le Sorne, 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

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Effect of material failure modelling

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⇒ Material failure not modelled
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Analytical and finite element models
Upper-bound theorem with plastic limit analysis

\[ \dot{E}_{\text{ext}} = \dot{E}_{\text{int}} \]

\[ P \dot{\delta} = \dot{E}_{\text{int}} \]

\[ = \int_V \sigma \dot{\varepsilon} dV \]
Internal energy rate

- Deformation pattern
- Strain rate

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

- Material law

- Material law
Internal energy rate

- Deformation pattern
- Strain rate

\[ \dot{e}_{ij} = \frac{1}{2} \left( \frac{\partial \dot{u}_i}{\partial X_j} + \frac{\partial \dot{u}_j}{\partial X_i} + \frac{\partial \dot{u}_k}{\partial X_i} \frac{\partial u_k}{\partial X_i} + \frac{\partial u_k}{\partial X_i} \frac{\partial \dot{u}_k}{\partial X_i} \right) \]

- Material law

- 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

![Graph showing stress-strain relationship]
Developments

Local crushing of impacted tubular members

Objectives

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

Effective plastic strain

1.125e-02
1.000e-02
8.750e-03
7.500e-03
6.250e-03
5.000e-03
3.750e-03
2.500e-03
1.250e-03
0.000e+00
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Cross-section denting: deformation pattern

- Rings and generators independent

\[ \dot{E} = \dot{E}_r + \dot{E}_g \]

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 $\xi_1$ and $\xi_2$)

Cross-section denting: generators

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

Cross-section denting: dent extension

\[ P_l(\delta) \ddot{\delta} = \dot{E} = \dot{E}_r + \dot{E}_g \]

- **Upper-bound theorem**
  \[ \Rightarrow \text{minimise crushing force} \]

\[ \frac{\partial P_I}{\partial \xi_1} = 0 ; \quad \frac{\partial P_I}{\partial \xi_2} = 0 \]
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Switch between denting and mechanism

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Horizontal and oblique tubular members

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

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Global deformation of the whole jacket

Objectives

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

- Similar to FE
- 1 tubular member
  → 1 3D beam element
- Specificities:
  - Second-order effects
  - Plastic hinges at 3 locations
  - Displacement control
Algorithm

- Elementary stiffness matrices $k$
  - Fully elastic
  - Plastic hinges at 3 locations
- Assembly
  \[ K = \sum_{assembly} R^T k R \]
- Displacement control
- Iterative resolution
  \[ \Delta u = K^{-1} \Delta \hat{F} \]
- Internal forces
  \[ \Delta s = k R \Delta u \]
Numerical validation

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Punching of legs by compressed braces

Objectives

- Compute punching
  - at 1 connection
  - for the whole jacket
Punching at one connection: deformation pattern

- Similar to local crushing
Punching at one connection: validation

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Punching in one plane: identification

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Compression - tension

Links between legs

Compression
Tension
Impacted
Rear
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:

\[ \sum P_{level} \]
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Deformation at the base of the jacket

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

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Objectives

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

Data (speed, position, jacket, Δt, ...)

Δδ = v_{ship}Δt

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 acceleration: a = \frac{F_{tot}}{m_{ship}}

v_{ship} \geq 0

No

Yes

Stop
Implementation

- Impact on a connection:
  - no 3-hinges mechanism
- \( \delta_{\text{crush}} + \delta_{\text{punch}} \leq D_e \)
- Axial force in braces computed with *global deformation* mode
- ...
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Collision scenario 1

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Collision scenario 3

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![Graphs showing resistive force and internal energy against ship penetration for semi-analytical and numerical methods.](image)
Collision scenario 4

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![Graphs showing force and energy vs. ship penetration]

- Semi-analytical
- Numerical
Collision scenario 5

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![Graphs showing resistant force and internal energy vs. ship penetration](image)

- **Resistant force [MN]**
  - Semi-analytical
  - Numerical

- **Internal energy [MJ]**
  - Semi-analytical
  - Numerical
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\(^b\)
  - \(\Rightarrow\) 200 scenarios in 10h

\(^a\) Intel® Xeon®, CPU E5-2630 v2 2.60 GHz (2 processors), RAM 64 Go (DDR3, 1600 MHz)

\(^b\) Intel® Core™ i3-3217U, CPU 1.80 GHz, RAM 8 Go (DDR3, 800 MHz)
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Summary and personal contributions

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Summary and personal contributions

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Industrial applications (I)

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Pre-design stage → semi-analytical

Final design stage → FE
Industrial applications (II)

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Future work

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Thank you
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Ship - jacket stiffnesses ratio

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- OSV
  - Jacket → 20%
  - Ship → 80%

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

H Le Sorne, A Barrera, and JB Maliakel. 2015.
Soil stiffness effect on base deformation

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Hourglass deformation modes

- Under-integrated shell element
- Fully integrated shell element
## Crashworthiness of OWT jackets

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<table>
<thead>
<tr>
<th></th>
<th>Thesis</th>
<th>USFOS</th>
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<td>Local crushing</td>
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<td>Punching</td>
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<tr>
<td>Base deformation</td>
<td>✔️</td>
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</table>
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

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