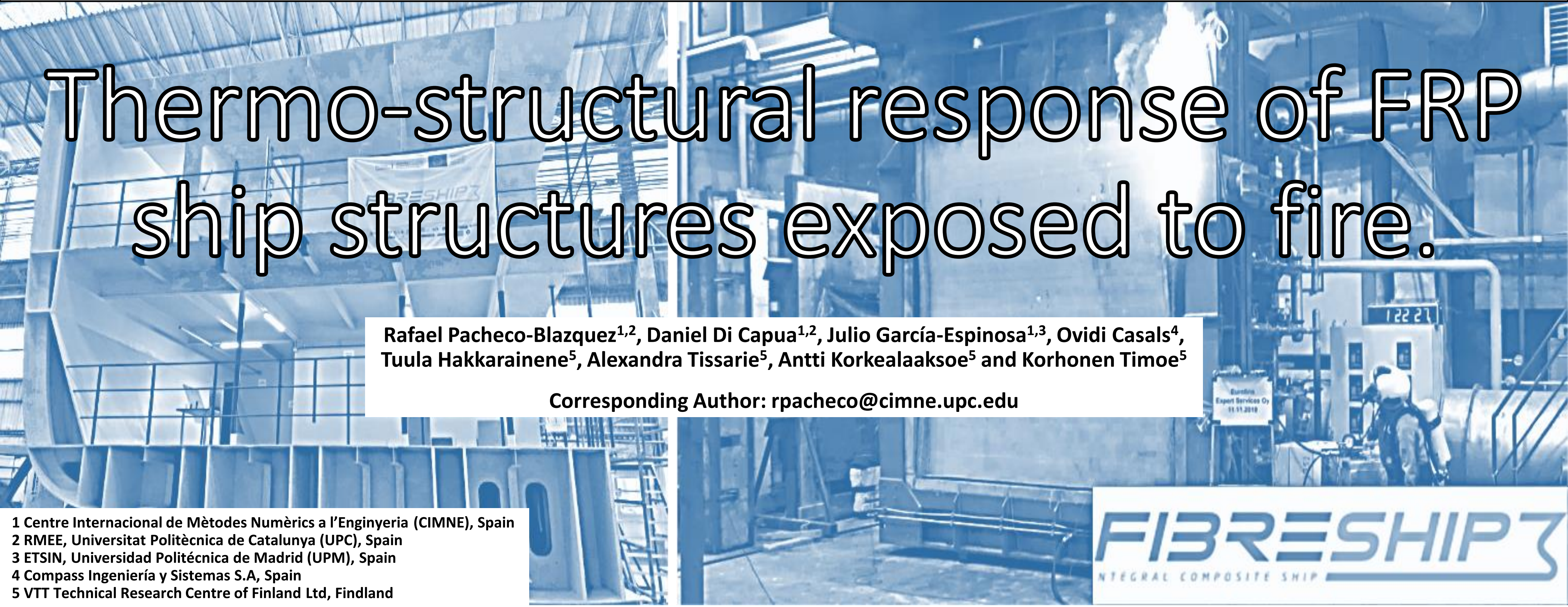

Thermo-structural response of FRP ship structures exposed to fire.

Rafael Pacheco-Blazquez[1,2], Daniel Di Capua[1,2], Julio García-Espinosa[1,3], Ovidi Casals[4], Tuula Hakkarainene[5], Alexandra Tissarie[5], Antti Korkealaaksoe[5] and Korhonen Timoe[5]

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4 Compass Ingeniería y Sistemas S.A, Spain
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INTRODUCTION

Fire specification, ship compartments configuration, wall thermal properties...

Fire dynamics analysis (FDS)

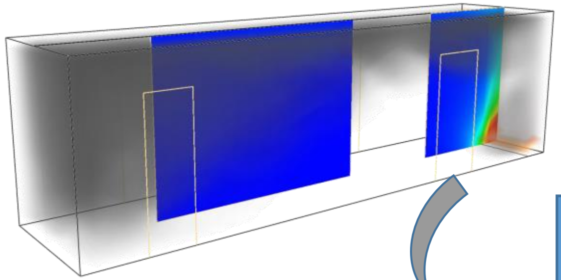
Temperature time evolution curves

Shells thermal analysis (RamSeries)

Through-thickness temperature distribution in beams and shells

Shells structural analysis (RamSeries)

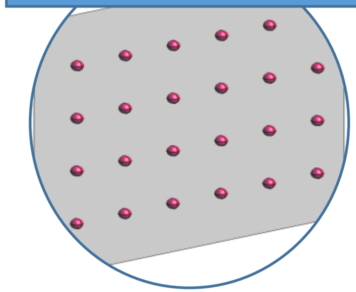
Collapse risk assessment



Fire dynamics analysis

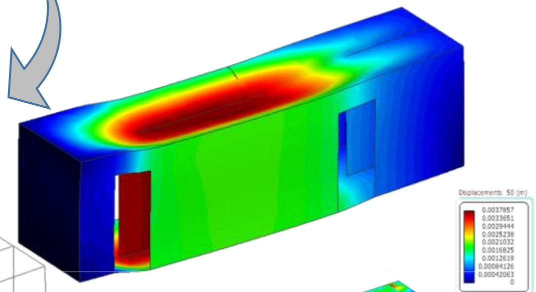
Temperature distribution due to is obtained at the surface of decks, bulkheads and other structural elements due to their exposure to fire.

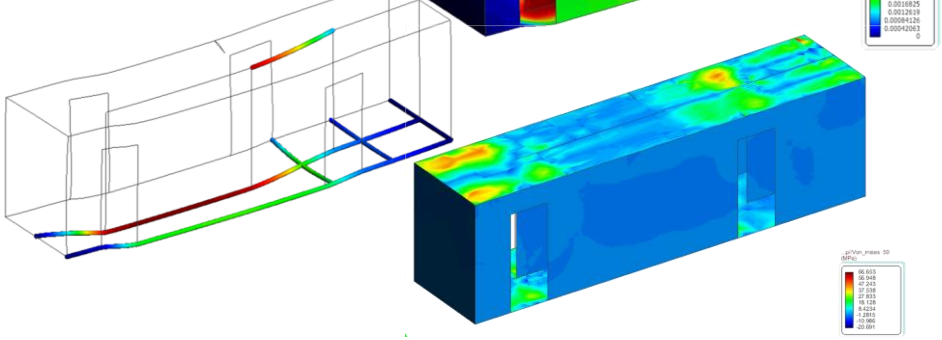
Transfer temperature information from control points to the structural model



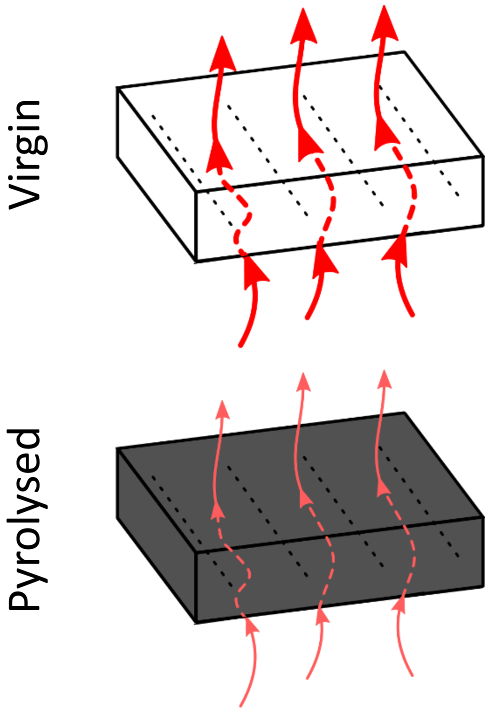
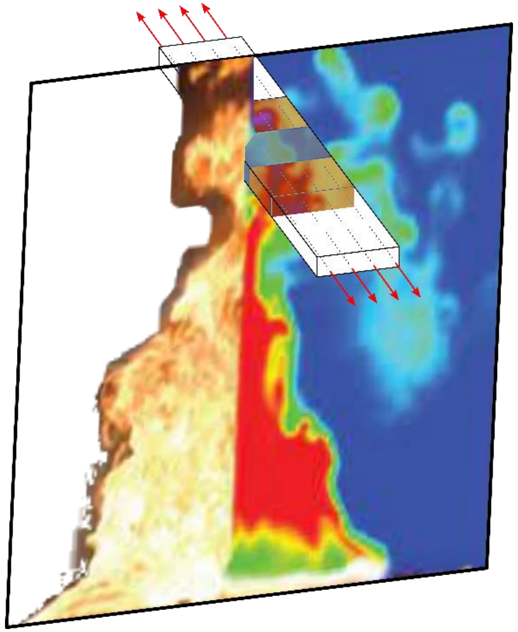
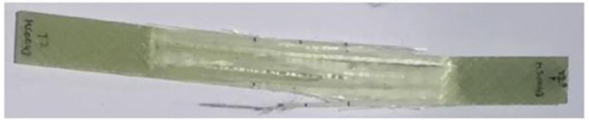
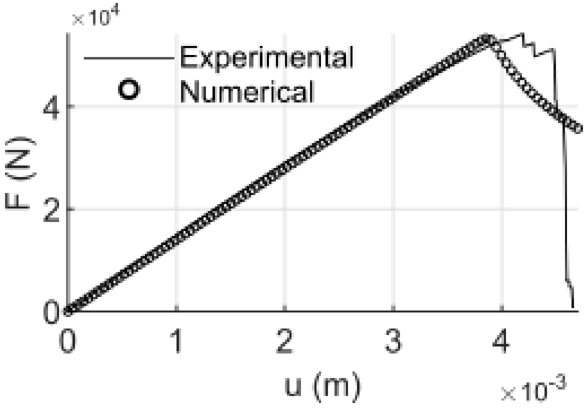
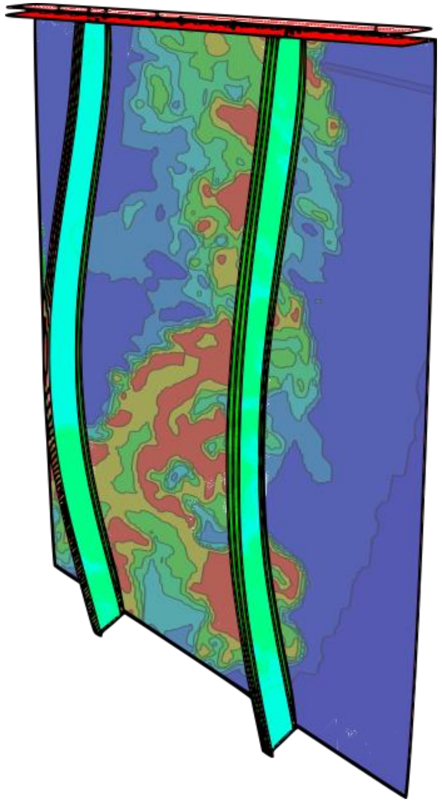
Thermomechanical analysis

Displacements, strains and stresses over structural components using a thermomechanical constitutive model including pyrolysis



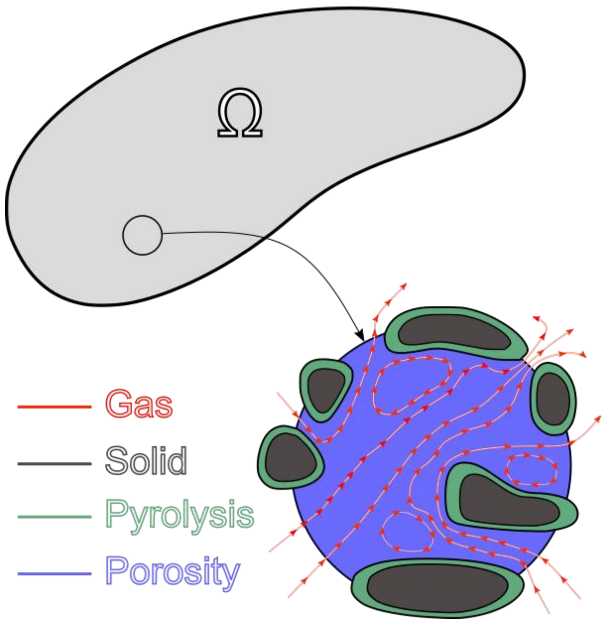


INTRODUCTION

Thermal Degradation	Thermo-mechanical degradation	Non-linear composite theory	Flexibility
			

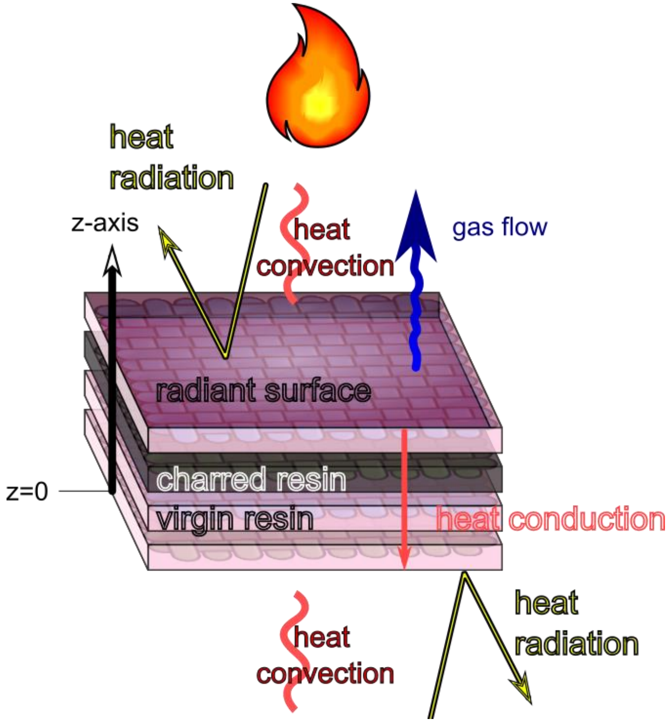
THERMAL MODEL

COMPOSITE CELL



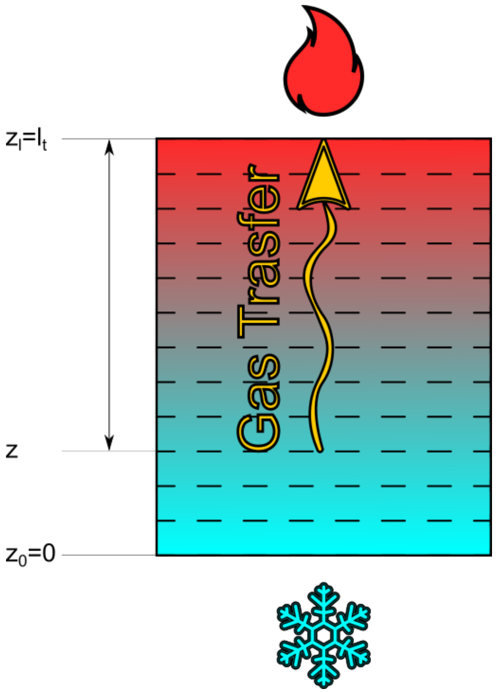
$$F = \frac{\rho_s - \rho_c}{\rho_v - \rho_c}$$

THERMAL PHYSICS



$$\underline{q} = \int_{\partial\Omega} \left[c_h (T_{\partial\Omega} - T_\infty) + c_\sigma c_\varepsilon (T_{\partial\Omega}^4 - {T_\infty}^4) \right] \, \mathrm{d}\Omega$$

GAS TRANSFER



$$\underline{q_{m}}_{g}(z,t) = \int_z^{l_t} \frac{\partial \rho}{\partial t} \, \mathrm{d}z$$

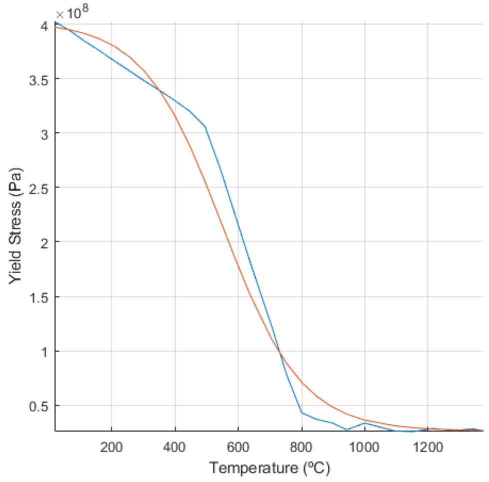
HENDERSON THERMAL MODEL [1]

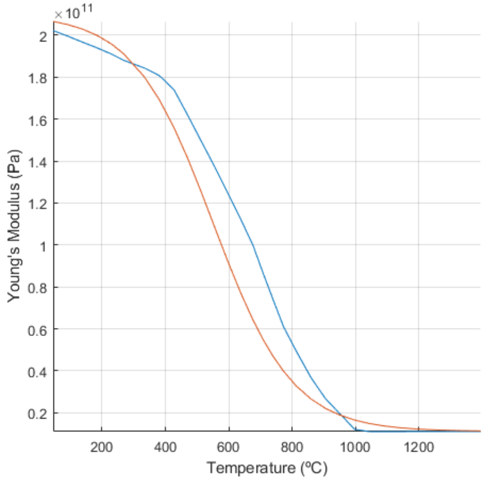
$$\int_\Omega \left[\rho c_p \frac{\partial T}{\partial t} \right] \mathrm{d}\Omega = \int_\Omega \left[\nabla \cdot (\Phi_{ms} c_{ks} \nabla T) - \underline{q_{m}}_{g} \nabla h_g \right] \mathrm{d}\Omega \; - \int_\Omega \left[\frac{\partial \rho}{\partial t} (h_p + h_s - h_g) \right] \mathrm{d}\Omega$$

THERMO-MECHANICAL MODEL

Mouritz-Gibson Degradation Function (Mouritz and Gibson(2006)[2])

$$P_i(T,F) = \left(\frac{P_{u,i} + P_{r,i}}{2} - \frac{P_{u,i} - P_{r,i}}{2} \tanh \chi_{1,i}(T - T_{g,i}) F^{\chi_{2,i}} \right), \quad \forall i \in f, m$$

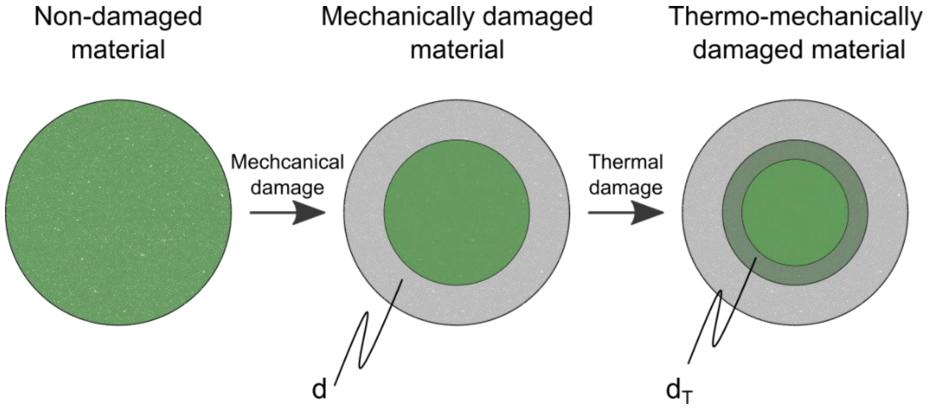




Thermal Isotropic Damage Model

(based on Simu&Ju,1987[3])

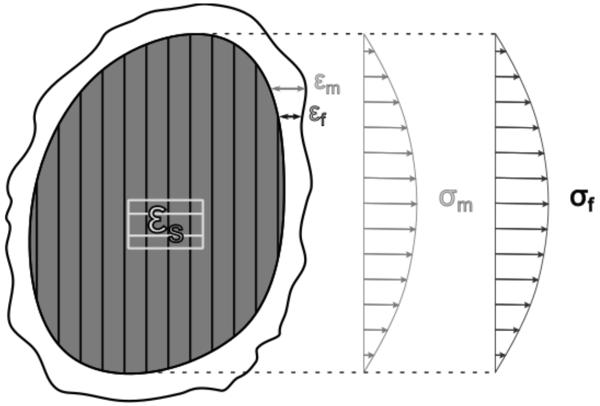
$$\begin{cases} \delta_i = \left(\varsigma + \dfrac{1-\varsigma}{\beta_i} \right) \sqrt{E_{0,i}} \sqrt{\dfrac{\bar{\boldsymbol{\sigma}}_{\mathbf{i}}}{\sigma_{y,i}} : (\mathbb{C}_{\mathbf{0,i}})^{-1} : \dfrac{\bar{\boldsymbol{\sigma}}_{\mathbf{i}}}{\sigma_{y,i}}} & \forall i \in f, m \\ A_i = \left(\dfrac{G_{f_i} E_i}{l_{c,i}\, \sigma_{y,i}^2} - \dfrac{1}{2} \right) \rightarrow \dfrac{G_{f_i} E_i}{\sigma_{y,i}^2} = \text{constant} & \forall i \in f, m \end{cases}$$

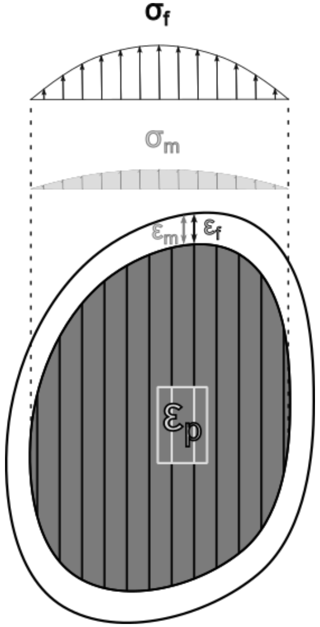


THERMO-MECHANICAL MODEL

Composite Model : Serial-Parallel Rule of Mixtures (Rastellini et al., 2008[4])

- Orthotropy derived by CLOSURE EQUATIOS.
- Separate internal variables.





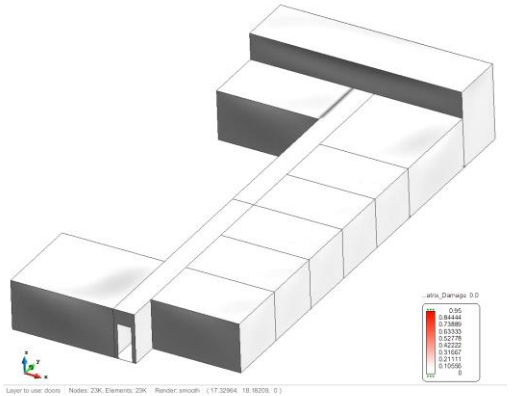
Serial direction $\begin{cases} \boldsymbol{\varepsilon}_s = k^f \boldsymbol{\varepsilon}_s^f + k^m \boldsymbol{\varepsilon}_s^m \\ \boldsymbol{\sigma}_s = \boldsymbol{\sigma}_s^f = \boldsymbol{\sigma}_s^m \end{cases}$

Parallel direction $\begin{cases} \boldsymbol{\varepsilon}_p = \boldsymbol{\varepsilon}_p^f = \boldsymbol{\varepsilon}_p^m \\ \boldsymbol{\sigma}_p = k^f \boldsymbol{\sigma}_p^f + k^m \boldsymbol{\sigma}_p^m \end{cases}$

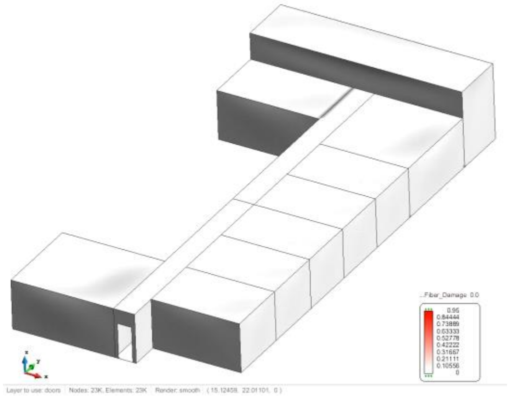
$$\boldsymbol{\sigma}_s^f - \boldsymbol{\sigma}_s^m(\boldsymbol{\varepsilon}_s^m) = 0$$

$$\left[\Delta\boldsymbol{\varepsilon}_s^m\right]_0 = \mathbf{A}:\left[\mathbf{C}_{ss}^f:\Delta\boldsymbol{\varepsilon}_s + k_f\left(\mathbf{C}_{sp}^f - \mathbf{C}_{sp}^m\right):\Delta\boldsymbol{\varepsilon}_p + k_f\Delta\boldsymbol{\sigma}_T^m - k_f\Delta\boldsymbol{\sigma}_T^f\right]$$

- Matrix Damage



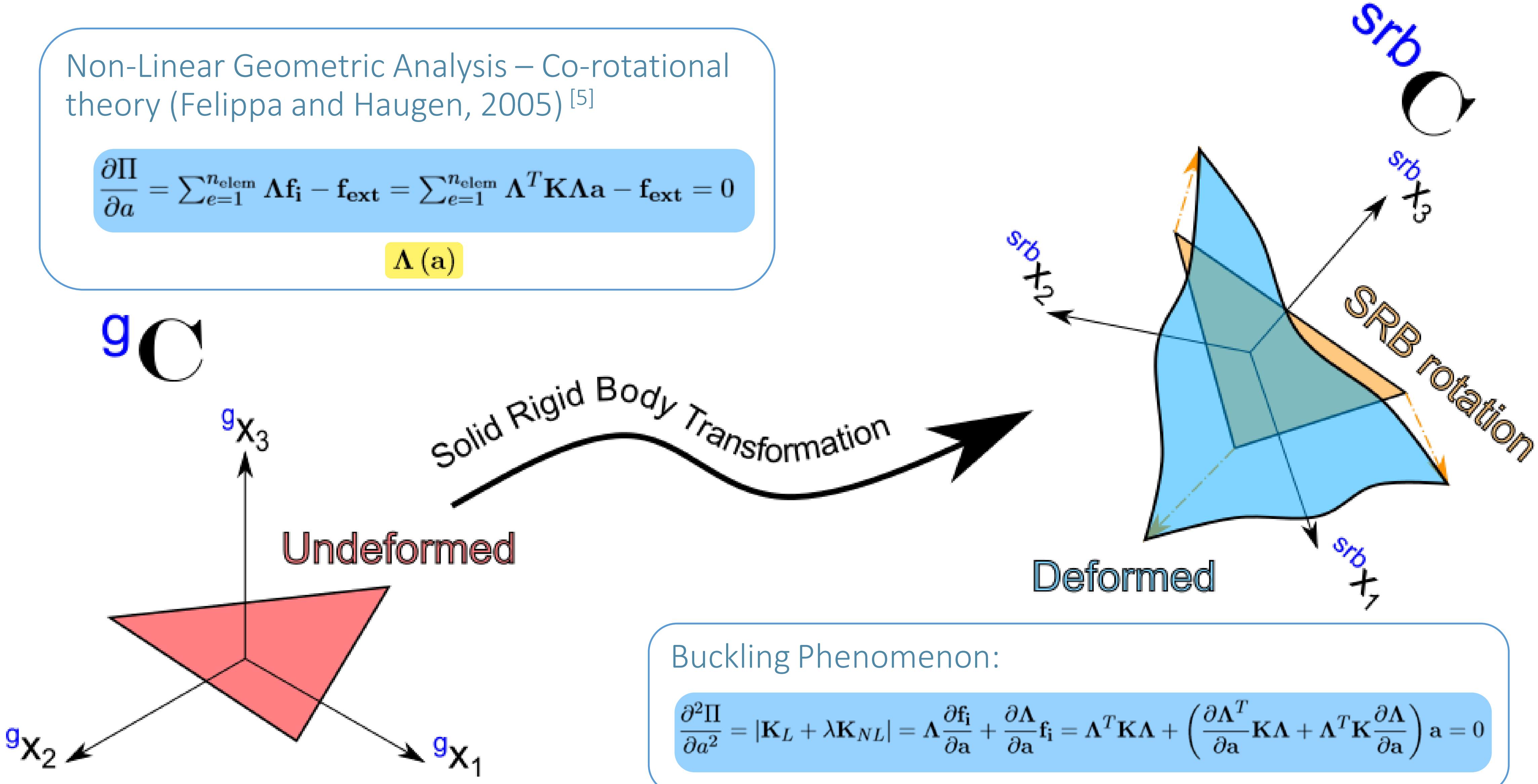
- Fibre Damage



Non-Linear Geometric Analysis – Co-rotational theory (Felippa and Haugen, 2005) [5]

$$\frac{\partial \Pi}{\partial a} = \sum_{e=1}^{n_{\mathrm{elem}}} \mathbf{\Lambda f_i} - \mathbf{f_{ext}} = \sum_{e=1}^{n_{\mathrm{elem}}} \mathbf{\Lambda}^T \mathbf{K \Lambda a} - \mathbf{f_{ext}} = 0$$

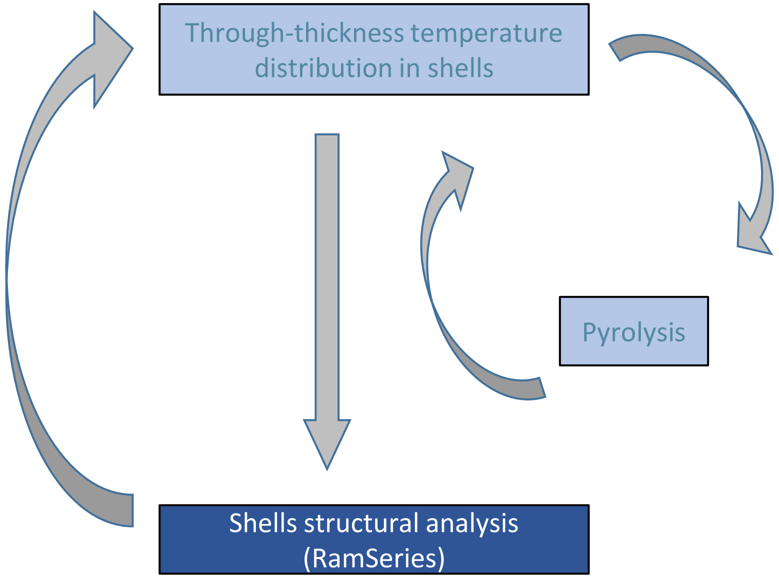
$\mathbf{\Lambda}\,(\mathbf{a})$



Buckling Phenomenon:

$$\frac{\partial^2 \Pi}{\partial a^2} = |\mathbf{K}_L + \lambda \mathbf{K}_{NL}| = \mathbf{\Lambda}\frac{\partial \mathbf{f_i}}{\partial \mathbf{a}} + \frac{\partial \mathbf{\Lambda}}{\partial \mathbf{a}}\mathbf{f_i} = \mathbf{\Lambda}^T\mathbf{K\Lambda} + \left(\frac{\partial \mathbf{\Lambda}^T}{\partial \mathbf{a}}\mathbf{K\Lambda} + \mathbf{\Lambda}^T\mathbf{K}\frac{\partial \mathbf{\Lambda}}{\partial \mathbf{a}}\right)\mathbf{a} = 0$$

THERMO-MECHANICAL MODEL



Algorithm 1: Non-linear thermomechanical coupling

$n = 0$ // Initialise;

while $n \leq n_{max}$ **do**

THERMAL PROBLEM;

$k = 0;$

$\mathbf{T}|_{n+1,k} = \mathbf{T}|_n;$

while $k \leq k_{max}$ **do**

$\mathbf{T}|_{n+1,k+1} = \mathbf{T}|_{n+1,k};$

$\mathbf{L_T}|_{n+1,k}\, \Delta\mathbf{T}|_{n+1,k+1} = -\, \mathbf{r_T}|_{n+1,k}$ // $\mathbf{L_T}|_{n+1,k} = \left.\dfrac{\partial \mathbf{r_T}}{\partial \mathbf{T}}\right|_{n+1,k};$

$\mathbf{T}|_{n+1,k+1} = \mathbf{T}|_{n+1,k} + \Delta\mathbf{T}|_{n+1,k+1}$ // Update $F|_{n+1,k+1};$

if $\dfrac{\left\| \mathbf{r_T}|_{n+1,k} \right\|}{\left\| \mathbf{q}_{ext}|_{n+1,k} \right\|} \leq tolerance;$

then

$\mathbf{T}|_{n+1} = \mathbf{T}|_{n+1,k+1};$

break;

else

$k = k + 1;$

THERMOMECHANICAL PROBLEM;

$k = 0;$

$\mathbf{a}|_{n+1,k} = \mathbf{a}|_n;$

while $k \leq k_{max}$ **do**

$\mathbf{a}|_{n+1,k+1} = \mathbf{a}|_{n+1,k};$

$\mathbf{K}|_{n+1,k}\, \Delta\mathbf{a}|_{n+1,k+1} = -\, \mathbf{r_a}(\mathbf{a}, \mathbf{T})|_{n+1,k}$ // $\mathbf{K}(\mathbf{a}, \mathbf{T})|_{n+1,k} = \left.\dfrac{\partial \mathbf{r_a}(\mathbf{a}, \mathbf{T})}{\partial \mathbf{a}}\right|_{n+1,k};$

$\mathbf{a}|_{n+1,k+1} = \mathbf{a}|_{n+1,k} + \Delta\mathbf{a}|_{n+1,k+1}$

if $\dfrac{\left\| \mathbf{r_a}(\mathbf{a}, \mathbf{T})|_{n+1,k} \right\|}{\left\| \mathbf{f}_{ext}|_{n+1,k} \right\|} \leq tolerance;$

then

$\mathbf{a}|_{n+1} = \mathbf{a}|_{n+1,k+1};$

break;

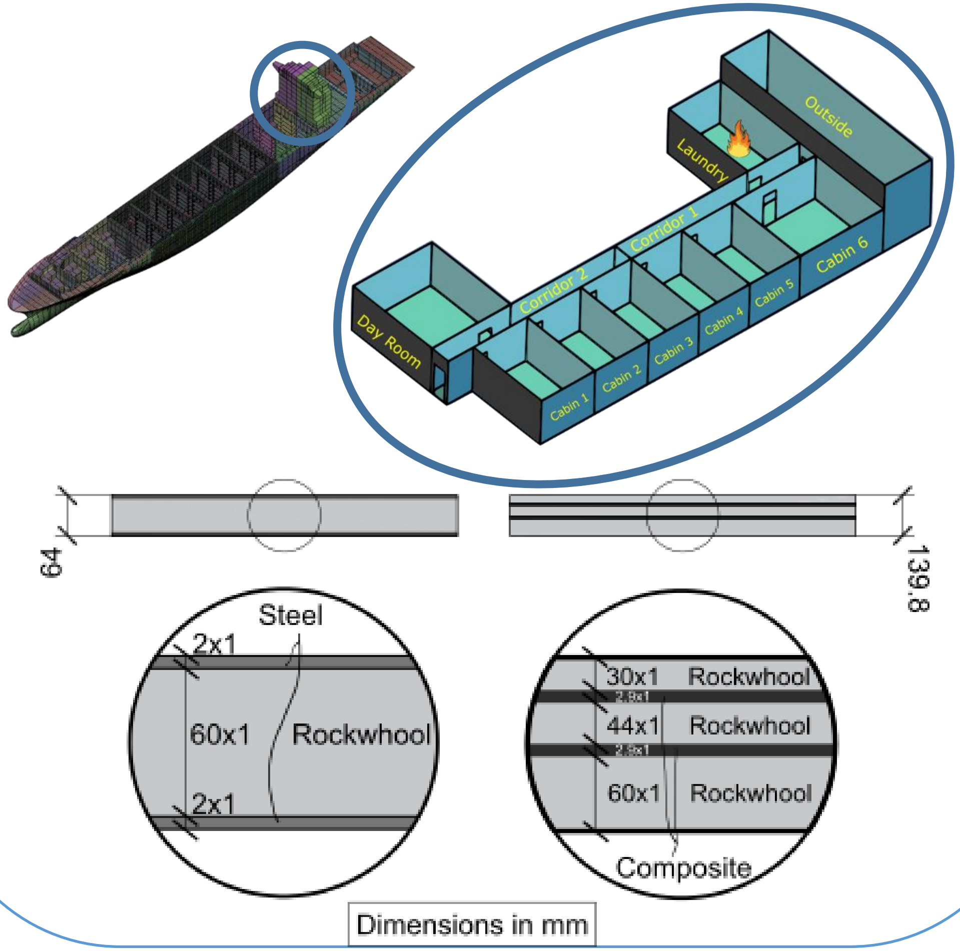
else

$k = k + 1;$

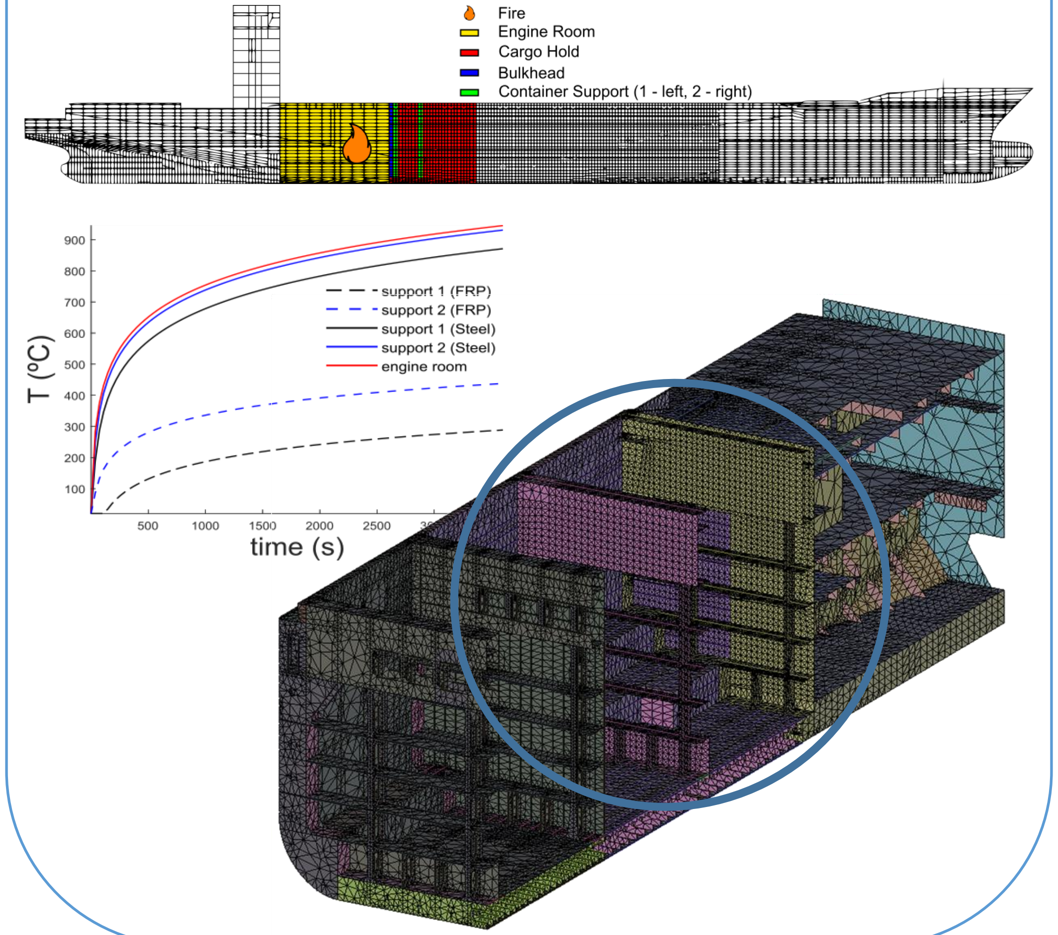
$n = n + 1;$

MARINE APPLICATION

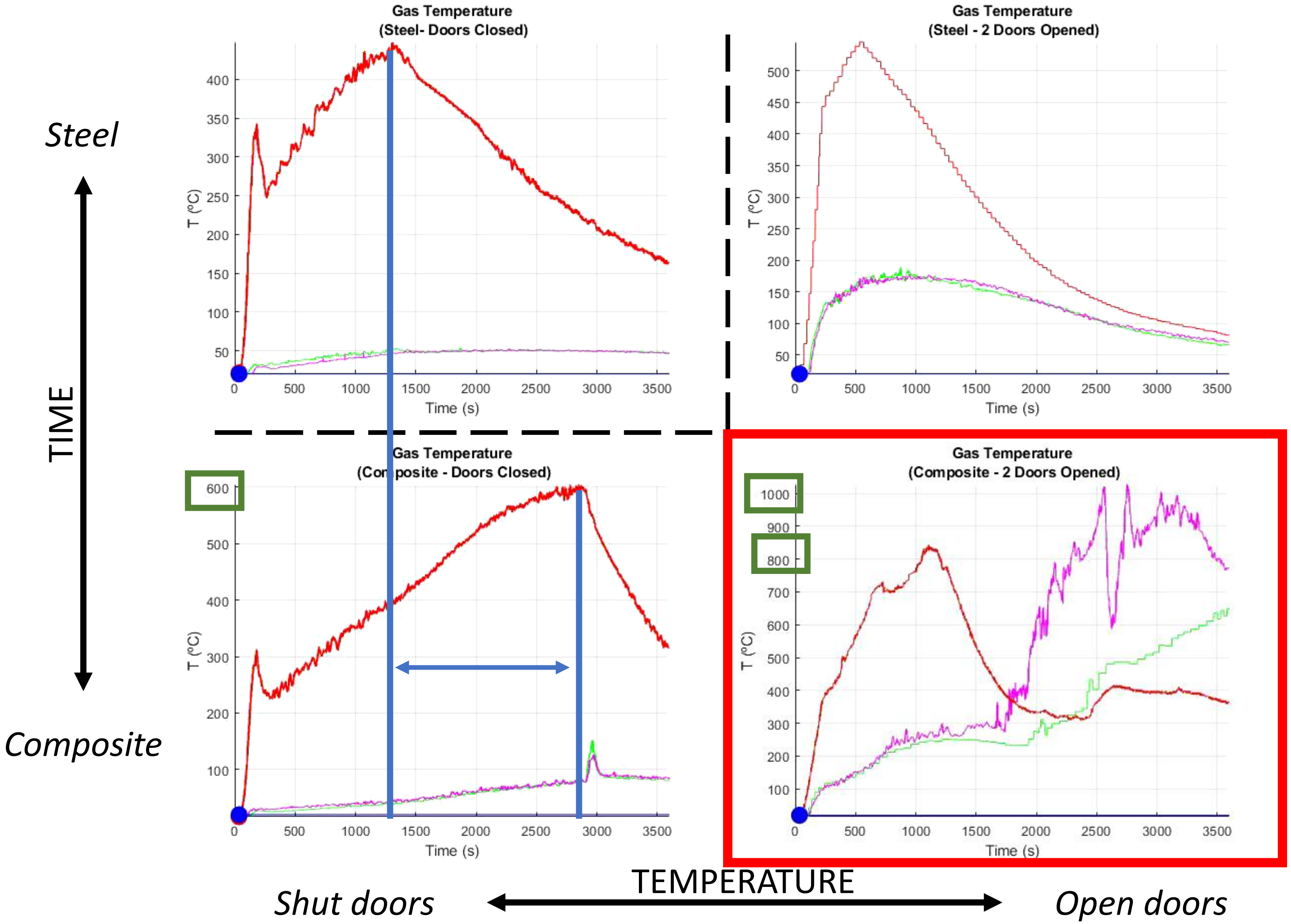
Fire Dynamic Simulator + Thermo-mechanical analysis of Superstructure

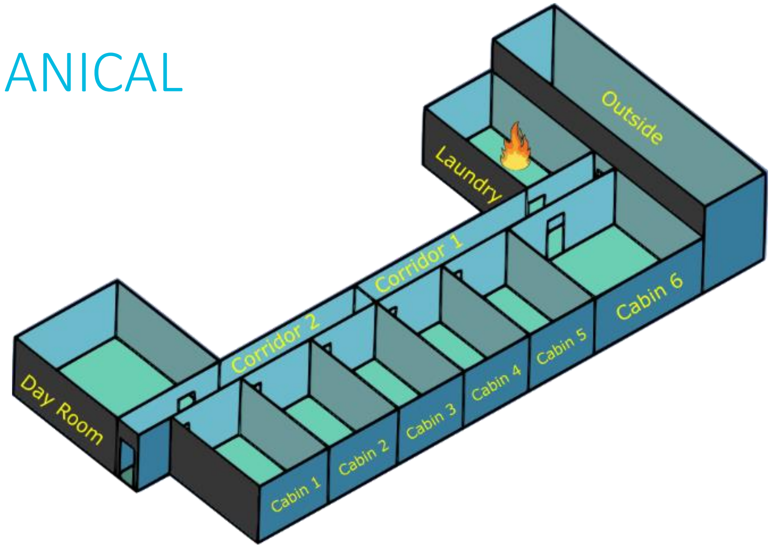


Thermo-mechanical analysis of a section

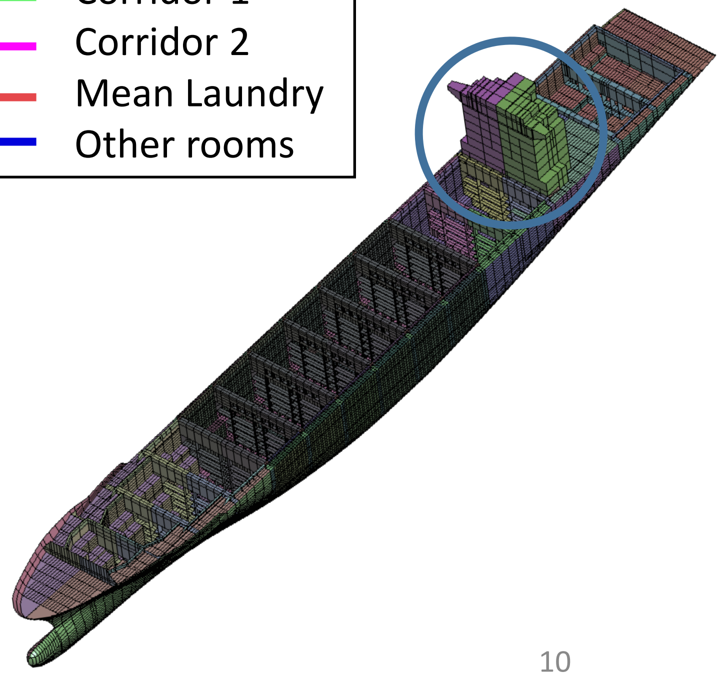


FIRE DYNAMICS SIMULATION COUPLING WITH THERMO-MECHANICAL



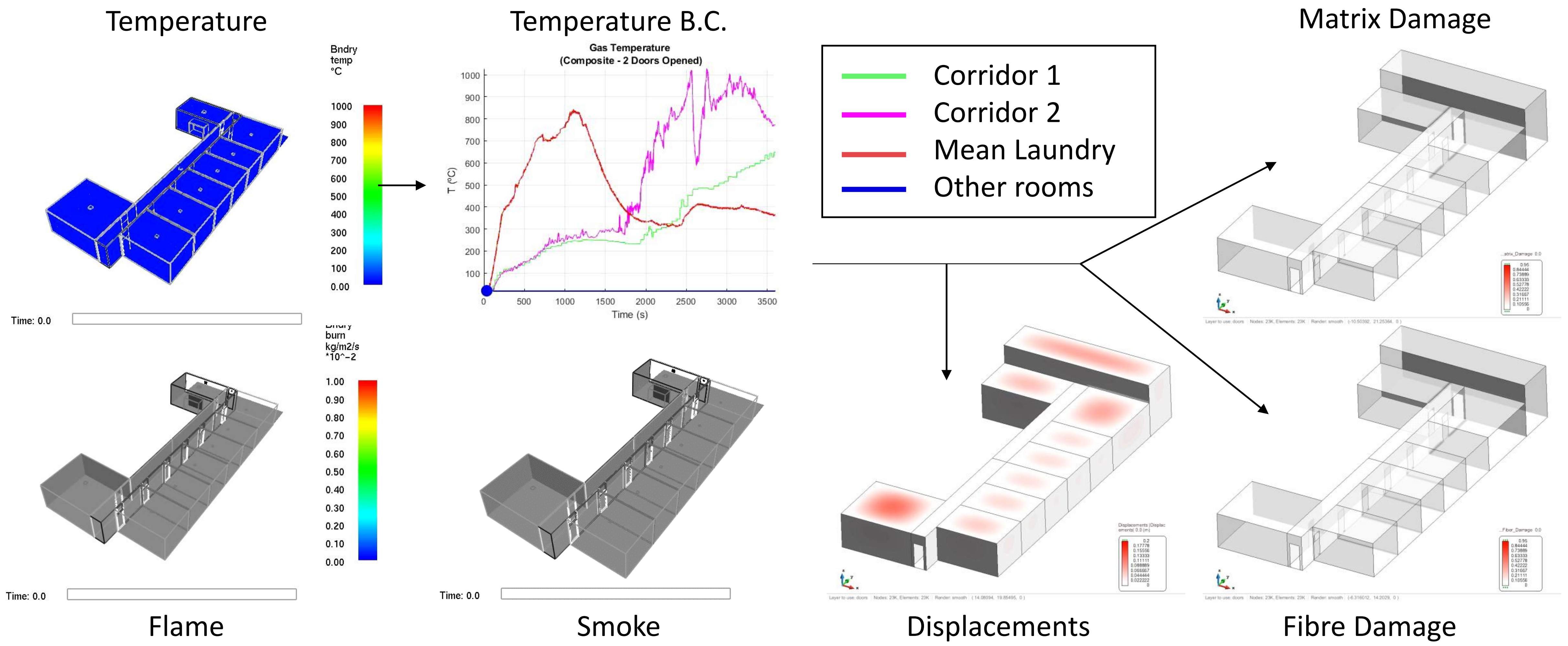


Corridor 1
Corridor 2
Mean Laundry
Other rooms

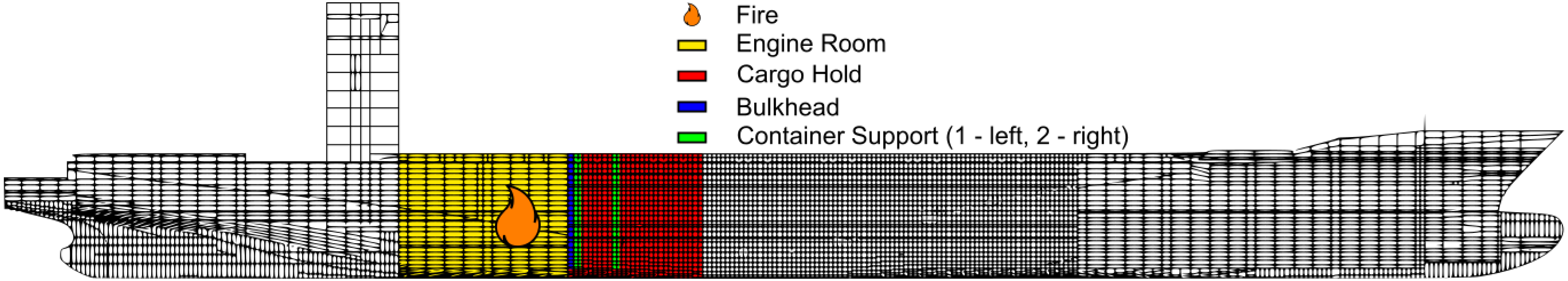


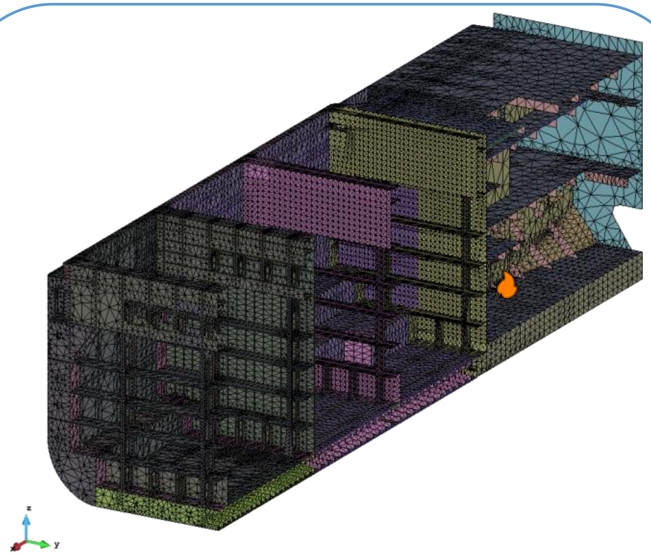
FIRE DYNAMICS SIMULATION COUPLING WITH THERMO-MECHANICAL

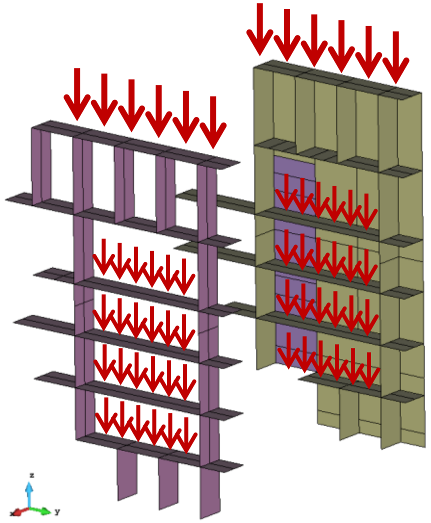
FRP and doors OPEN

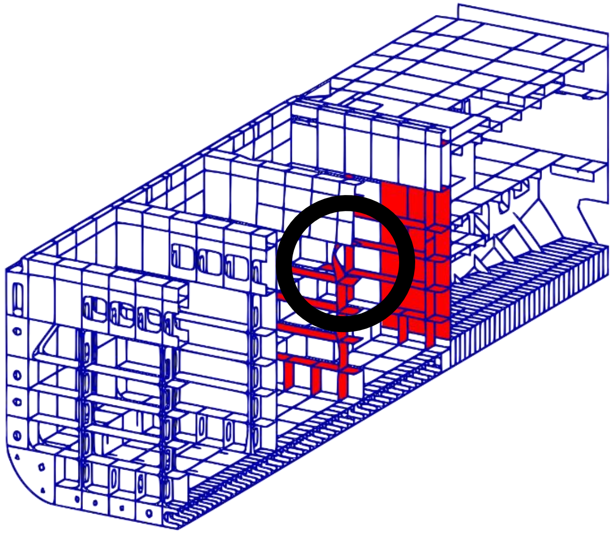


FIRE COLLAPSE OF A CONTAINER-SHIP



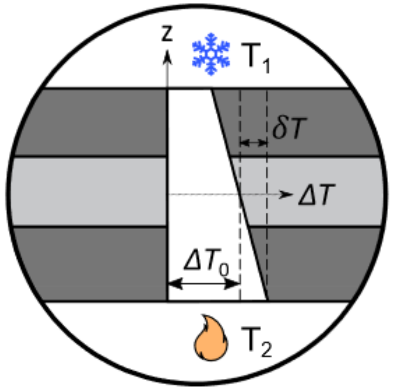




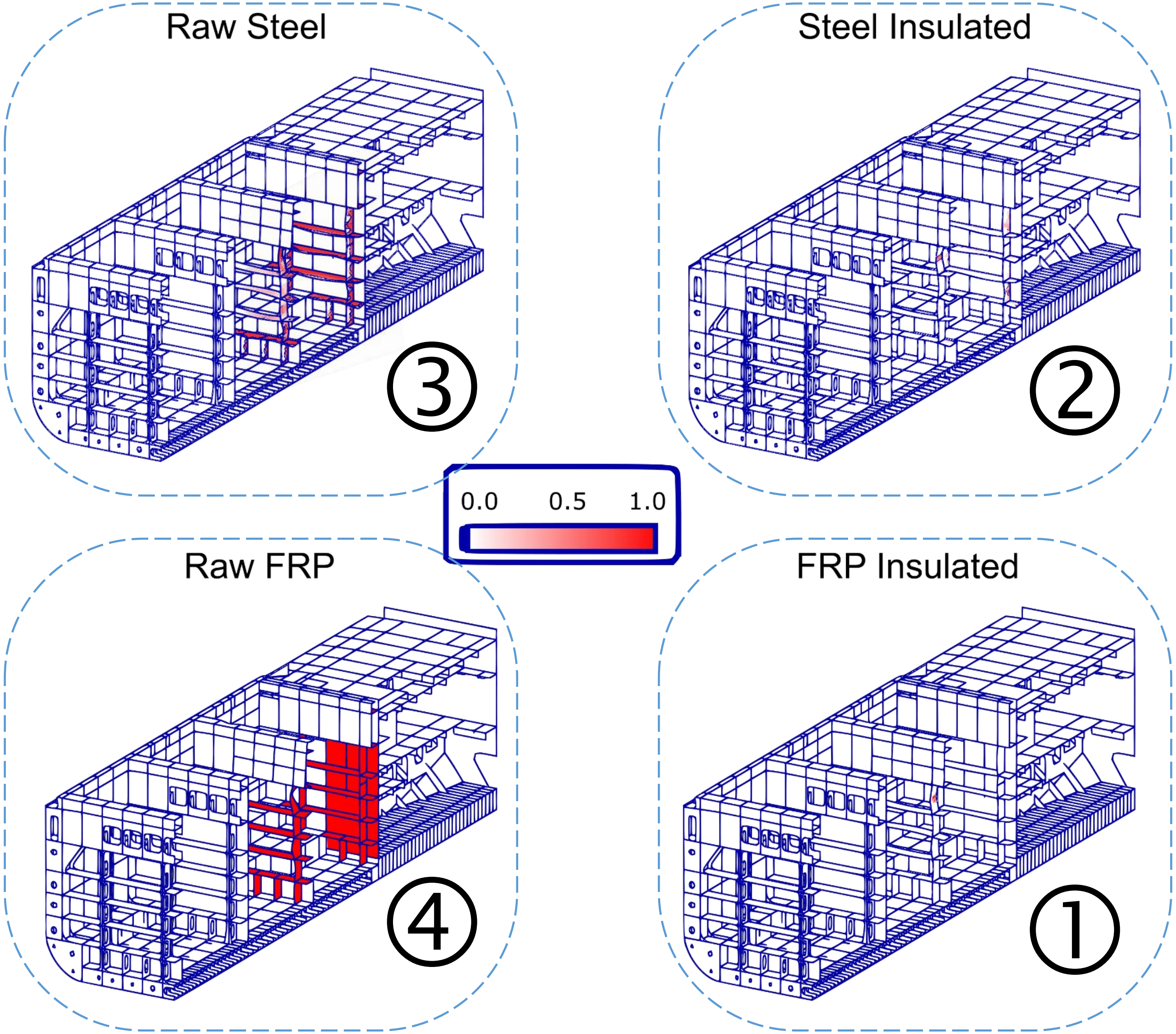


FIRE COLLAPSE OF A CONTAINER-SHIP

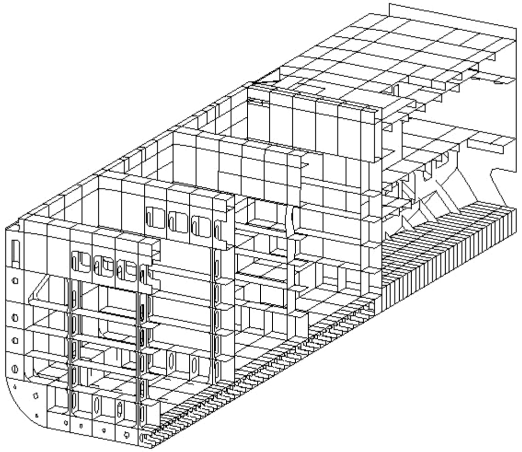
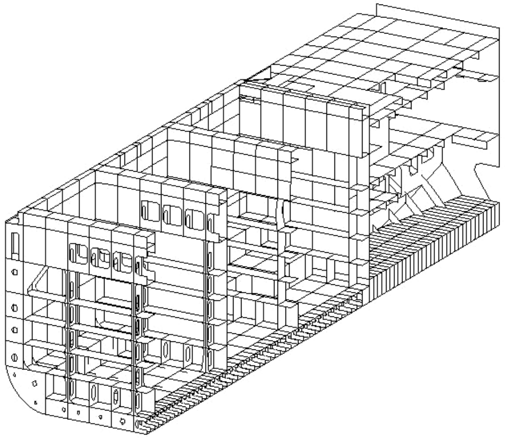
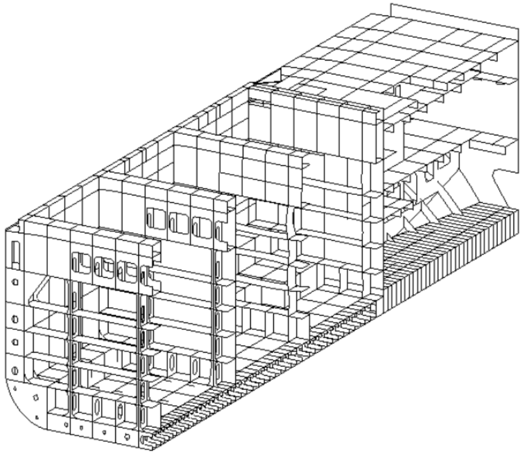
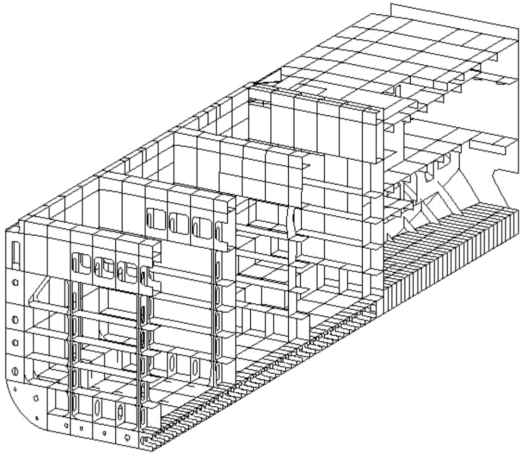
- Conductivity
- Flexibility
  - Inelastic-thermal-buckling
  - (buckling > fluency)

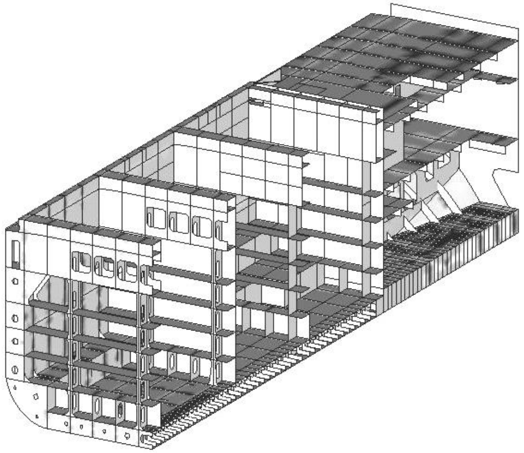
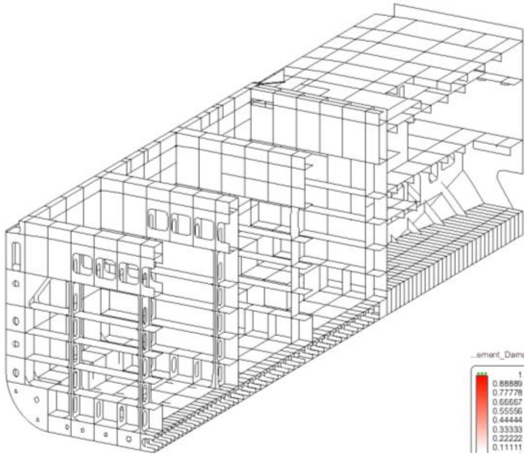


Steel Equivalent

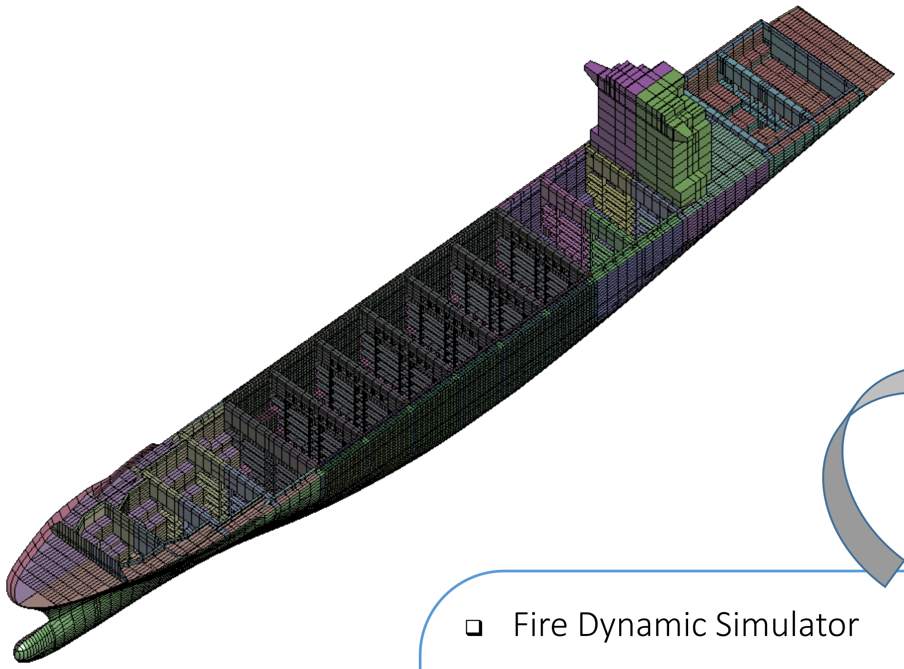


FIRE COLLAPSE OF A CONTAINER-SHIP

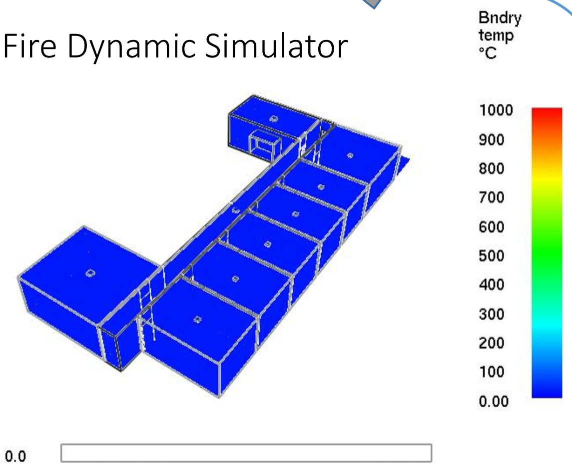
FRP Raw		FRP Insulated	
Matrix Raw	Fibre Raw	Matrix Insulated	Fibre Insulated
			

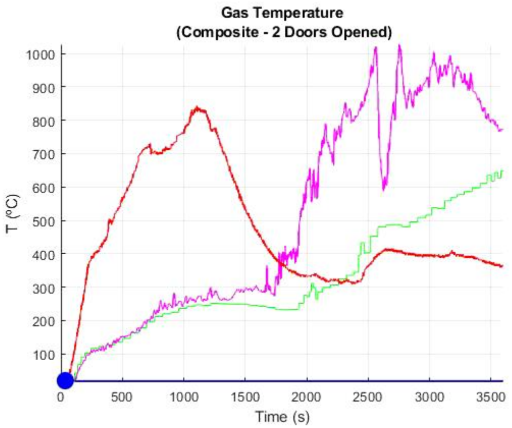
Steel Raw	Steel Insulated
	

CONCLUSIONS

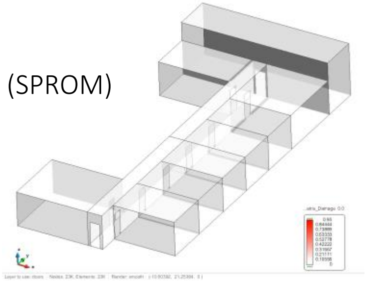


- Fire Dynamic Simulator

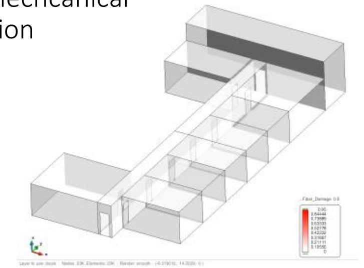




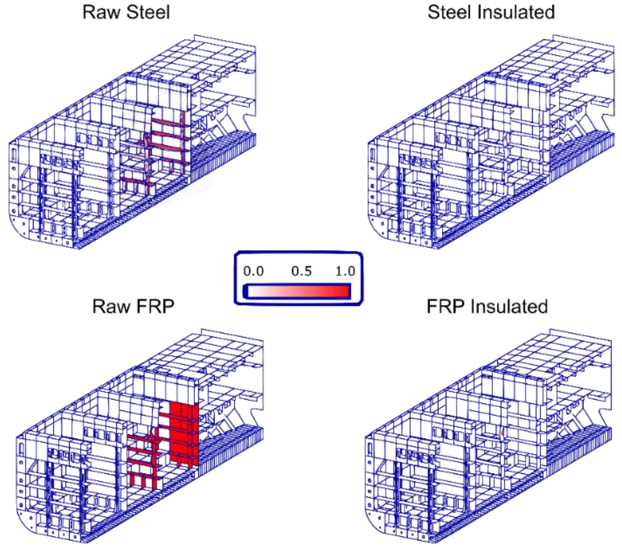
- Unique Tool
  - Composite (SPROM)
  - Pyrolysis



  - Themo-mechcanical degradation



  - **Large deformation (post-/buckling)**



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