Institut Catholique d'Arts et Métiers

Institut de Recherche en Génie Civil et Mécanique

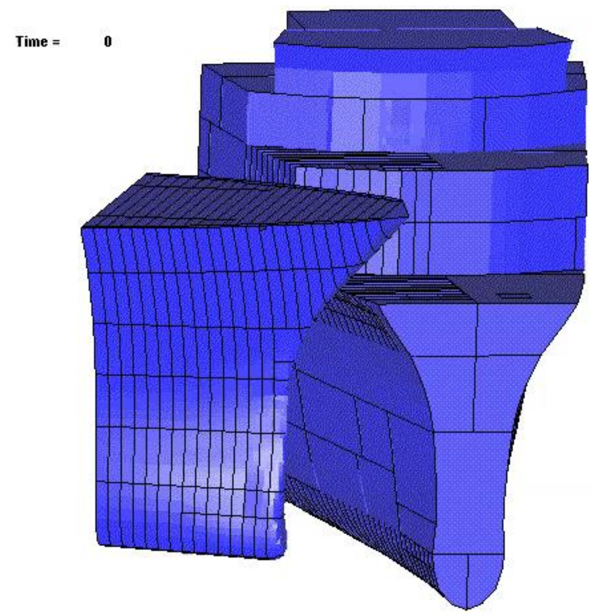
The super-element method for ship collision and grounding fast analysis

Hervé Le Sourne
ICAM Engineering School – Nantes campus (France)

ICSOS – 1st of September 2020

1. INTRODUCTION

- **Finite Element Analysis**
  - Worldwide used today



1. INTRODUCTION

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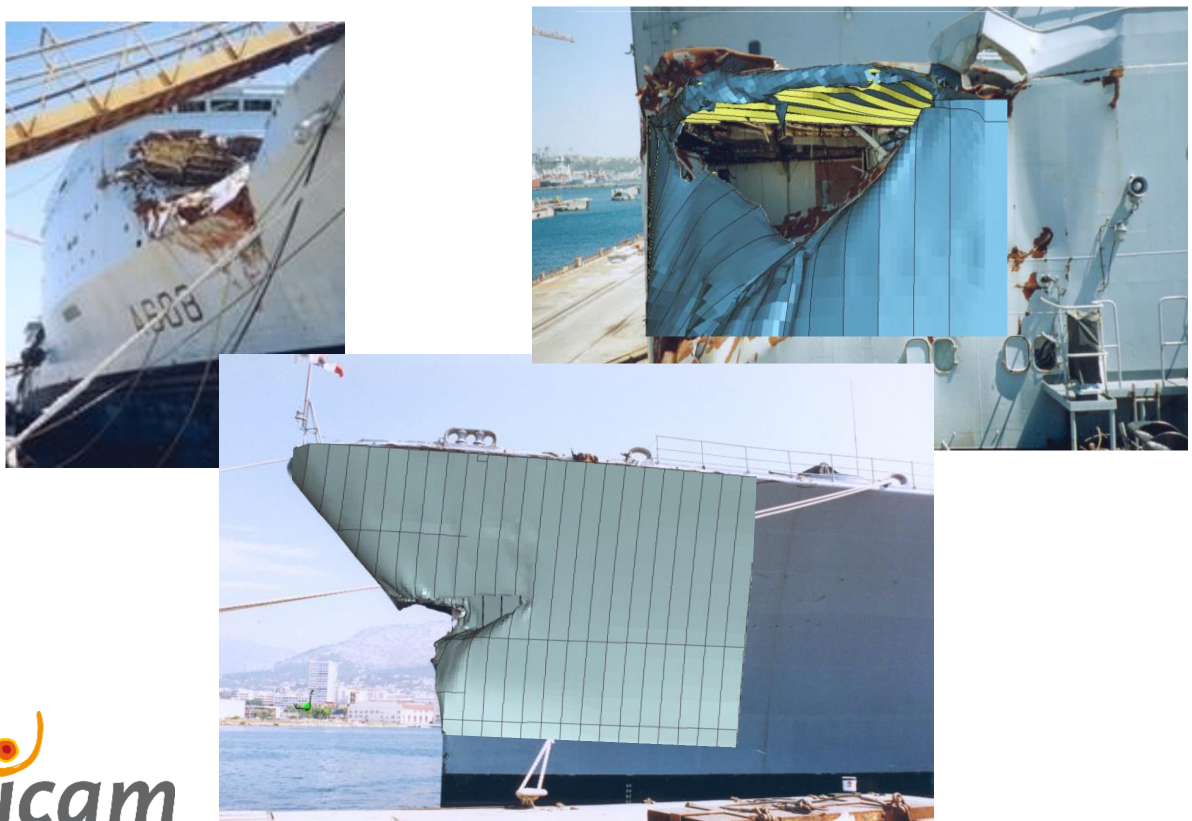
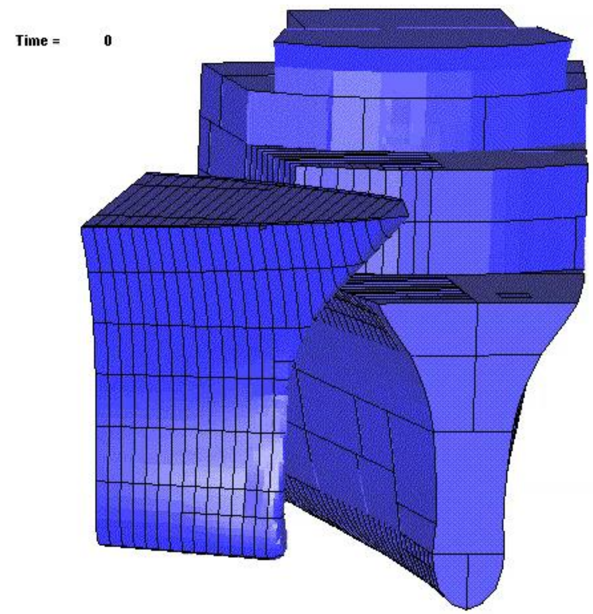
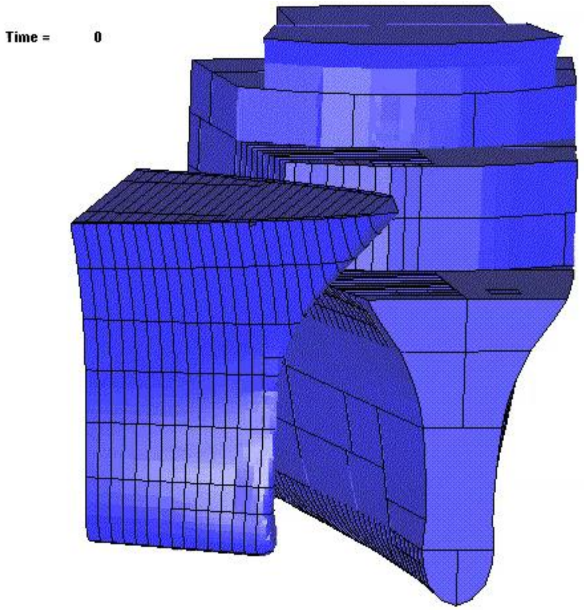




1. INTRODUCTION

- **Finite Element Analysis**
  - Worldwide used today
  - Validated
- **But …**
  - Long and costly
  - Not well suited for risk analysis
  - Requires some expertise



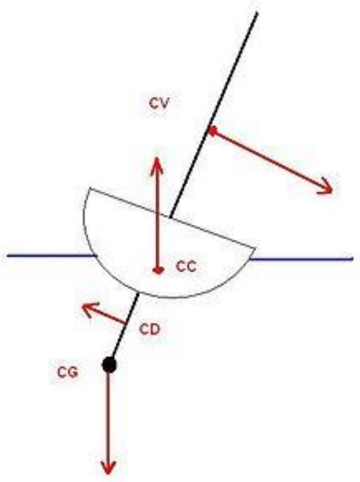
1. INTRODUCTION

- **Finite Element Analysis**
  - Worldwide used today
  - Validated
- **But …**
  - Long and costly
  - Not well suited for risk analysis
  - Requires some expertise
- **… need some tool:**
  - … rapid
  - … simple to used

CONTENT

2. SHIP EXTERNAL DYNAMICS

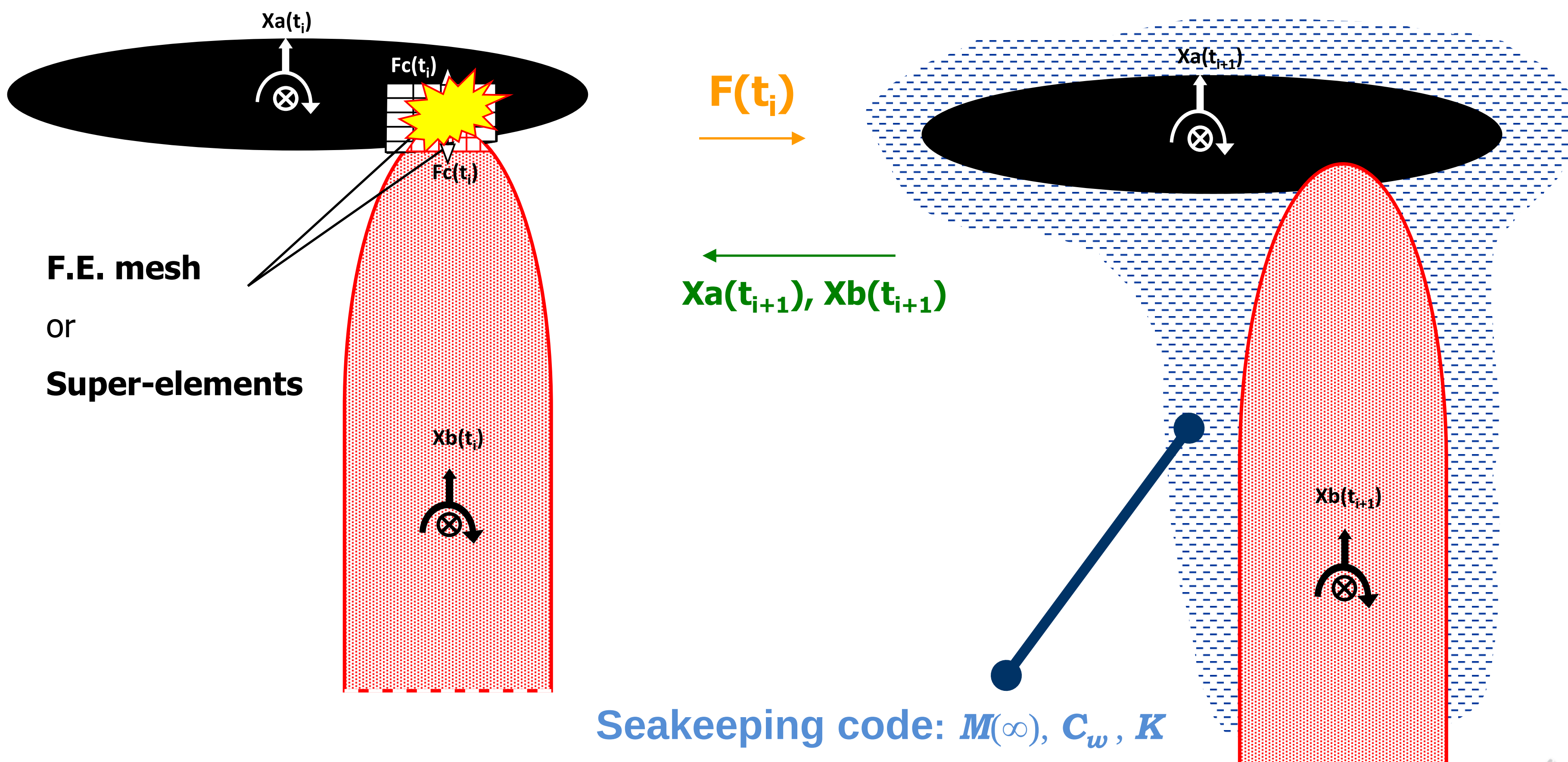
- **Ship external dynamics is driven by**
  - Inertia forces $M(\infty)$
  - Dissipative forces
    - Wave radiation $C(\omega)$
    - Drag D
  - Buoyancy forces K



2. SHIP EXTERNAL DYNAMICS

Structure solver: internal dynamics

MCOL: external dynamics



2. SHIP EXTERNAL DYNAMICS

- **Ship external dynamics is driven by**
  - Inertia forces $\boldsymbol{M(\infty)}$
  - Dissipative forces
    - Wave radiation $\boldsymbol{C(\omega)}$
    - Drag D
  - Hydrostatic restoring forces $\boldsymbol{K}$

- **Solve numerically**

Structural mass

Acceleration at CoG

$$\left[\boldsymbol{M} + \boldsymbol{M}(\infty)\right]\ddot{\boldsymbol{x}} + \left[\boldsymbol{C}_w + \boldsymbol{C}(\boldsymbol{y}) + \boldsymbol{D}(\boldsymbol{y})\right]\dot{\boldsymbol{x}} + \begin{bmatrix} \boldsymbol{R}^T & 0 \\ 0 & \boldsymbol{R}^T \end{bmatrix} \boldsymbol{K}\,\boldsymbol{x} = \boldsymbol{F}$$

Water added mass

2. SHIP EXTERNAL DYNAMICS

- **Ship external dynamics is driven by**
  - Inertia forces ***M(∞)***
  - Dissipative forces
    - Wave radiation ***C(ω)***
    - Drag *D*
  - Hydrostatic restoring forces ***K***

- **Solve numerically**

$$\left[\boldsymbol{M}+\boldsymbol{M}(\infty)\right]\ddot{\boldsymbol{x}}+\left[\overbrace{\boldsymbol{C}_w}^{\text{Wave radiation}}+\underbrace{\boldsymbol{C}(\boldsymbol{y})}_{\text{Gyroscopic effects}}+\underbrace{\boldsymbol{D}(\boldsymbol{y})}_{\text{Drag effects}}\right]\overbrace{\dot{\boldsymbol{x}}}^{\text{Velocity}}+\begin{bmatrix}\boldsymbol{R}^T & 0\\ 0 & \boldsymbol{R}^T\end{bmatrix}\boldsymbol{K}\,\boldsymbol{x}=\boldsymbol{F}$$

2. SHIP EXTERNAL DYNAMICS

- **Ship external dynamics is driven by**
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    - Wave radiation $\boldsymbol{C(\omega)}$
    - Drag D
  - Hydrostatic restoring forces $\boldsymbol{K}$

- **Solve numerically**

Large rotations

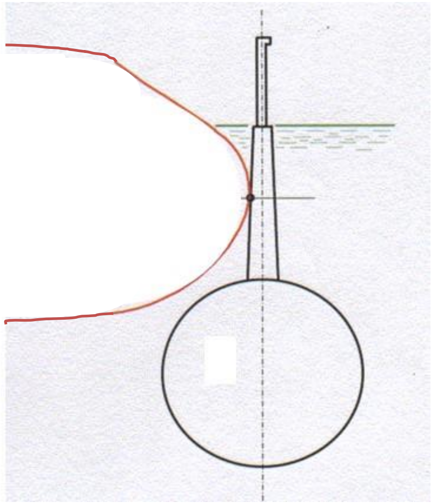
Hydrostatic restoring

$$\left[\boldsymbol{M} + \boldsymbol{M}(\infty)\right]\ddot{\boldsymbol{x}} + \left[\boldsymbol{C}_w + \boldsymbol{C}(\boldsymbol{y}) + \boldsymbol{D}(\boldsymbol{y})\right]\dot{\boldsymbol{x}} + \begin{bmatrix} \boldsymbol{R}^T & 0 \\ 0 & \boldsymbol{R}^T \end{bmatrix} \boldsymbol{K}\,\boldsymbol{x} = \boldsymbol{F}$$

Displacement

Contact force

- **Example:** **Oil carrier bulb against submarine**



Impact on superstructure

Reference
H. Le Sourne, E.R. Donner, F. Besnier, M. Ferry – External dynamics of ship-submarine collision – 2nd International Conference on Collision and Grounding of Ships, pp 137-144, Copenhagen 2001

2. SHIP EXTERNAL DYNAMICS

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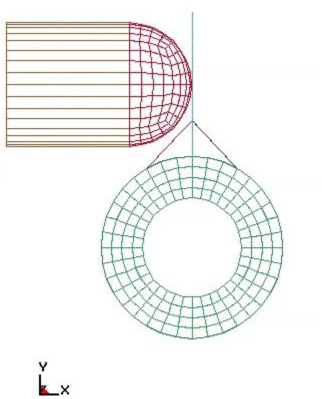
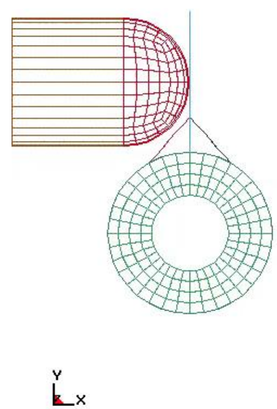
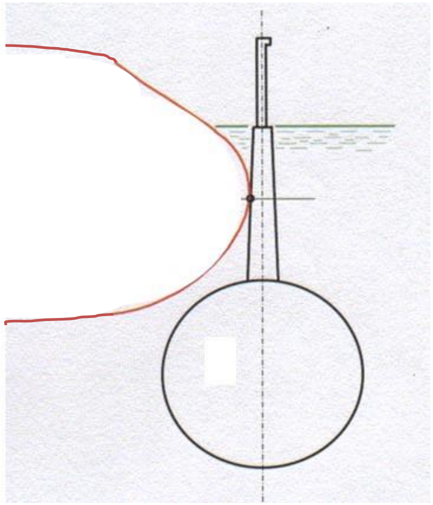


LS-DYNA



LS-DYNA + MCOL



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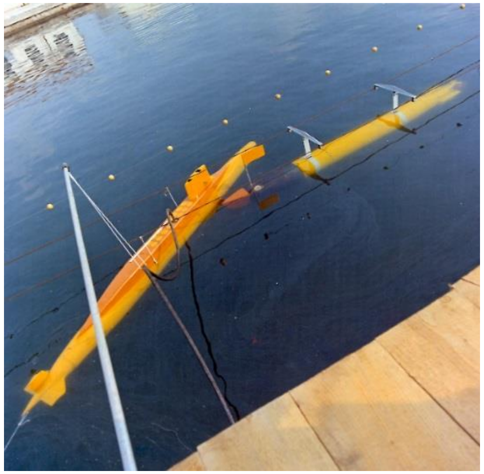
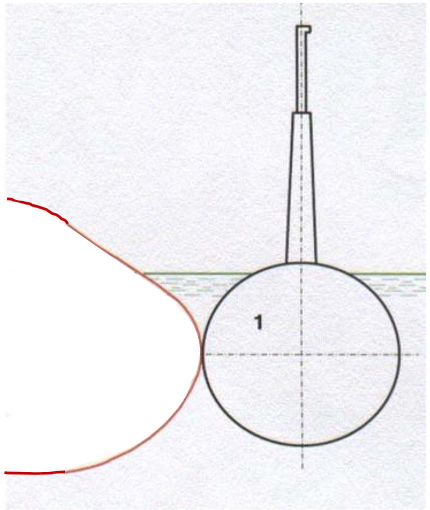
2. SHIP EXTERNAL DYNAMICS

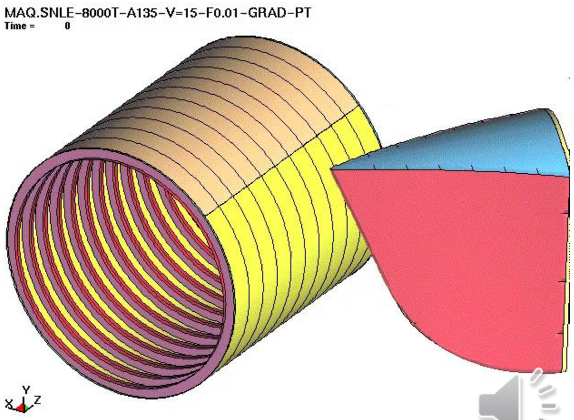
- **Validation:** **Cargo bow against submarine**



Experimental test on scaled models



Impact on main hull



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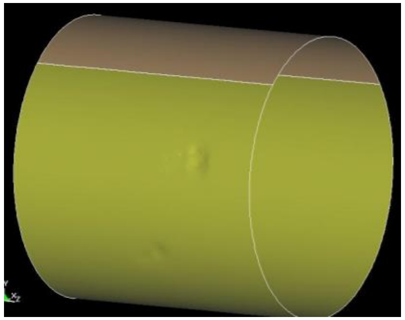

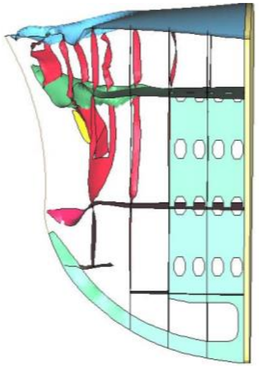

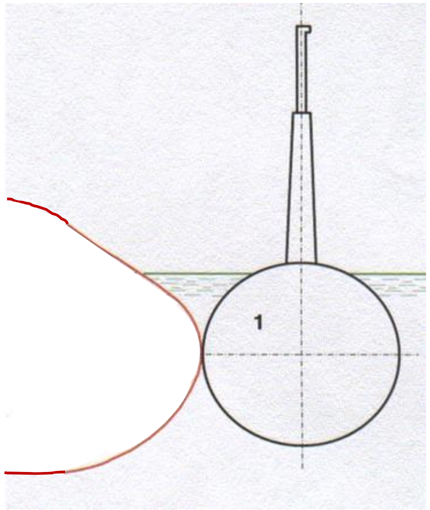

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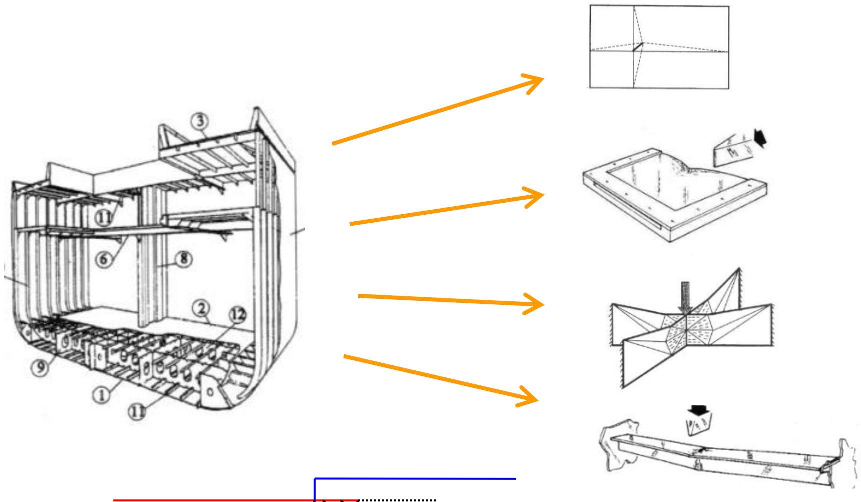
CONTENT

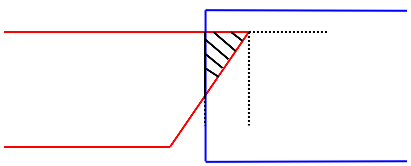
3. SUPER-ELEMENT METHOD

- **Principle of the method**

1. Split struck and striking ships into super-elements



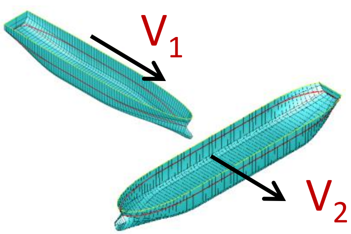
2. Identify the impacted elements



3. Compute the crushing force

$$F_T = \sum F_e$$

4. Update the ships velocities (MCOL)



5. If $V_2 \geq V_1$ then stop

3. SUPER-ELEMENT METHOD

- **External force work rate**

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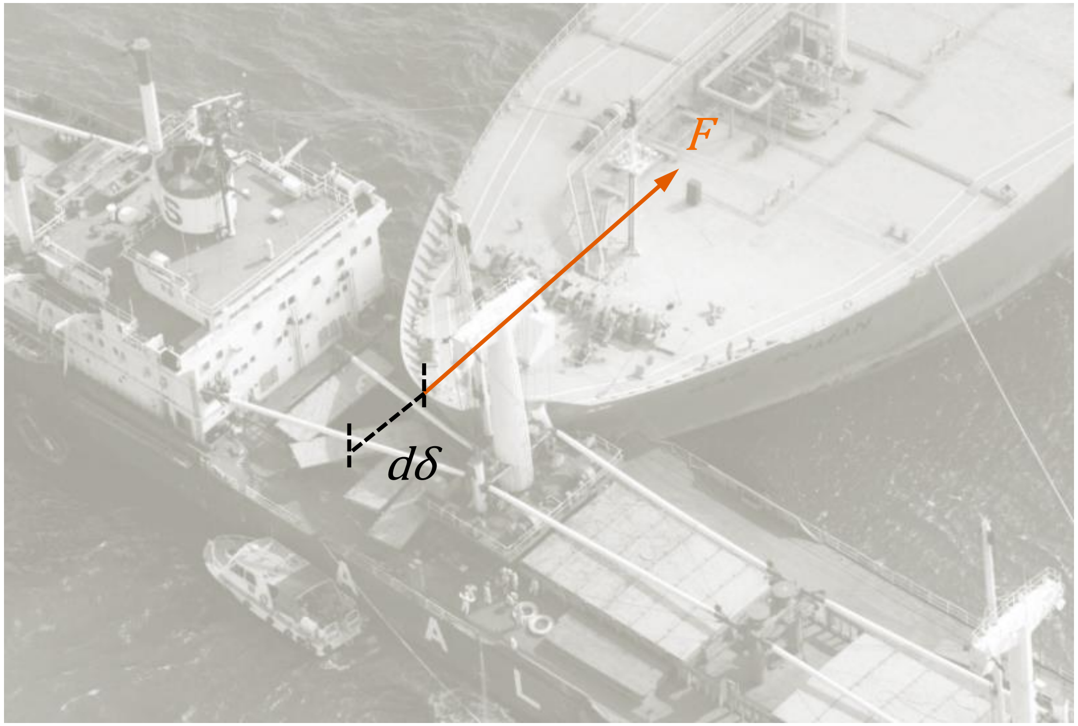
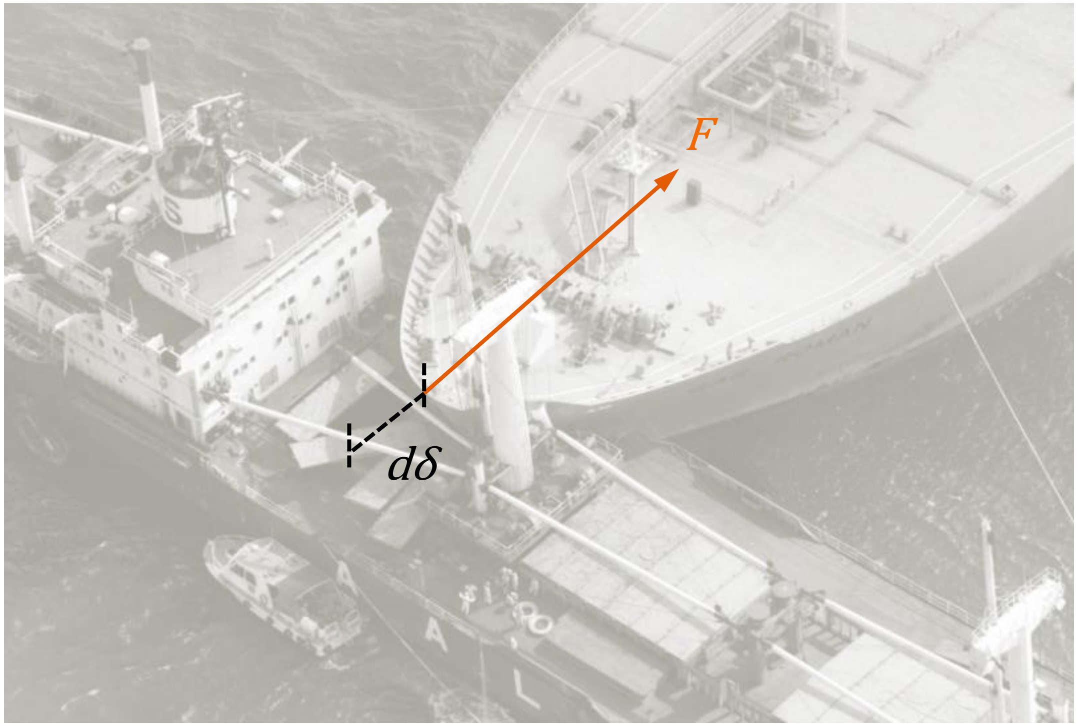


3. SUPER-ELEMENT METHOD

- **External force work rate**



$$dE_{ext} = F \cdot d\delta \Rightarrow \dot{E}_{ext} = F \cdot \dot{\delta}$$

- **Internal energy rate**

3. SUPER-ELEMENT METHOD

- **Upper-bound theorem** (N. Jones, 1989)

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

$$\Leftrightarrow F \cdot \dot{\delta} = \dot{E}_{int} \Rightarrow F = \frac{\dot{E}_{int}}{\dot{\delta}}$$

Reference: N. Jones, 1997. Structural Impact, Cambridge University, Cambridge, UK.

3. SUPER-ELEMENT METHOD

- **Upper-bound theorem** (N. Jones, 1989)

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

$$\Leftrightarrow F \cdot \dot{\delta} = \dot{E}_{int} \Rightarrow F = \boxed{\frac{\dot{E}_{int}}{\dot{\delta}}}$$

Calculate the resistant force

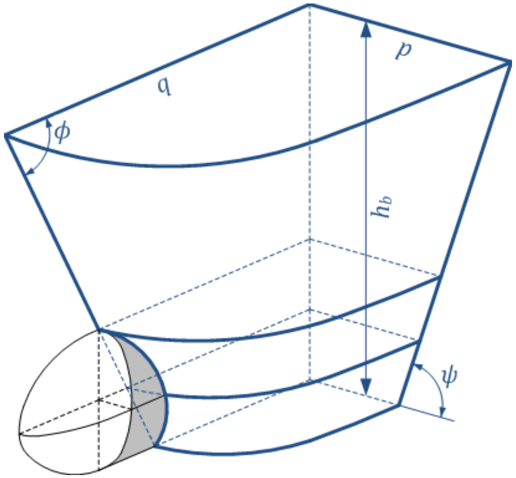
$\Updownarrow$

Calculate the internal energy rate

Reference: N. Jones, 1997. Structural Impact, Cambridge University, Cambridge, UK.

3. SUPER-ELEMENT METHOD

- **1st step: choose a mechanism**
  - The more realistic as possible
  - *U* compatible with boundary conditions
  - Account for the striking shape



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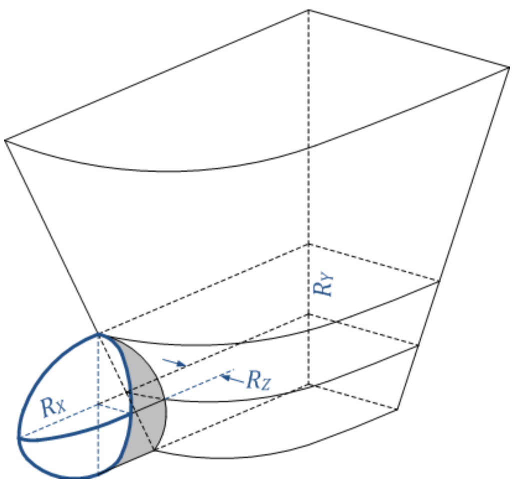


3. SUPER-ELEMENT METHOD

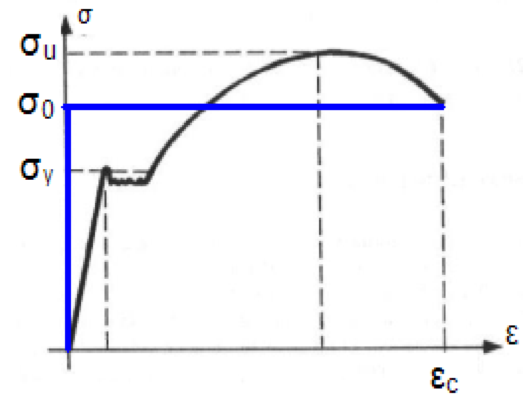
- **1st step: choose a mechanism**
  - The more realistic as possible
  - *U* compatible with boundary conditions
  - Account for the striking shape

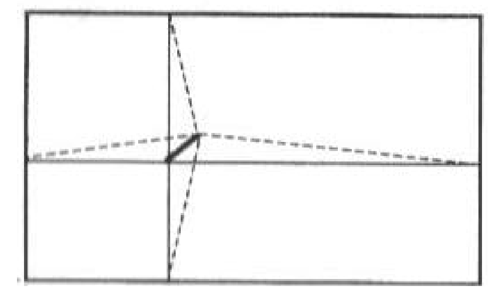
- **2nd step: derive strain rate**
  - Large displacements
  - Green-Lagrange deformations

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

- **3rd step: derive internal energy rate:**
  - Consider a Rigid Plastic behavior law
  - Choose a plasticity criteria
  - **Example:** plaque impacted perpendicularly

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



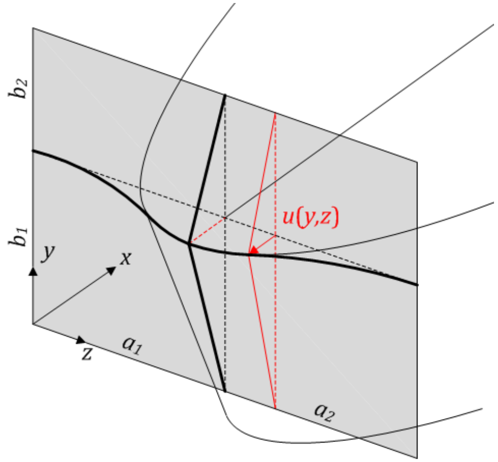


CONTENT

4. APPLICATIONS

Ship / ship collisions

- **Developed super-elements**
  - **Side shell**



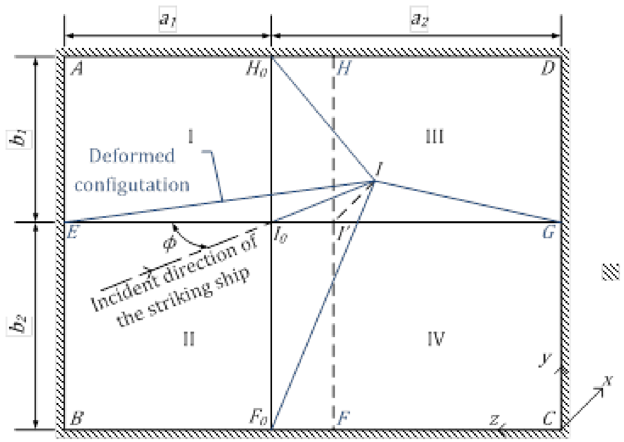
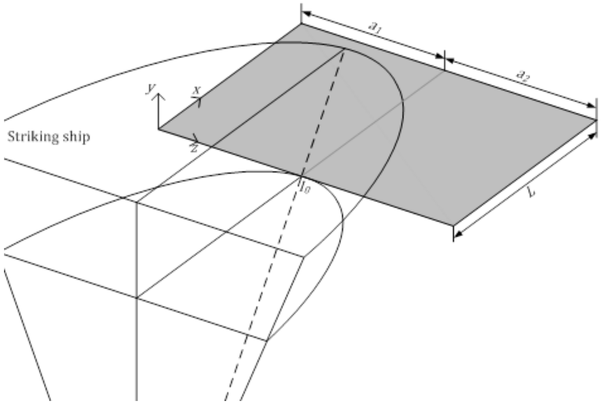


Plate clamped on its 4 edges

4. APPLICATIONS

Ship / ship collisions

- **Developed super-elements**
  - Side Shell
  - Decks, bottom



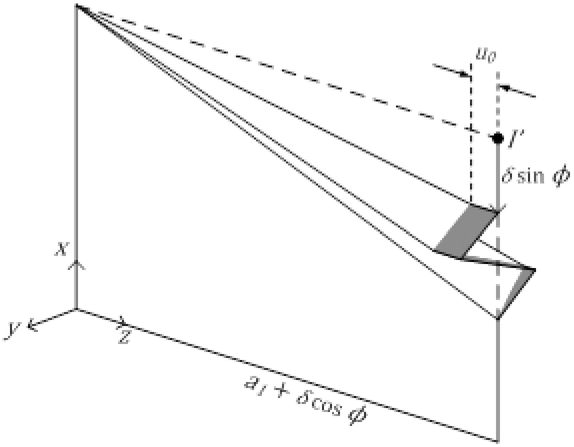
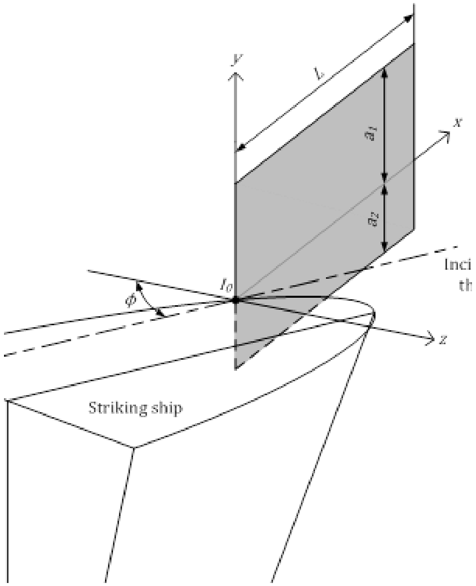


Plate clamped on 3 edges

4. APPLICATIONS

Ship / ship collisions

- **Developed super-elements**
  - Side Shell
  - **Decks, bottom**
  - **Transverse bulkheads**



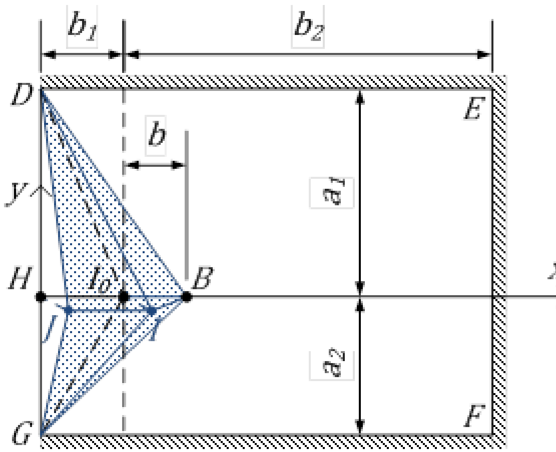
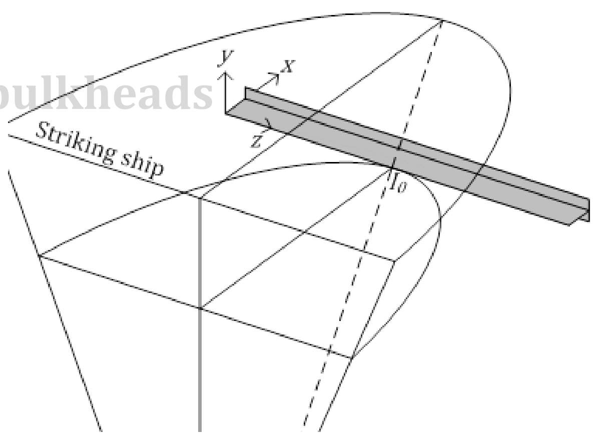


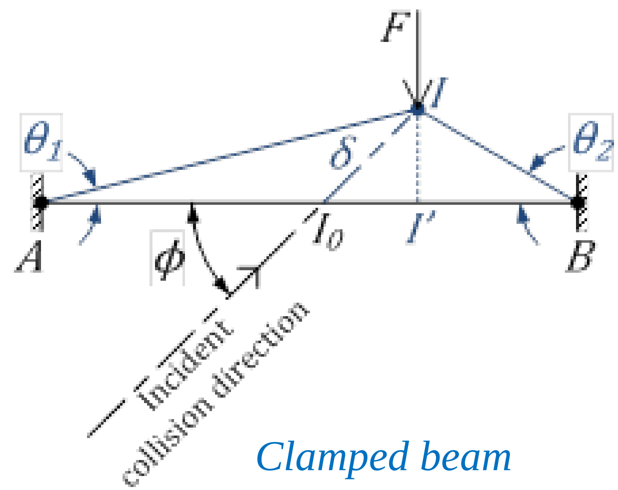
Plate clamped on 3 edges

4. APPLICATIONS

Ship / ship collisions

- **Developed super-elements**
  - Side Shell
  - Decks, bottom
  - Transverse bulkheads
  - **Stiffeners**



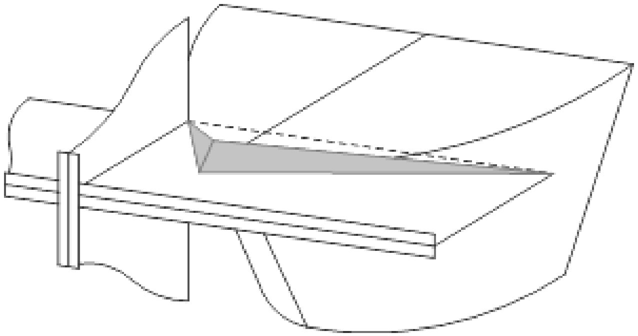


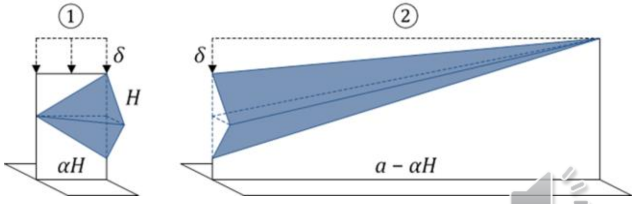
Clamped beam

4. APPLICATIONS

Ship / ship collisions

- **Developed super-elements**
  - Side Shell
  - **Decks, bottom**
  - **Transverse bulkheads**
  - **Stiffeners**
  - **Intersection**





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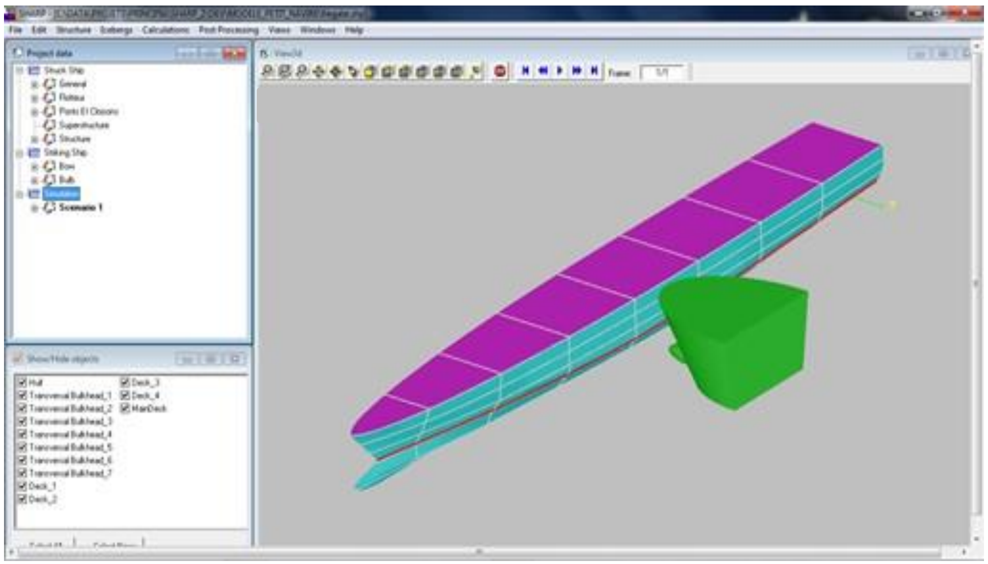
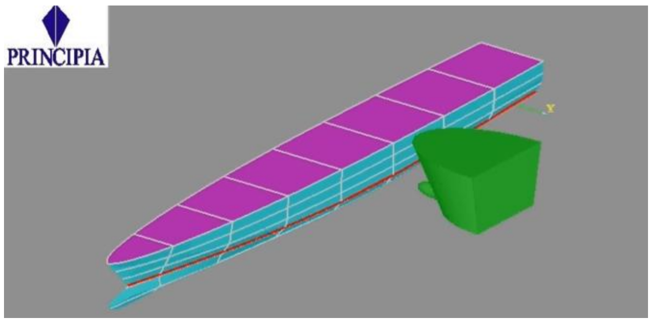
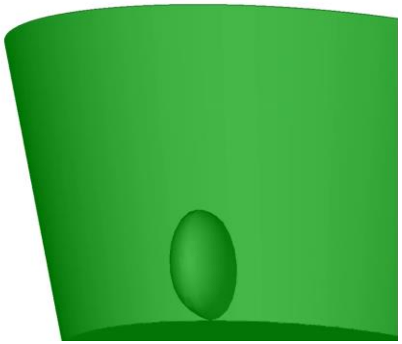
4. APPLICATIONS

Ship / ship collisions

- **SHARP collision analysis tool**







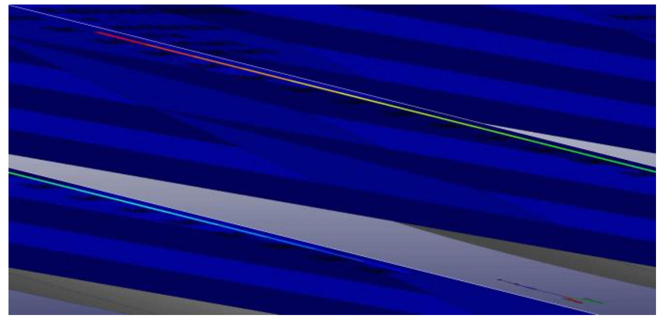
  - Discrepancy / FEA < 15%

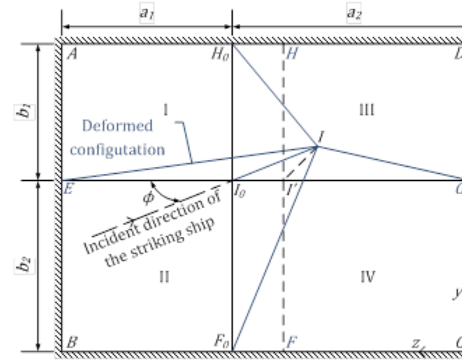
Reference
H. Le Sourne, N. Besnard, C. Cheylan, N. Buannic – A Ship Collision Analysis Program Based on Upper Bound Solutions and Coupled with a Large Rotational Ship Movement Analysis Tool – Journal of Applied Mathematics, 2012 – DOI 10.1155/2012/375686

4. APPLICATIONS

Ship grounding

- **Developed super-elements**
    - **Bottom stranding**



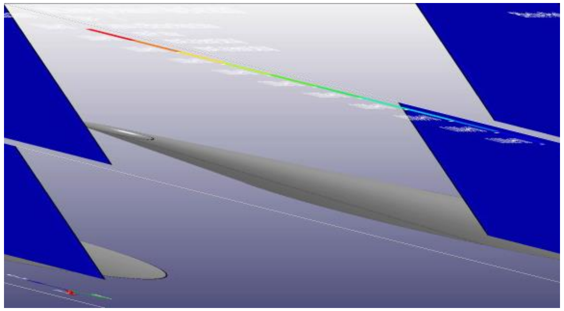


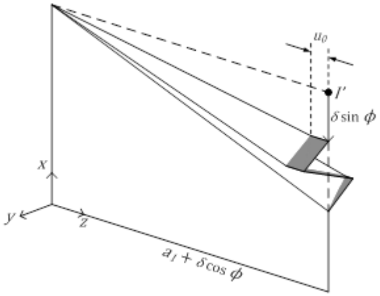
Plastic bending, membrane straining

4. APPLICATIONS

Ship grounding

- **Developed super-elements**
  - Bottom stranding
  - **Floor/girders stranding**



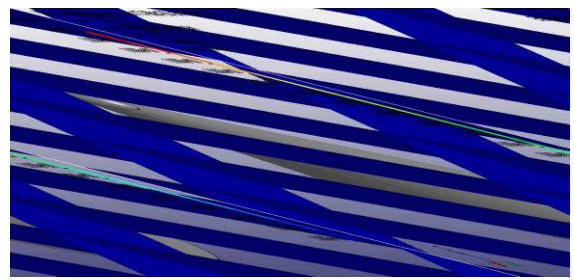


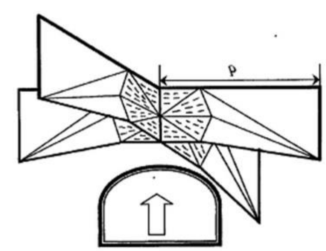
Plastic bending, membrane straining

4. APPLICATIONS

Ship grounding

- **Developed super-elements**
  - **Bottom stranding**
  - **Floor/girders stranding**
  - **Intersection**



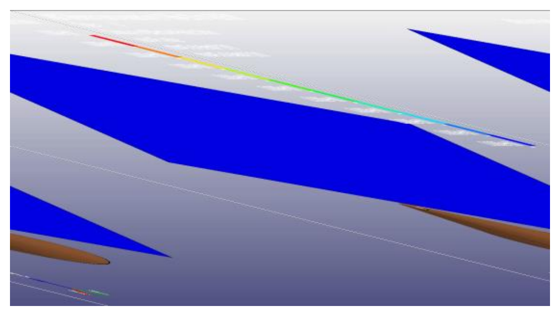


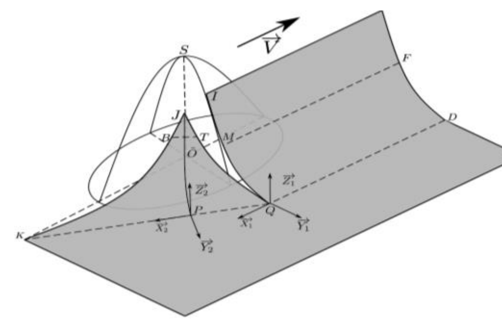
Plastic hinges, membrane straining

4. APPLICATIONS

Ship grounding

- **Developed super-elements**
  - Bottom stranding
  - Floor/girders stranding
  - Intersection
  - **Bottom raking**



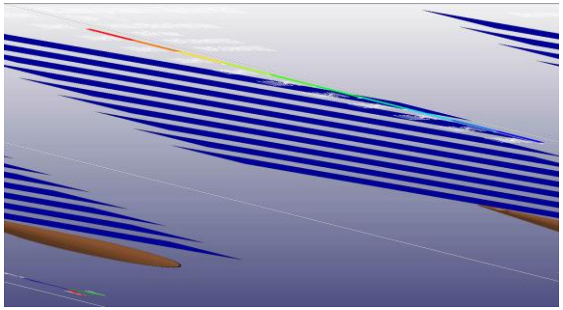


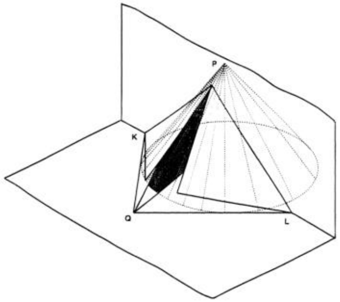
Plastic bending, membrane straining, tearing and friction

4. APPLICATIONS

Ship grounding

- **Developed super-elements**
    - Bottom stranding
    - Floor/girders stranding
    - Intersection
    - Bottom raking
    - **Floor raking**



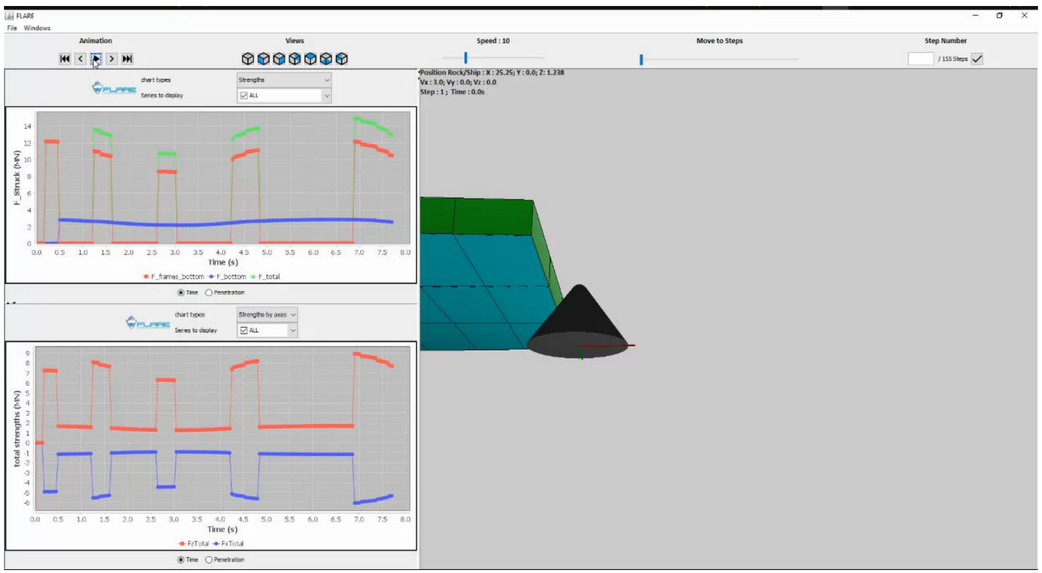


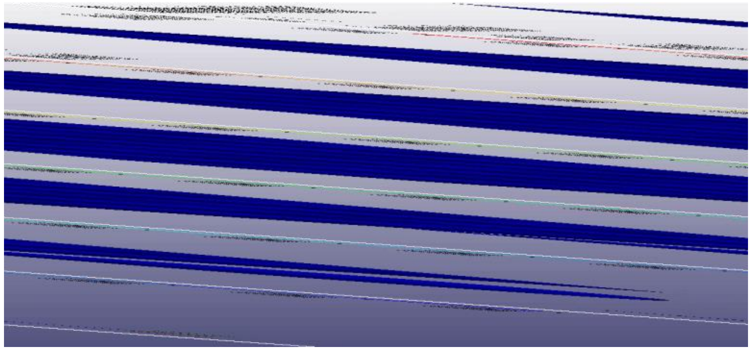
Plastic bending, tearing and friction

4. APPLICATIONS

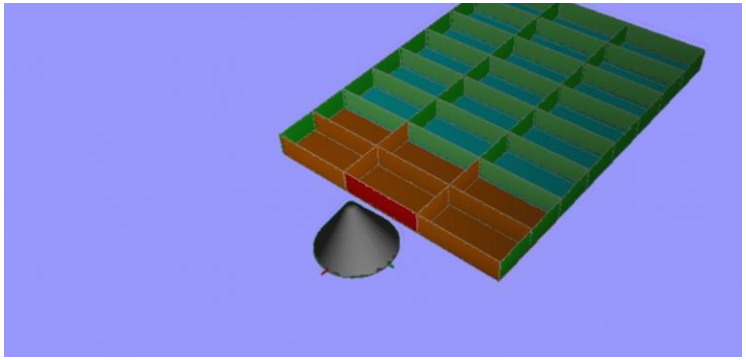
Ship grounding

- **FLARE grounding analysis tool**





LS-DYNA / MCOL : CPU time = 28h17min

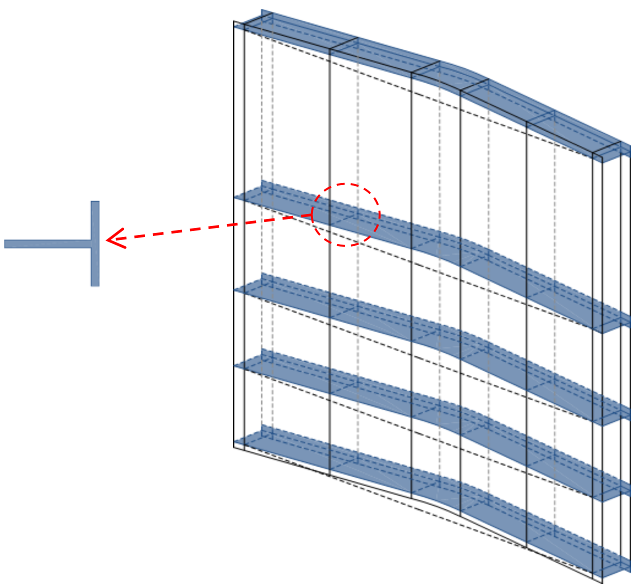


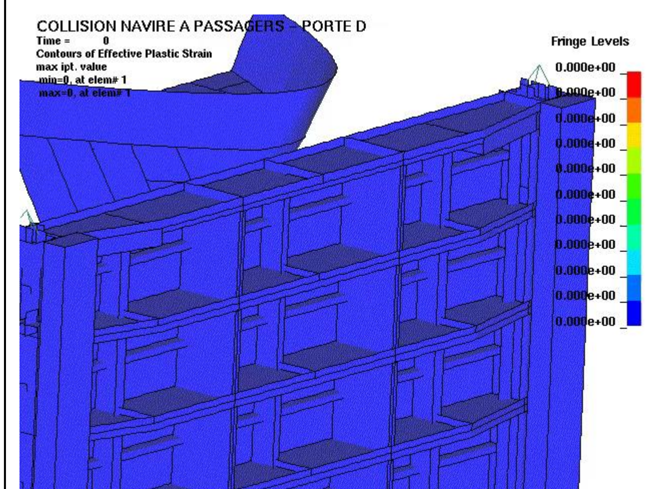
FLARE / MCOL : CPU time = 10 sec.

4. APPLICATIONS

Ship collision against lock gates

- Local crushing then **global deformation**
- Global deformation (bending + membrane) mainly governed by gate side and horizontal stiffeners





Reference
H. Le Sourne, J.C. Rodet, C. Clanet – Crashworthiness Analysis of a Lock Gate Impacted by Two Different River Ships – International Journal of Crashworthiness, Vol 7 n°4 pp 371-396, 2002

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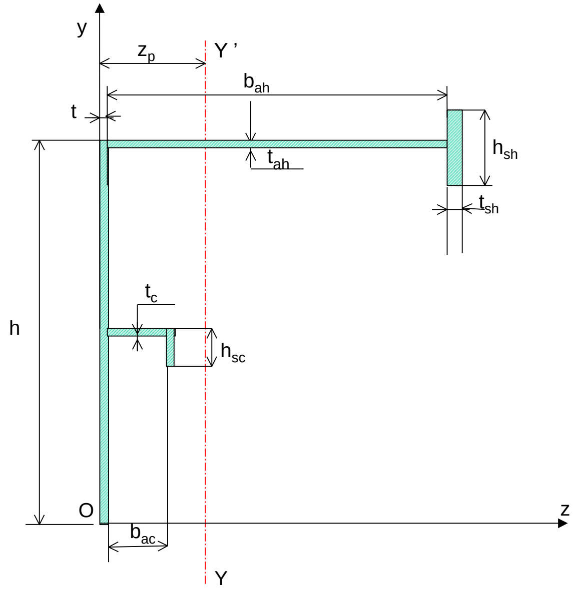

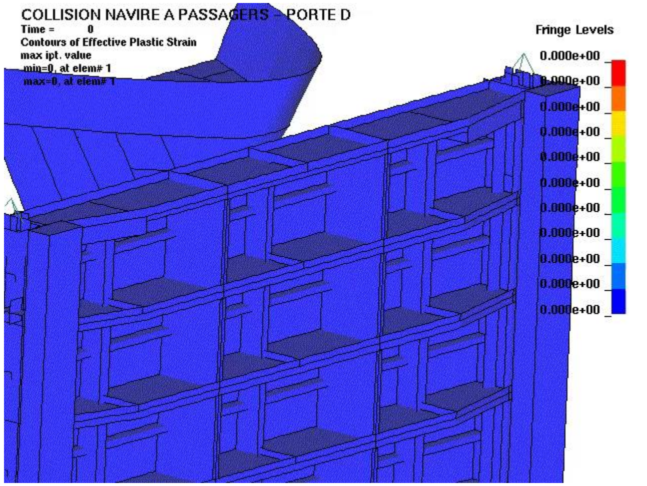

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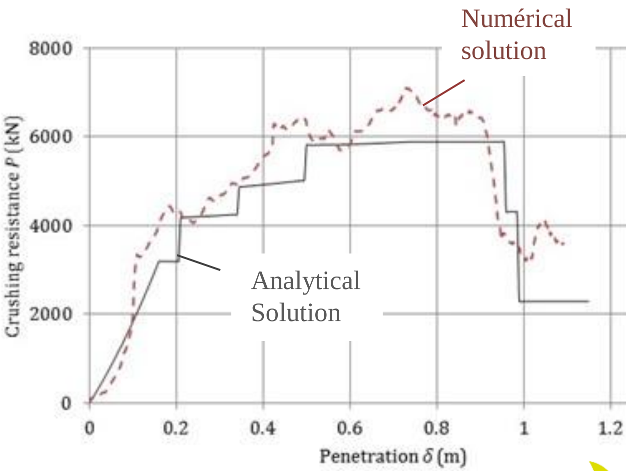
4. APPLICATIONS

Ship collision against lock gates

- Local crushing then global deformation
- Global deformation (bending + membrane) mainly governed by gate side and horizontal stiffeners
- Extension of super-element method
  - Elastic deformation
  - Stiffener damaged sections

Porte d'écluse busquée



Reference

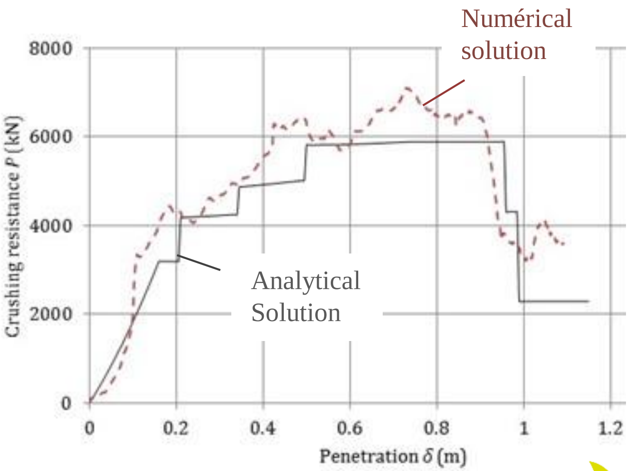
L. Buldgen, H. Le Sourne, Ph. Rigo – Simplified analytical method for estimating the resistance of lock gates to ship impacts – Journal of Applied Mathematics, 2012 – DOI 10.1155/2012/763849

4. APPLICATIONS

Ship collision against lock gates

- Local crushing then global deformation
- Global deformation (bending + membrane) mainly governed by gate side and horizontal stiffeners
- Extension of super-element method
  - Elastic deformation
  - Stiffener damaged sections
  - Adaptation to mitred gates
  - Extension to impact of barge

Porte d'écluse busquée



References

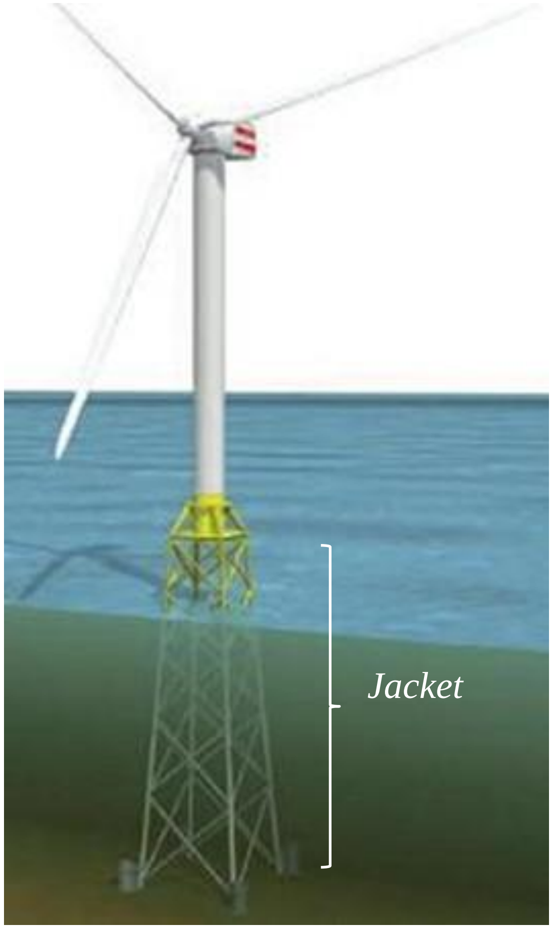
L. Buldgen, H. Le Sourne, Ph. Rigo – Fast Strength Assessment of Mitred Gates to Ship Impact – International Journal of Crashworthiness, 2013 – DOI 10.1080/13588265.2013.802146

L. Buldgen, H. Le Sourne – A simplified analytical method to estimate the resistance of plane lock gates impacted by river barges – Marine Structures, Vol 43, 2015 – DOI 10.1016/j.marstruc.2015.06.001

4. APPLICATIONS

Ship collision against offshore wind turbine

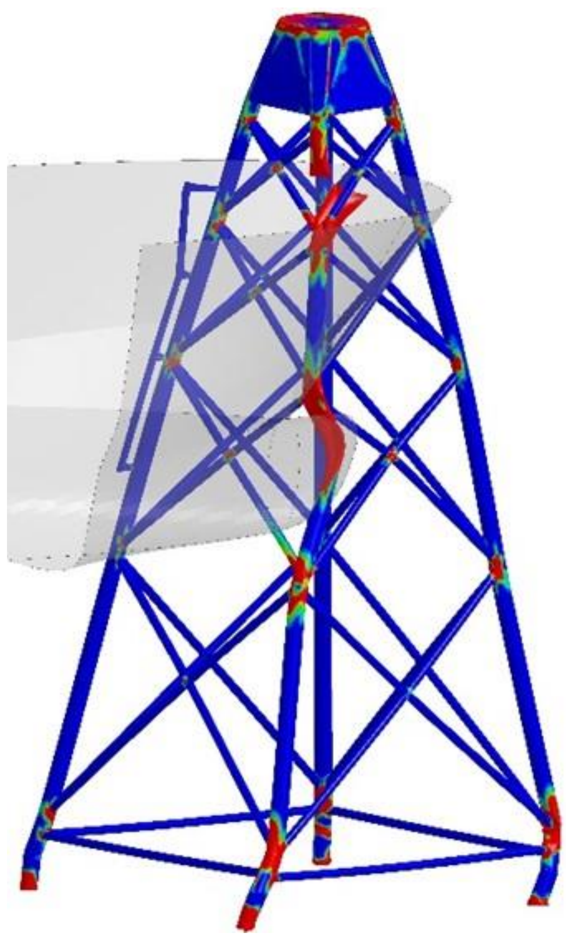
- **Jacket:** cylindrical tubes assembly



4. APPLICATIONS

Ship collision against offshore wind turbine

- Jacket: cylindrical tubes assembly
- **Detailed F.E.A**
  - Different scenarios, different striking ships
  - Sensitivity analysis (gravity, soil, etc.)



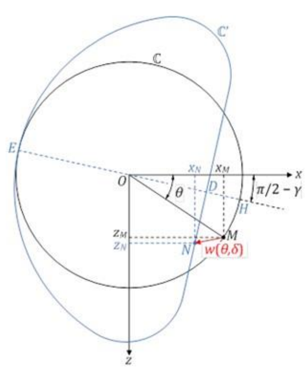
Reference
H. Le Sourne, A. Barrera, J.B. Maliakel – Numerical crashworthiness analysis of an offshore wind turbine jacket impacted by a ship – Journal of Marine Science and Technology, Vol 23 (5) pp 694-704, 2015 – DOI: 10.6119/JMST-015-0529-1

4. APPLICATIONS

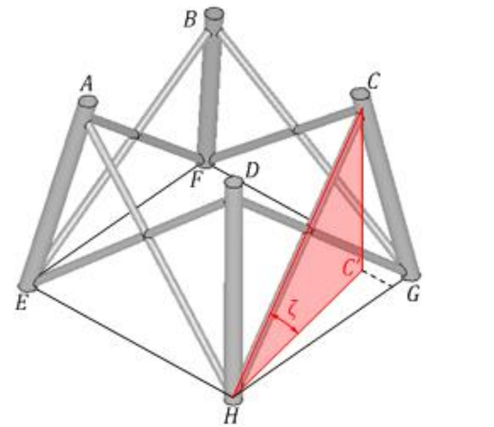
Ship collision against offshore wind turbine

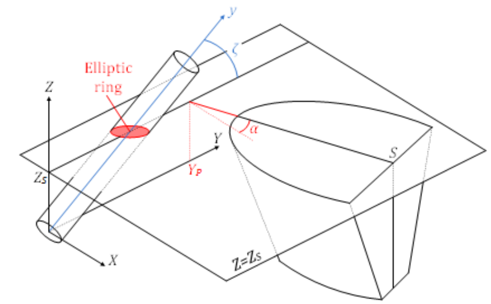
- Jacket: cylindrical tubes assembly
- Detailed F.E.A
  - Different scenarios, different striking ships
  - Sensitivity analysis (gravity, soil, etc.)

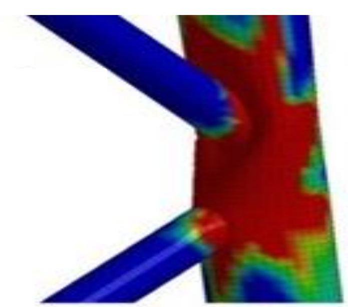
- **Super-element « cylinder »**
  - Tube crushed by ship bow or bulb
  - Tube punched by another tube



Deformation mechanism of a tube section







Reference
L. Buldgen, H. Le Sourne, T. Pire – Extension of the super-element method to the analysis of a jacket impacted by a ship – Marine Structures, Vol 38 pp 44-71, 2014

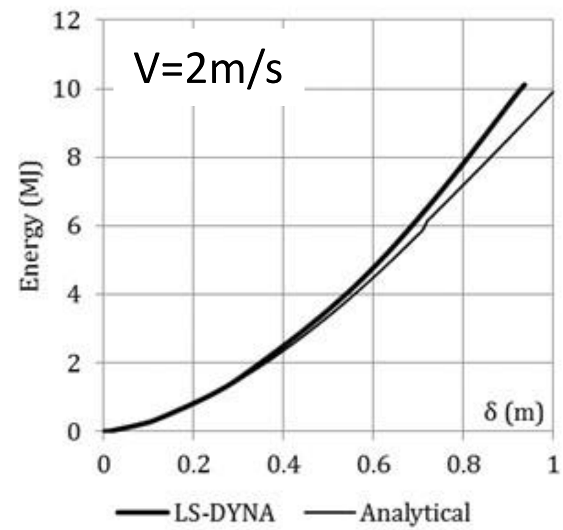
4. APPLICATIONS

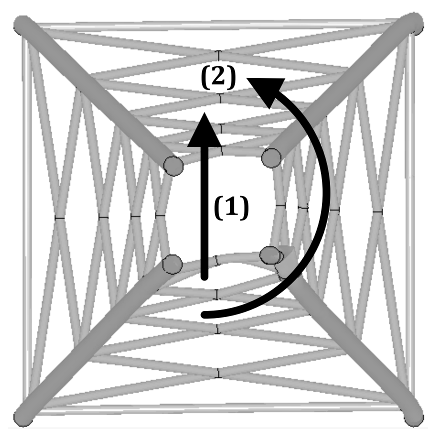
Ship collision against offshore wind turbine

- **Jacket: cylindrical tubes assembly**
- Detailed F.E.A
  - Different scenarios, different striking ships [HLS_2015]
  - Sensitivity analysis (gravity, soil, etc.)

- Super-element « cylinder »
  - Tube crushed by ship bow or bulb
  - Tube punched by another tube

- **Results**
  - Ok for low energy impact ($V_{OSV} \leq 2$m/s)
  - Else, coupling the S.E. becomes necessary





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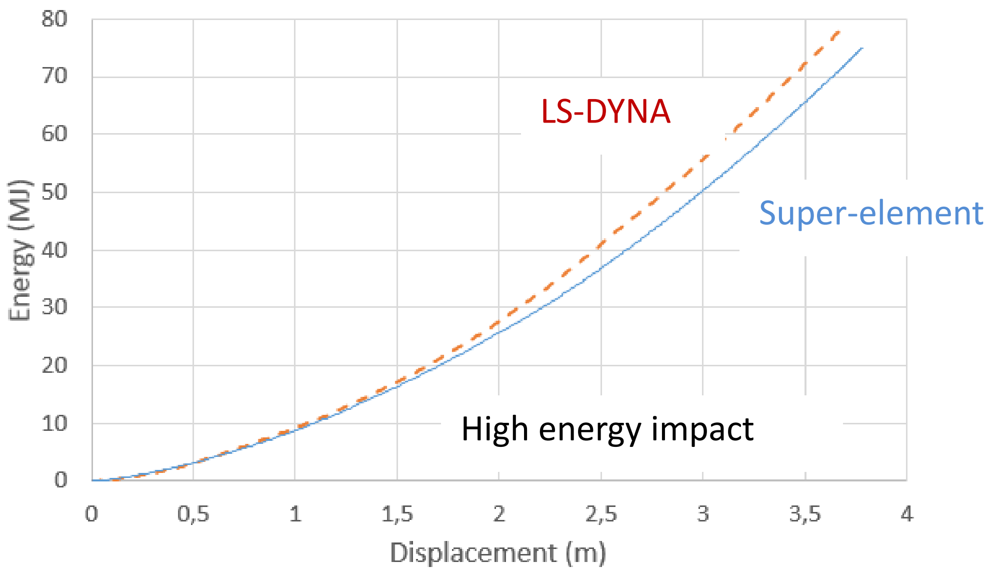
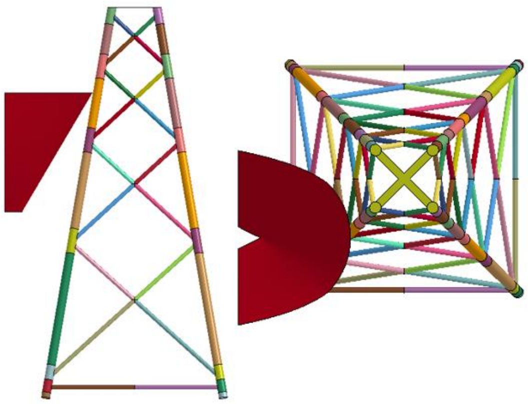
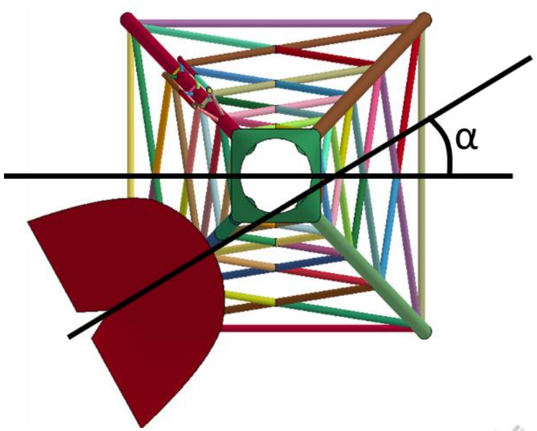
4. APPLICATIONS

Ship collision against offshore wind turbine

- **Recent developments on jackets**
  - Include super-element coupling
  - Include legs and brackets local buckling
  - Implement all deformation modes into the same solver







Reference
Crashworthiness of offshore wind turbine jackets based on the continuous element method - PhD thesis ULiège / ICAM (2018)

4. APPLICATIONS

Ship collision against offshore wind turbine

- **Monopile**
  - Detailed F.E.A
    - Different scenarios, different striking ships
    - Sensitivity analysis (Soil, wind direction, etc.)
  - Super-element under development

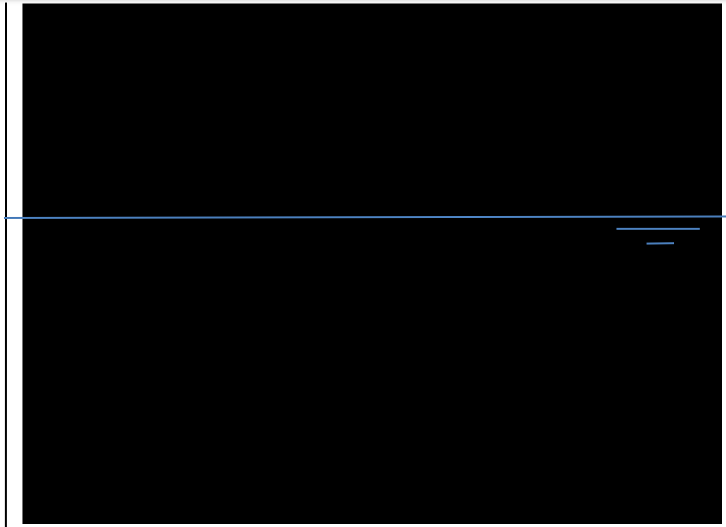
Reference
Andreea Bela, Hervé Le Sourne, Loïc Buldgen, Philippe Rigo – Ship Collision Analysis on Offshore Wind Turbine Monopile Foundation - Marine Structures 51 (2017) pp 220-241

4. APPLICATIONS

Ship collision against offshore wind turbine

- Monopile
  - Detailed F.E.A
    - Different scenarios, different striking ships
    - Sensitivity analysis (Soil, wind direction, etc.)
  - Super-element under development

- **Floating Platforms**
  - Detailed F.E.A
    - Different scenarios, different striking ships
    - External dynamics (MCOL)
    - Multiple impacts
  - Super-element under development



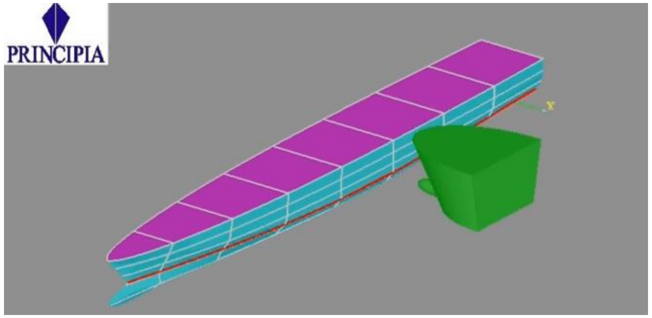
Reference
Sara Echeverry, Hervé Le Sourne, Lucas Marquez, Philippe Rigo – Numerical Crashworthiness Analysis of a Spar Floating Offshore Wind Turbine impacted by a Ship – 8th International Conference on Collision and Grounding of Ships, Lisbon 2019

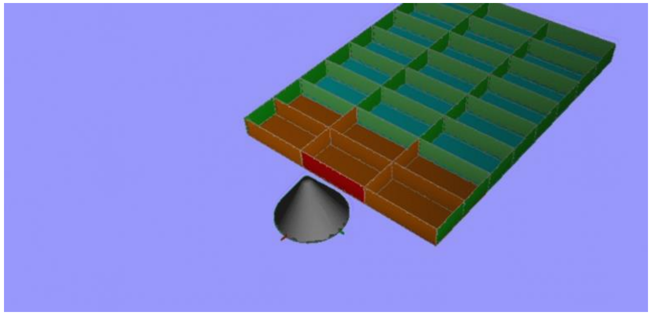
CONTENT

5. CONCLUSION

- **A Pre-design method**
  - Rapid and reliable
  - Suitable for complete risk analysis
  - Allows for structural optimization

- **But…**
  - This is a simplified method
  - … based on several hypotheses
  - … to be used in complementarity with F.E.A





Thank you for your attention

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