Analytical Formulations for Ship-Offshore Wind Turbine Collisions

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- Numerical validation
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INTRODUCTION

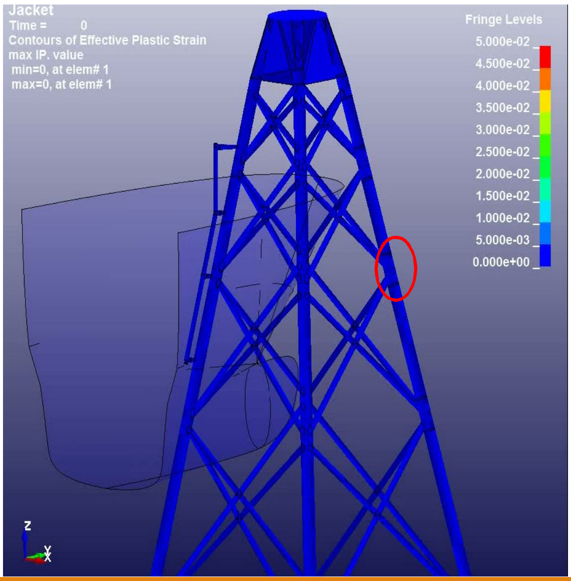
- Green energy is taken seriously nowadays.
- Ship collision is one of the major hazards of jacket foundation.
- Rapid assessment of crashworthiness is necessary.


[1]


[2]

OBJECTIVE

- Energy dissipation
  - impacted leg ≈ 60%
  - rear leg ≈ 15%
  - other legs/braces ≈ 25 %
- New super-element for punching phenomenon.



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ANALYTICAL FORMULAS DEVELOPMENT

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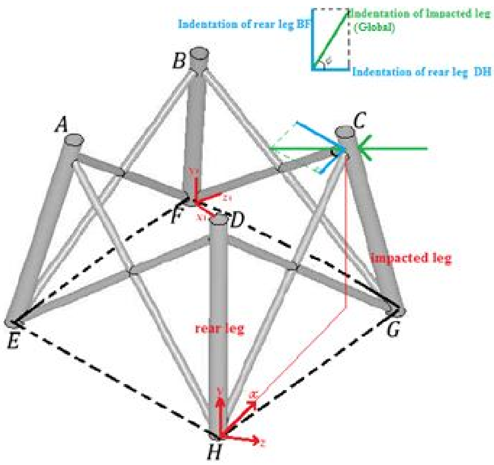
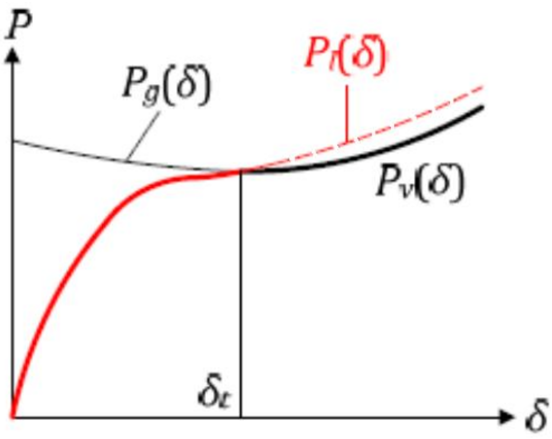
DEFORMATION PATTERN

- Punching phenomena is obvious while one or two junctions are collided by the stem or bulb.
- The punching indentation occurs only in x direction of rear leg local coordinate system.



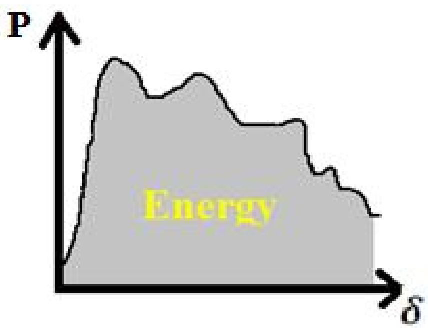
CRUSHING PROCESS



VIRTUAL WORK

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

  $\dot{E}_{int} = \iiint_V \sigma_{ij} \cdot \dot{\epsilon}_{ij} \cdot dV$
- $P = \frac{\dot{E}_{int}}{\dot{\delta}}$



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LOCAL ENERGY RATE-RING

- Crushing energy rate of ring

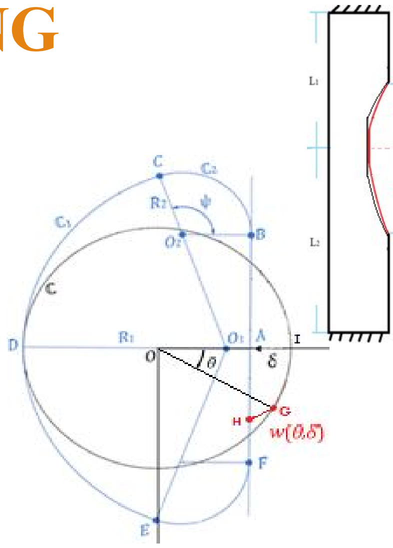
$$\dot{E}_r = \dot{E}_b \left(a + \frac{\xi_1+\xi_2}{2}\right)$$

$$\dot{E}_b = 2M_0\left[\frac{V_B}{R_2} + \left(\frac{1}{R_2} - \frac{1}{R_1}\right)V_C + \int_C^D \dot{\kappa}_1 dl + \int_B^C \dot{\kappa}_2 dl\right]$$

M_0: fully plastic bending moment

V_B V_C : tangential velocity of plastic hinge

$\dot{\kappa}_1, \dot{\kappa}_2$: change of curvature of C_1 and C_2



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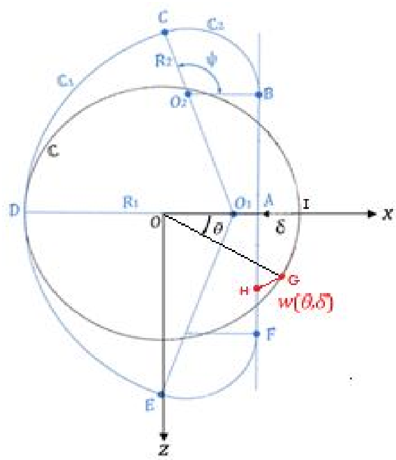
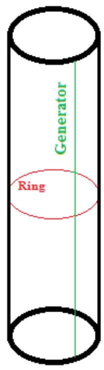
DISPLACEMENT FIELD-RING [4]

- $R_1 = R + \frac{\delta(\psi - \sin\psi)}{\pi(1-\cos\psi) - 2(\psi - \sin\psi)}$
- $R_2 = R - \frac{\delta(\pi - \psi + \sin\psi)}{\pi(1-\cos\psi) - 2(\psi - \sin\psi)}$
- $\overline{AB} = (R_1 - R_2)\sin\psi$
- $w(\theta,\delta) = \sqrt{(x_H - x_G)^2 + (z_H - z_G)^2}$





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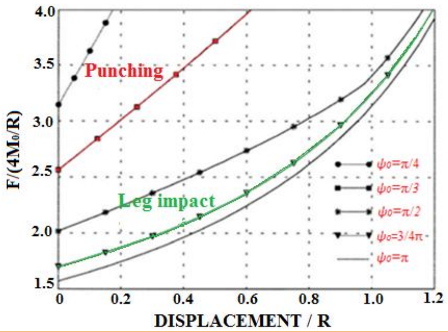
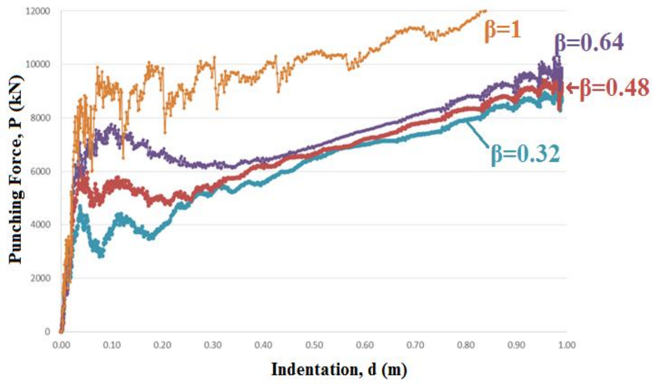
DISPLACEMENT FIELD-RING

- $\psi = \psi_0 + (\frac{1}{2}\pi - \psi_0)\frac{\delta}{2R}$

$\psi_0 = \frac{1}{3}\pi$





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LOCAL ENERGY RATE-GENERATOR

- Crushing energy rate of generator

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

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

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

n_0 : fully plastic membrane force per unit

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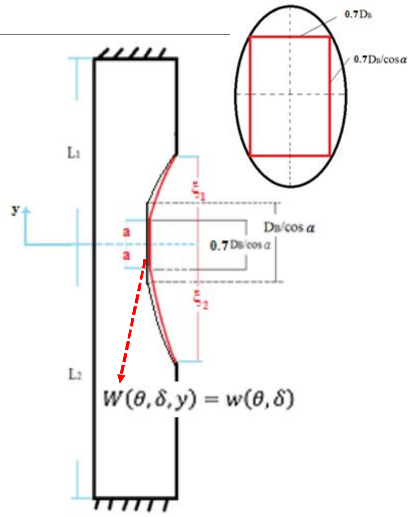
DISPLACEMENT FIELD-GENERATOR

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

$$W(\theta,\delta,y) = w(\theta,\delta) \quad \text{for } y \in [-a\,;\,a]$$

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



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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 ξ_1 and ξ_2

$$\frac{\partial P_l}{\partial \xi_1}=0 \Rightarrow \xi_1 = min\left(a+\sqrt{\frac{2E'_m}{E_b}};L_1\right)$$

$$\frac{}{-a}+\frac{1}{\xi_2-a}\Big)\Big\}/\delta$$

$$\frac{\partial P_l}{\partial \xi_2}=0 \Rightarrow \xi_2 = min\left(a+\sqrt{\frac{2E'_m}{E_b}};L_2\right)$$

TRANSITION OF CRUSHING MODE & GLOBAL CRUSHING RESISTANCE

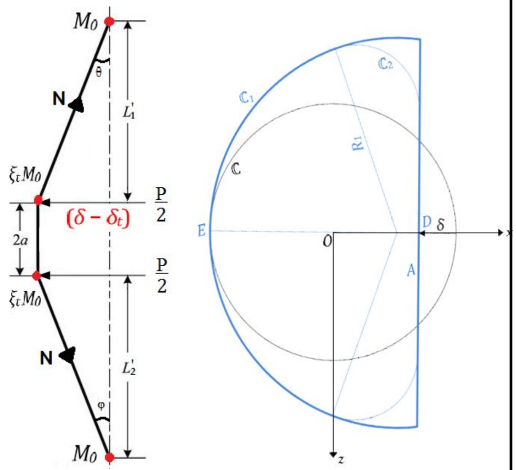
- 4 plastic hinges mechanism

$$W_{hinge} = M_0\theta + M_0\varphi + \xi_t M_0\theta + \xi_t M_0\varphi$$

$$\Vert$$

$$W_p = \frac{P(\delta_t)}{2}L'_1\theta + \frac{P(\delta_t)}{2}L'_2\varphi$$

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



TRANSITION OF CRUSHING MODE & GLOBAL CRUSHING RESISTANCE

- Threshold

$$P_l(\delta_t) = P_c(\delta_t) = \frac{L'_1 + L'_2}{L'_1 L'_2}\left(1 + \beta \times \sqrt{Q_\beta} \times \xi(\delta_t)\right)M_0$$

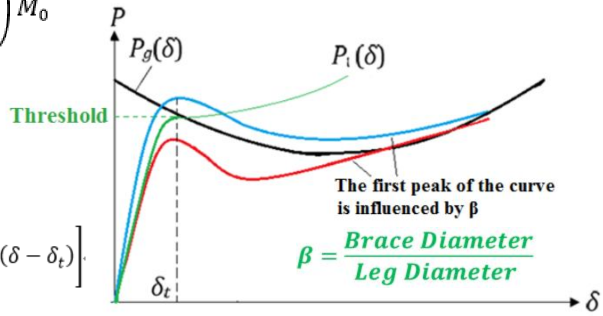
$$Q_\beta = 1 \qquad \text{for } \beta \le 0.6$$

$$= \frac{0.3}{\beta(1-0.833\beta)} \qquad \text{for } \beta > 0.6$$

- Global resistance

$$P_g(\delta) = \frac{L'_1 + L'_2}{L'_1 L'_2}\left[\left(1 + \beta \times \sqrt{Q_\beta} \times \xi_t\right)M_0\left(1 - \frac{N(\delta)^2}{N_0^2}\right) + N(\delta)(\delta - \delta_t)\right]$$

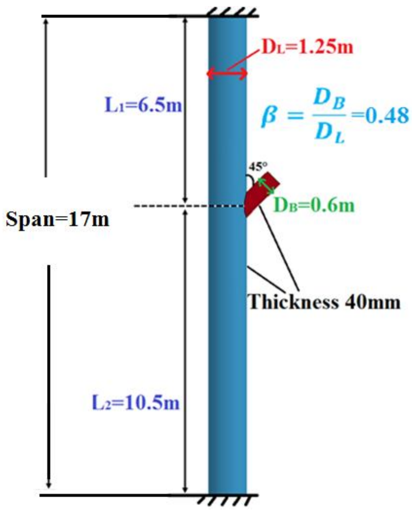
$$N(\delta) = min\left(\frac{N_0^2(\delta - \delta_t)}{2(1 + \beta \times \sqrt{Q_\beta} \times \xi_t M_0)}; N_0\right)$$



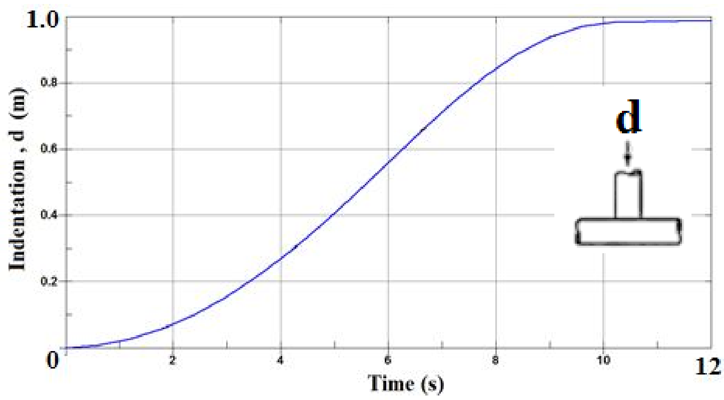
NUMERICAL VALIDATION-SIMPLE TUBE JOINT

MODEL DESCRIPTION

- Jacket-like cylinder dimension

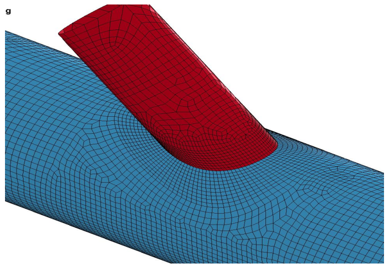


- Material and prescribed displacement



MESH SIZE CONVERGENCE STUDY

- Mesh size: 100mm => 25mm

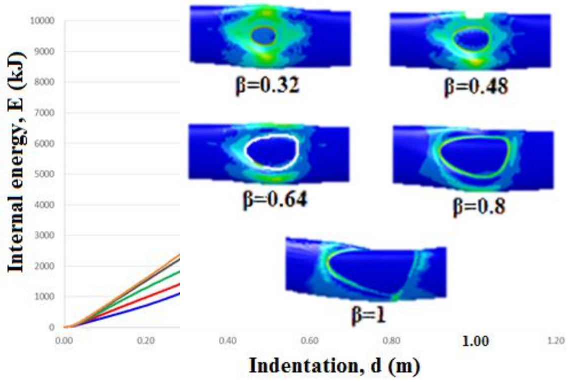


Smallest mesh size	Number of element	Discrepancy of energy	Discrepancy of force	Simulation time
100 mm	7040	--	--	67 s
50 mm	7630	≈3.5%	≈8%	111 s
25 mm	16320	≈6%	≈12%	298 s

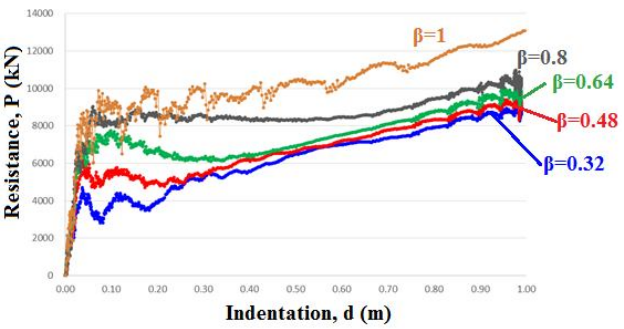
DIFFERENT β RATIOS

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

Internal energy



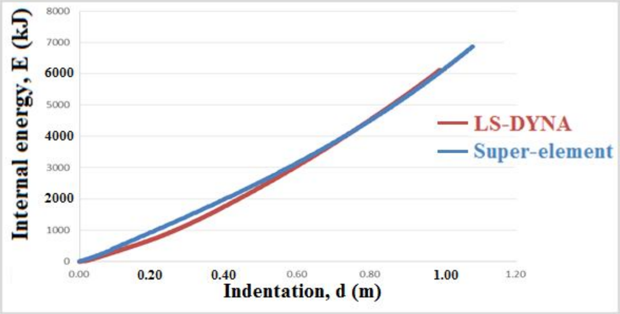
Crushing resistance

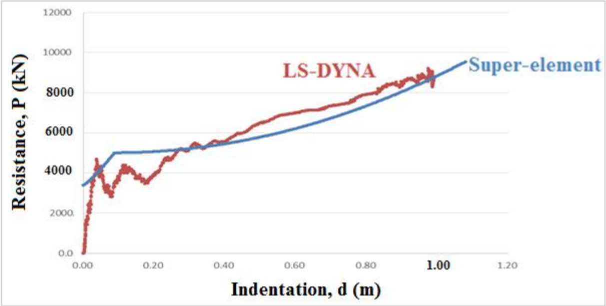


DIFFERENT β RATIOS

- β=0.32 (small brace diameter)
- d=0,2~0,4m => 35% discrepancy

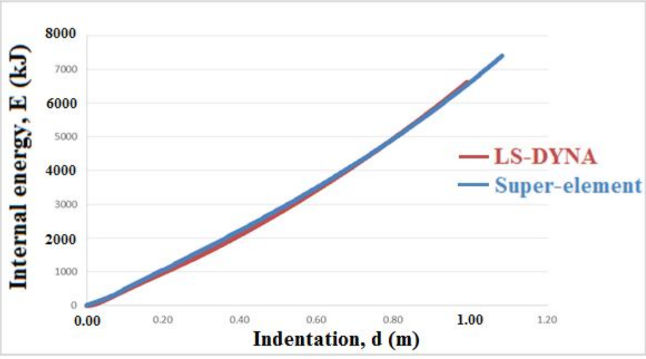
$$Discrepancy = \frac{E_{super\ element} - E_{LS\ DYNA}}{E_{LS\ DYNA}}$$

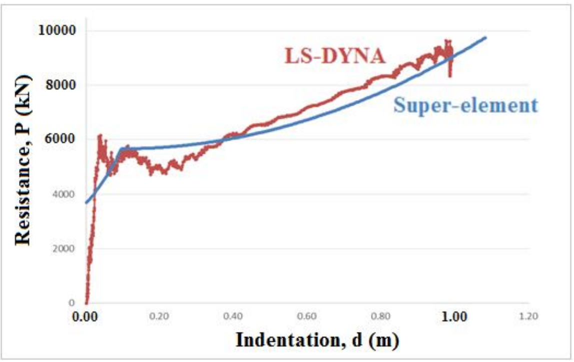




DIFFERENT β RATIOS

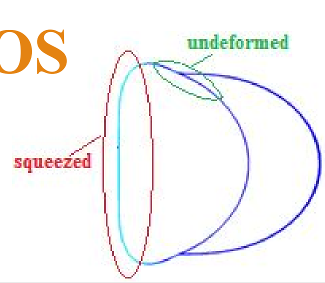
- β=0.48 (jacket-like)
- d≈0,37m => 8% discrepancy

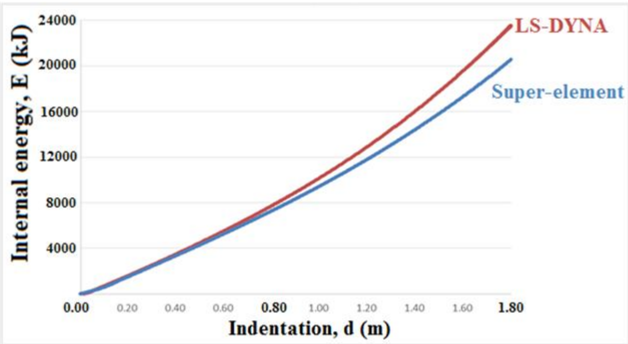


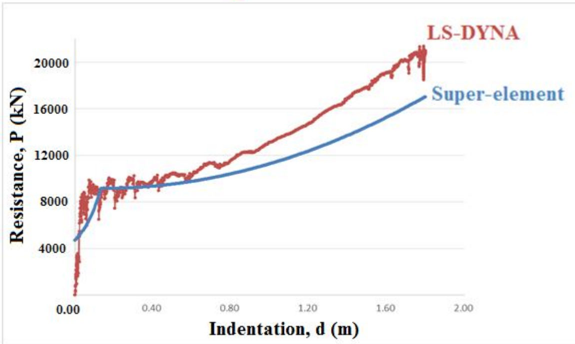


DIFFERENT β RATIOS

- β=1 (large brace diameter, D_B=D_L)
- d≈1,8m => -14,7% discrepancy



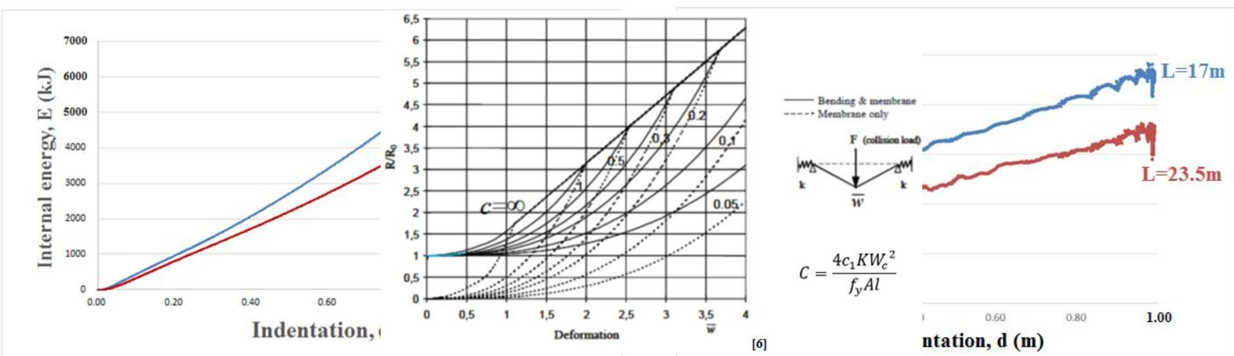




DIFFERENT SPAN

Internal energy

Crushing resistance



$$C = \frac{4c_1 K W_c^2}{f_y A l}$$

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DIFFERENT SPAN

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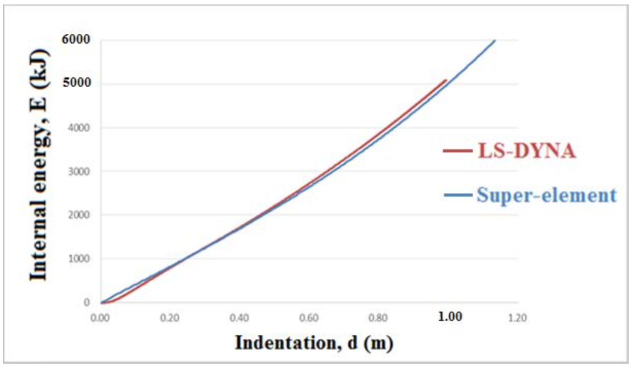
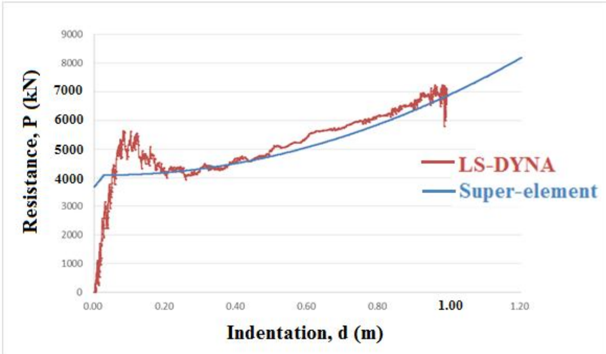
- *L*=23,5 m
- d≈0,8m => -3% discrepancy





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TWO JOINTS WITH GAP

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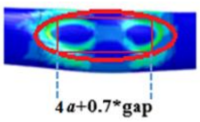
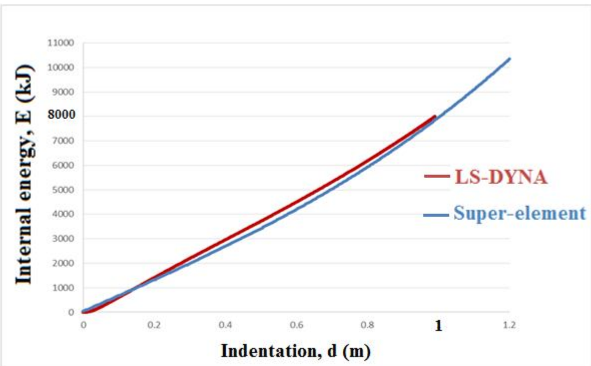
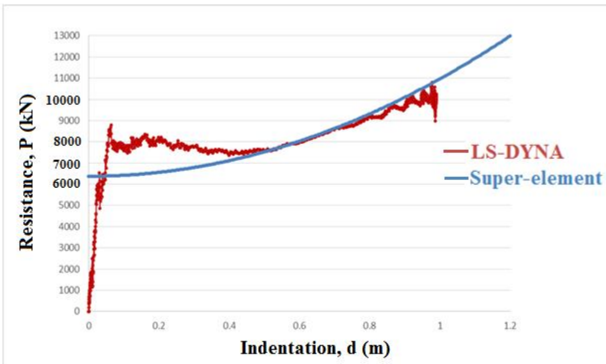
- *L*=17 m (L_1=7,5m, L_2=9,5m)
- d≈0,36m => -9,6% discrepancy

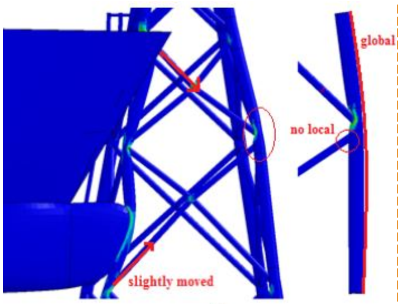






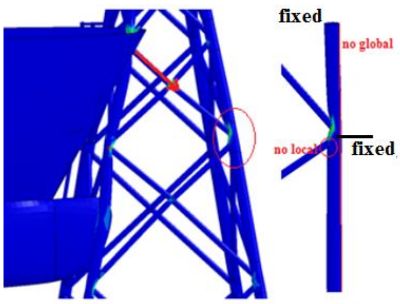
NUMERICAL VALIDATION- REAL JACKET FOUNDATION

JACKET PUNCHING SCENARIOS



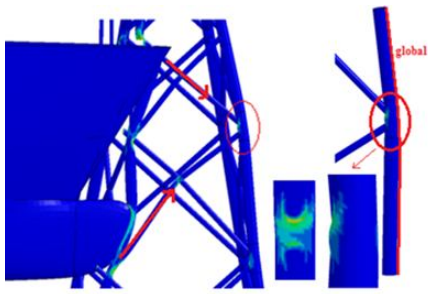
I

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.

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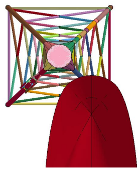
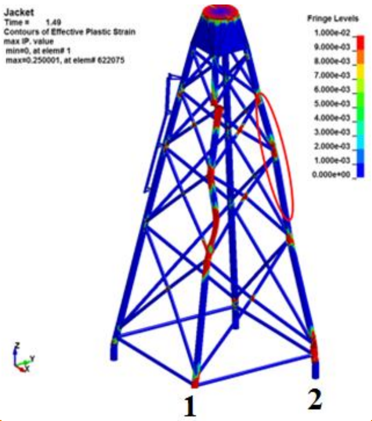
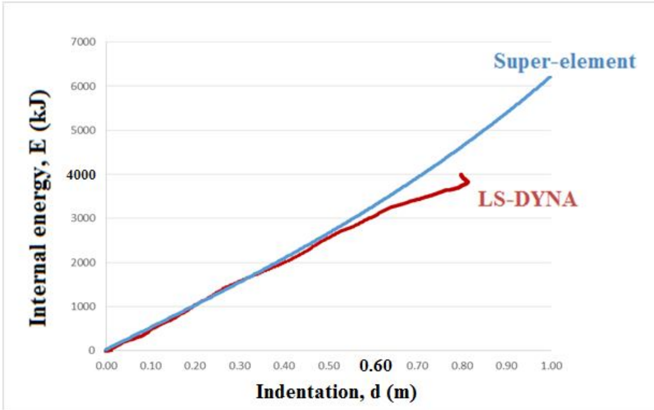
CASE 1: 90°-SCENARIO *I*



- L_1: 9m, L_2: 14,5m



- Buckling of braces at d=0,6m



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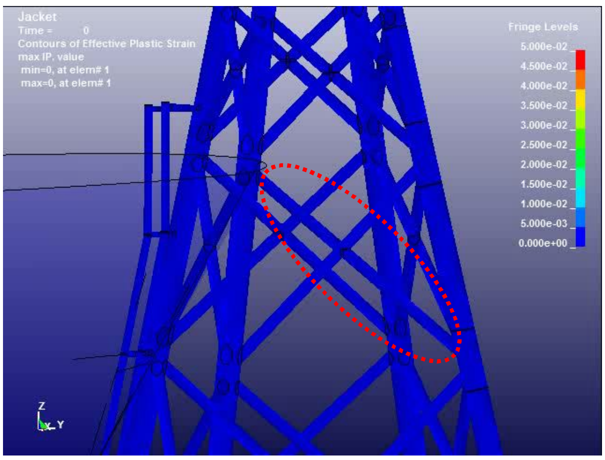
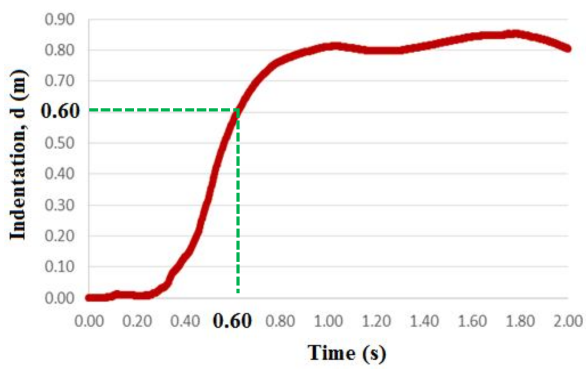
CASE 1: 90°-SCENARIO *I*





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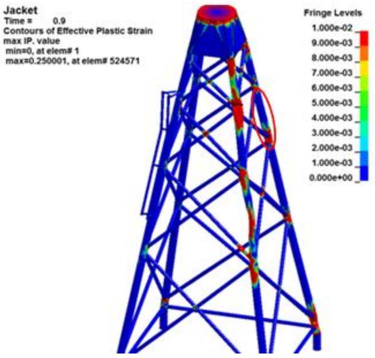
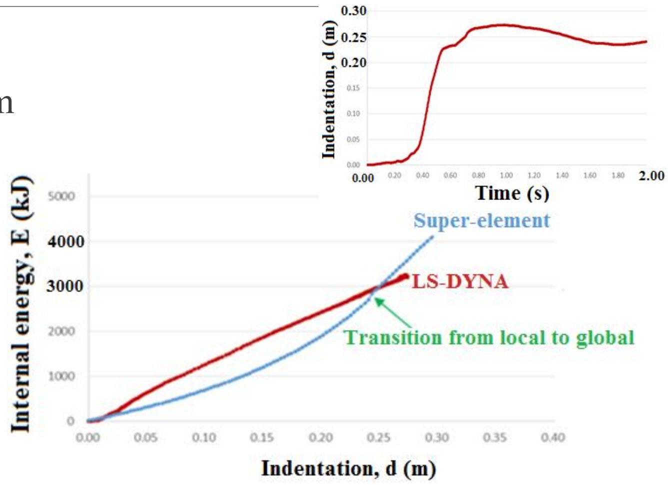
CASE 2: 90°-SCENARIO *II*

- L_1: 9m, L_2: 1,5m
- Buckling of braces at d=0,23m





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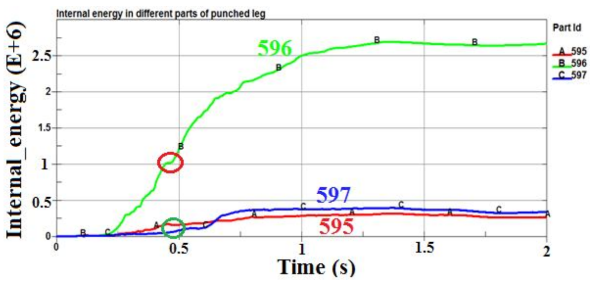
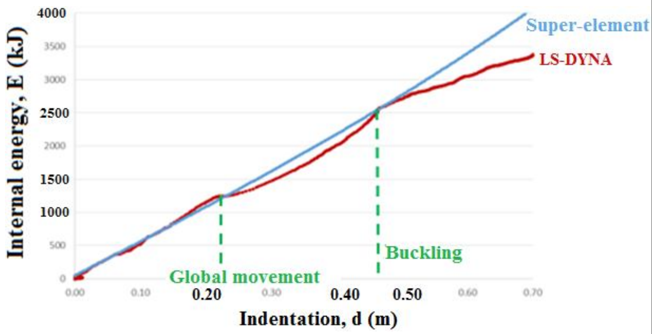
CASE 3: 90°-SCENARIO *III*

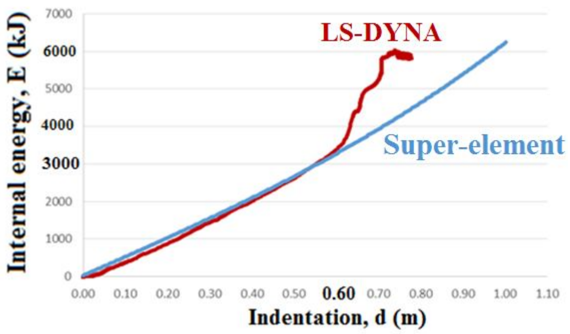
- L_1: 10m, L_2: 13,5m, gap=0,82m
- Abrupt global movement at d=0,23m
- Bulcking of braces at d=0,46m

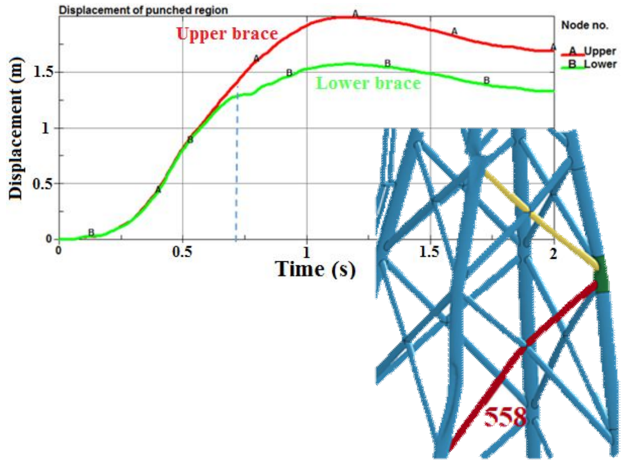




CASE 4: 60°-SCENARIO *I*

- L_1: 9m, L_2: 14,5m
- Buckling of brace 558 at *d*=0,61m





CONCLUSIONS & FUTURE WORKS

CONCLUSIONS

- Scenario *II* should be improved.
- Energy obtained by super-e

  Bow ≈ 20%

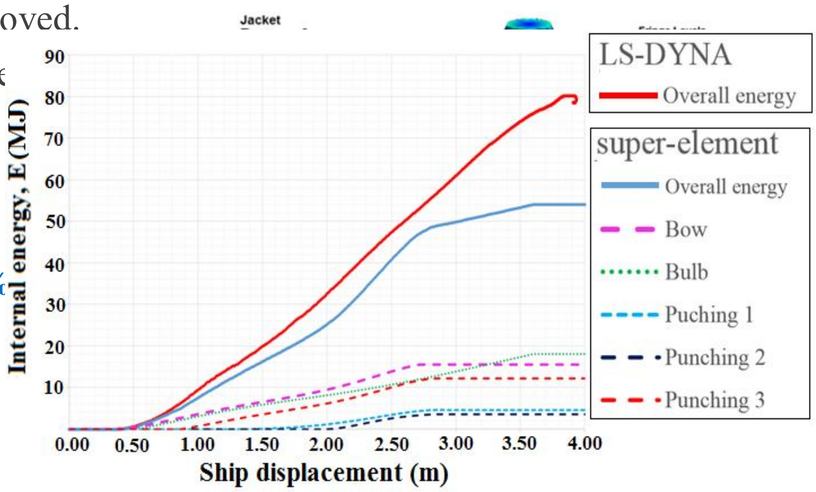
  Bulb ≈ 23%

  Punching 1 ≈ 6%

  Punching 2 ≈ 5%

  Punching 3 ≈ 15%

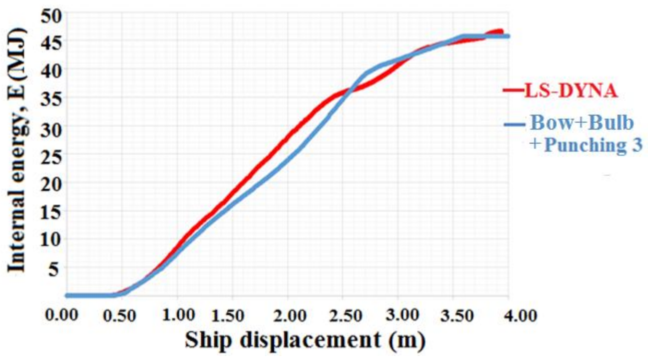
  } ≈ 26%



CONCLUSIONS

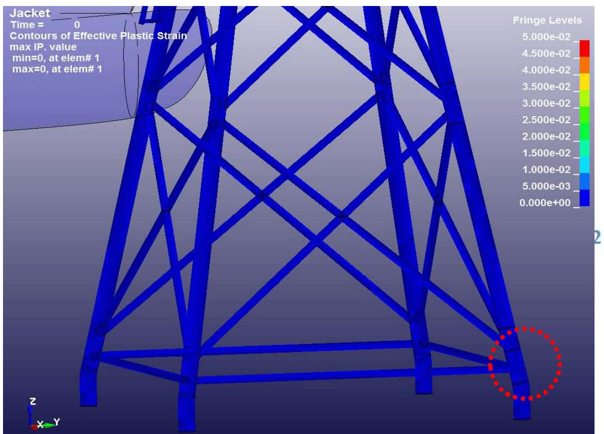
Collided Leg

- Punching 3 => overestimated



Rear Leg

- Shearing effect => 30% of rear leg energy

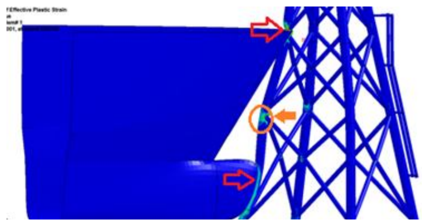


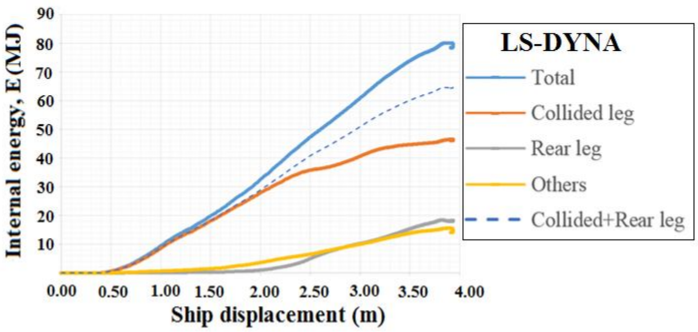
CONTRIBUTIONS OF THIS STUDY

- Development of a new super-element for punching
- Validation of the super-element for different β
- 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

WWW.EMSHIP.EU

REFERENCE

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