Analytical Formulations for Ship-Offshore Wind Turbine Collisions

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CONTENTS

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INTRODUCTION

- Green energy is taken seriously nowadays.
- Ship collision is one of the major hazards of jacket foundation.
- Rapid assessment of crashworthiness is necessary.

OBJECTIVE

- Energy dissipation
  - impacted leg ≈ 60%
  - rear leg ≈ 15%
  - other legs/braces ≈ 25%
- New super-element for punching phenomenon.
Punching phenomena is obvious while one or two junctions are collided by the stem or bulb.

The punching indentation occurs only in the x direction of the rear leg local coordinate system.
**CRUSHING PROCESS**

[Local mode]-Energy rate

[Local mode]-Crushing resistance

If local resistance exceed threshold or not?

Yes

No

[Global mode]-Crushing resistance

[Global mode]-Energy rate

**VIRTUAL WORK**

- \( \dot{E}_{ext} = \dot{E}_{int} \)
- \( \dot{E}_{ext} = P \dot{\delta} \)
- \( \dot{E}_{int} = \int \int \int_{V} \sigma_{ij} \cdot \dot{\varepsilon}_{ij} \cdot dV \)
- \( P = \frac{\dot{E}_{int}}{\dot{\delta}} \)
LOCAL ENERGY RATE-RING

- Crushing energy rate of ring

\[ \dot{E}_r = \dot{E}_b \left( a + \frac{\xi_1 + \xi_2}{2} \right) \]

\[ \dot{E}_b = 2M_0 \left[ \frac{V_B}{R_2} + \left( \frac{1}{R_2} - \frac{1}{R_1} \right) V_C + \int_C \kappa_1 dl + \int_B \kappa_2 dl \right] \]

- \( M_0 \): fully plastic bending moment
- \( V_B, V_C \): tangential velocity of plastic hinge
- \( \kappa_1, \kappa_2 \): change of curvature of \( C_1 \) and \( C_2 \)

DISPLACEMENT FIELD-RING [4]

- \( R_1 = R + \frac{\delta(\psi - \sin \psi)}{\pi(1 - \cos \psi) - 2(\psi - \sin \psi)} \)
- \( R_2 = R - \frac{\delta(\pi - \psi + \sin \psi)}{\pi(1 - \cos \psi) - 2(\psi - \sin \psi)} \)
- \( AB = (R_1 - R_2) \sin \psi \)
- \( w(\theta, \delta) = \sqrt{(x_H - x_C)^2 + (z_H - z_C)^2} \)
**DISPLACEMENT FIELD-RING**

\[ \psi = \psi_0 + \left( \frac{1}{2} \pi - \psi_0 \right) \frac{\delta}{2R} \]

\[ \psi_0 = \frac{1}{3} \pi \]

**LOCAL ENERGY RATE-GENERATOR**

- Crushing energy rate of generator

\[ \dot{E}_g = \int_C \dot{E}_m dl = \left[ \frac{1}{\xi_1 - a} + \frac{1}{\xi_2 - a} \right] \dot{E'}_m \]

\[ \dot{E}_m(\theta, \delta) = n_0 \int_{-\xi_2}^{\xi_1} \dot{\epsilon}_m(\theta, \delta, y) dy = n_0 w(\theta, \delta) \frac{\partial w}{\partial \delta} \delta \left[ \frac{1}{\xi_1 - a} + \frac{1}{\xi_2 - a} \right] \]

\[ \dot{\epsilon}_m(\theta, \delta, y) = \frac{\partial w}{\partial y} \frac{\partial w}{\partial y} = \text{axial extension rate} \]

\[ n_0 : \text{fully plastic membrane force per unit} \]
DISPLACEMENT FIELD-GENERATOR

\[
W(\theta, \delta, y) = w(\theta, \delta) \left(1 - \frac{y-a}{\xi_1-a}\right) \quad \text{for } y \in [a; \xi_1]
\]
\[
W(\theta, \delta, y) = w(\theta, \delta) \quad \text{for } y \in [-a; a]
\]
\[
W(\theta, \delta, y) = w(\theta, \delta) \left(1 - \frac{y+a}{\xi_2-a}\right) \quad \text{for } y \in [-\xi_2; -a]
\]

LOCAL CRUSHING RESISTANCE

- Total energy rate
  \[
  \dot{E} = \dot{E}_r + \dot{E}_g = \dot{E}_b \left(a + \frac{\xi_1 + \xi_2}{2}\right) + \dot{E}_m \left(\frac{1}{\xi_1 - a} + \frac{1}{\xi_2 - a}\right)
  \]
- Evaluation of \(\xi_1\) and \(\xi_2\)
  \[
  \frac{\partial P_1}{\partial \xi_1} = 0 \Rightarrow \xi_1 = \min\left(a + \sqrt{\frac{2E_m}{E_b}} \cdot L_1, \frac{1}{a + \frac{1}{\xi_2 - a}}\right) / \delta
  \]
  \[
  \frac{\partial P_1}{\partial \xi_2} = 0 \Rightarrow \xi_2 = \min\left(a + \sqrt{\frac{2E_m}{E_b}} \cdot L_2, \frac{1}{a + \frac{1}{\xi_1 - a}}\right)
  \]
TRANSITION OF CRUSHING MODE & GLOBAL CRUSHING RESISTANCE

- 4 plastic hinges mechanism
  \[ W_{hinge} = M_0 \theta + M_0 \phi + \xi_2 M_0 \theta + \xi_1 M_0 \phi \]

- \[ W_p = \frac{P(\delta_1)}{2} L_1 \theta + \frac{P(\delta_2)}{2} L_2 \phi \]

- \[ \xi(\delta) = \frac{1}{2} \left( \frac{\delta}{2R} \right)^2 - 1 \left( \frac{\delta}{2R} - 2 \right) \]

TRANSITION OF CRUSHING MODE & GLOBAL CRUSHING RESISTANCE

- Threshold
  \[ P_t(\delta_t) = P_c(\delta_t) = \frac{L_1' + L_2'}{L_1' L_2'} \left( 1 + \beta \times Q_\beta \times \xi(\delta_t) \right) M_0 \]
  \[ Q_\beta = \begin{cases} 1 & \text{for } \beta \leq 0.6 \\ \frac{0.3}{\beta(1-0.833\beta)} & \text{for } \beta > 0.6 \end{cases} \]

- Global resistance
  \[ P_g(\delta) = \frac{L_1' + L_2'}{L_1' L_2'} \left[ \left( 1 + \beta \times Q_\beta \times \xi_1 \right) M_0 \left( 1 - \frac{N(\delta)^2}{N_0^2} \right) + N(\delta)(\delta - \delta_t) \right] \]
  \[ N(\delta) = \min \left( \frac{n^2(\delta - \delta_t)}{2 \left( 1 + \beta \times Q_\beta \times \xi_1 M_0 \right) N_0} \right) \]
NUMERICAL VALIDATION - SIMPLE TUBE JOINT

MODEL DESCRIPTION

- Jacket-like cylinder dimension
- Material and prescribed displacement
MESH SIZE CONVERGENCE STUDY

- Mesh size: 100mm => 25mm

<table>
<thead>
<tr>
<th>Smallest mesh size</th>
<th>Number of element</th>
<th>Discrepancy of energy</th>
<th>Discrepancy of force</th>
<th>Simulation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm</td>
<td>7040</td>
<td>--</td>
<td>--</td>
<td>67 s</td>
</tr>
<tr>
<td>50 mm</td>
<td>7630</td>
<td>≈3.5%</td>
<td>≈8%</td>
<td>111 s</td>
</tr>
<tr>
<td>25 mm</td>
<td>16320</td>
<td>≈6%</td>
<td>≈12%</td>
<td>298 s</td>
</tr>
</tbody>
</table>

DIFFERENT $\beta$ RATIOS

$\beta = \frac{Brace\ Diameter}{Leg\ Diameter}$

- Internal energy
- Crushing resistance

Internal energy
- $\beta = 0.32$
- $\beta = 0.48$
- $\beta = 0.64$
- $\beta = 1$

Crushing resistance
- $\beta = 0.32$
- $\beta = 0.48$
- $\beta = 0.64$
- $\beta = 0.8$
DIFFERENT $\beta$ RATIOS

- $\beta=0.32$ (small brace diameter)
- $d=0.2\sim0.4m \Rightarrow 35\%$ discrepancy

$$\text{Discrepancy} = \frac{E_{\text{super element}} - E_{\text{LS DYNA}}}{E_{\text{LS DYNA}}}$$

- $\beta=0.48$ (jacket-like)
- $d \approx 0.37m \Rightarrow 8\%$ discrepancy
**DIFFERENT β RATIOS**

- β=1 (large brace diameter, $D_B=D_L$)
- $d=1.8\text{m} \Rightarrow -14.7\%$ discrepancy

![Graph showing internal energy vs. indentation and resistance vs. indentation for LS-DYNA and Super-element models.]

**DIFFERENT SPAN**

<table>
<thead>
<tr>
<th>Internal energy</th>
<th>Crushing resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graph showing internal energy vs. indentation for different spans L=17m and L=23.5m." /></td>
<td><img src="image" alt="Graph showing crushing resistance vs. indentation for different spans L=17m and L=23.5m." /></td>
</tr>
</tbody>
</table>
DIFFERENT SPAN

- \( L = 23.5 \text{ m} \)
- \( d \approx 0.8 \text{ m} \Rightarrow -3\% \text{ discrepancy} \)

TWO JOINTS WITH GAP

- \( L = 17 \text{ m} \) \( (L_1 = 7.5 \text{ m}, L_2 = 9.5 \text{ m}) \)
- \( d \approx 0.36 \text{ m} \Rightarrow -9.6\% \text{ discrepancy} \)
NUMERICAL VALIDATION- REAL JACKET FOUNDATION

JACKET PUNCHING SCENARIOS

I
The rear leg is punched by 1 brace (upper brace).

II
The rear leg is punched by upper brace, and restrained by lower brace.

III
The rear leg is punched by 2 brace simultaneously.
CASE 1: 90°-SCENARIO I

- L_1: 9m, L_2: 14.5m
- Buckling of braces at d=0.6m
CASE 2: **90°-SCENARIO II**
- $L_1$: 9m, $L_2$: 1.5m
- Buckling of braces at $d=0.23$m

CASE 3: **90°-SCENARIO III**
- $L_1$: 10m, $L_2$: 13.5m, gap=0.82m
- Abrupt global movement at $d=0.23$m
- Bulcking of braces at $d=0.46$m
CASE 4: 60°-SCENARIO I

- L₁: 9m, L₂: 14,5m
- Buckling of brace 558 at d=0,61m

CONCLUSIONS & FUTURE WORKS
CONCLUSIONS

- Scenario II should be improved.
- Energy obtained by super-element:
  - Bow ≈ 20%
  - Bulb ≈ 23%
  - Punching 1 ≈ 6%
  - Punching 2 ≈ 5%
  - Punching 3 ≈ 15%
  \[ \approx 26\% \]

CONCLUSIONS

Collided Leg
- Punching 3 \(\Rightarrow\) overestimated

Rear Leg
- Shearing effect \(\Rightarrow\) 30\% of rear leg energy
CONTRIBUTIONS OF THIS STUDY

- Development of a new super-element for punching
- Validation of the super-element for different $\beta$
- Validation of the super-element on real jacket model for different scenarios

FUTURE WORKS

- Programming the new super-element in C++
- Calculation of jacket nodes displacement
- Another pattern of punching scenario (to be more accurate)
- Buckling of the braces and shearing near the mudline
- Energy absorbed by other legs/braces (20%)
Thank you for your attention

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REFERENCE