Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Computatinal Structural Mechanics using High Performance Computing

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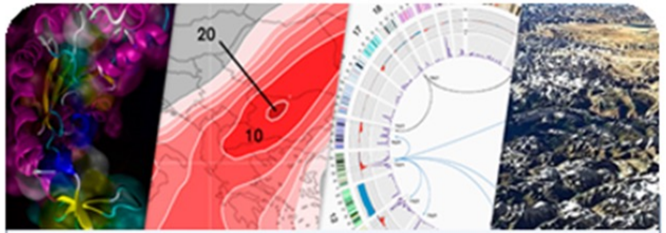
27.01.2023

Amade Day Winter 2023

Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS)

BSC-CNS OBJECTIVES

Supercomputing services to Spanish and EU researchers



R&D in Computer, Life, Earth and Engineering Sciences

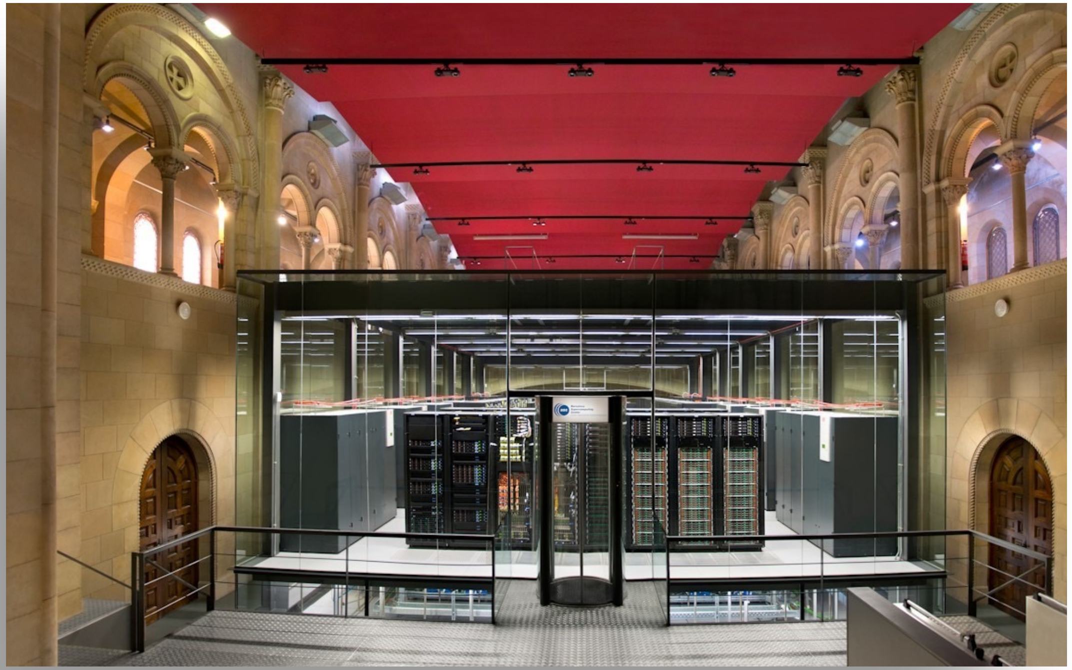
PhD programme, technology transfer, public engagement

BSC-CNS is a consortium that includes

Spanish Government	60%	
Catalan Government	30%	Generalitat de Catalunya Departament d'Empresa i Coneixement
Univ. Politècnica de Catalunya (UPC)	10%	UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS)

- Spanish National Supercomputing Center
- Located at the Technical University of Catalonia **- BarcelonaTech**
- Around **800 people** from several disciplines
- Four main departments**: Engineering (CASE),** Computer Science, Life Science and Earth Science
- BSC holds **MareNostrum IV** (13.4 PetaFLOPS)



MareNostrum 5: Pre-exascale supercomputing

- >310 PetaFLOPS peak performance (> 310 x 10^{15})
- > 2PetaBytes of storage
- 400PetaBytes of active archive
- Aggregated Investment of €223 million
- + Experimental Platform to create supercomputing technology "made in Europe"

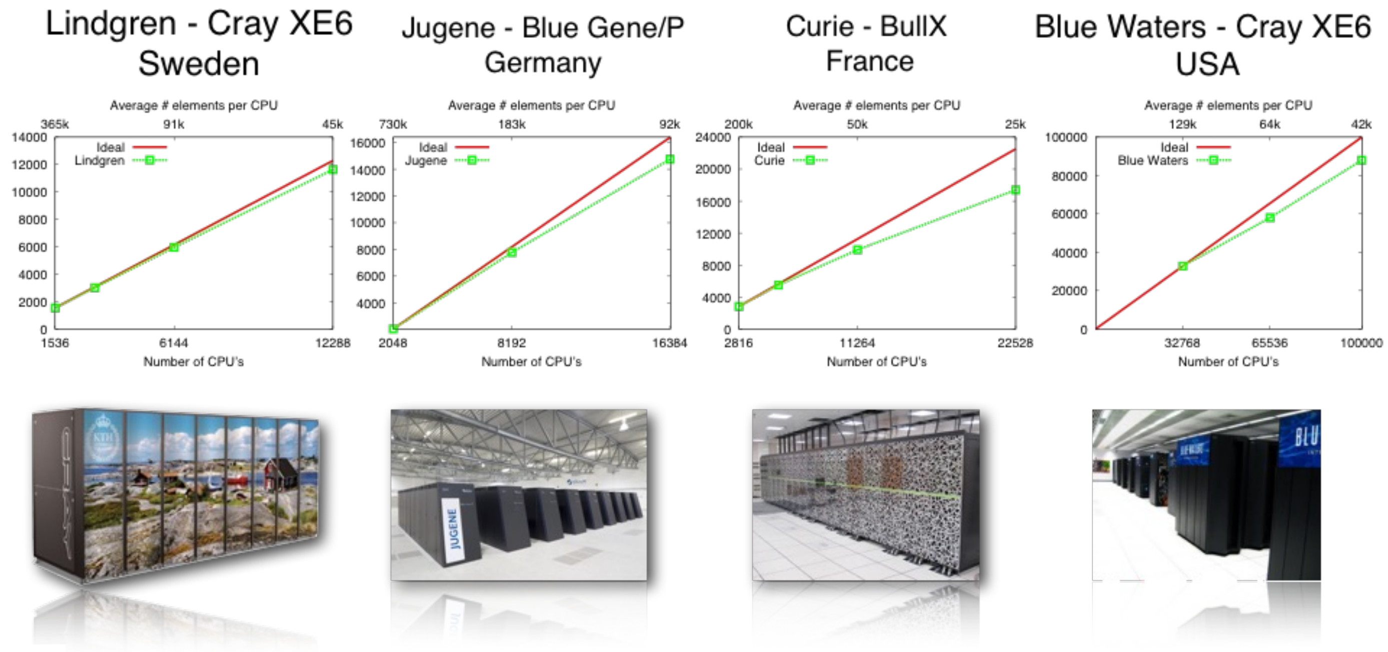
Hosting Consortium:

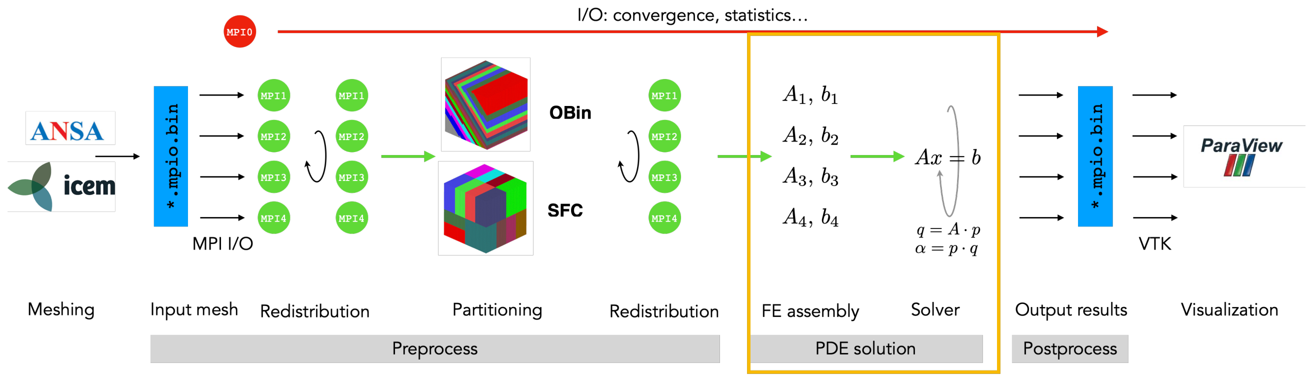
Spain | Portugal | Turkey | Croatia

The acquisition and operation of the EuroHPC supercomputer is funded jointly by the EuroHPC Joint Undertaking, through the European Union's Connecting Europe Facility and the Horizon 2020 research and innovation programme, as well as the Participating States Spain, Portugal, and Turkey

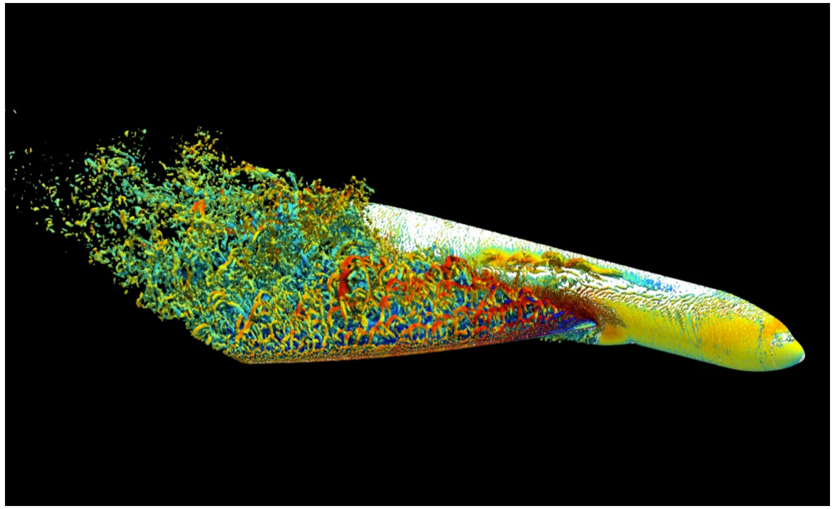
Introduction of Alya Multiphysics code

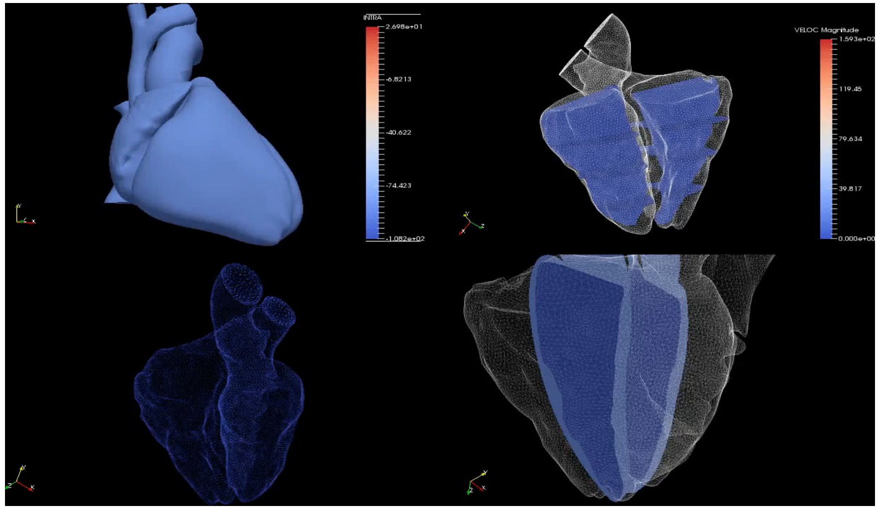
- **FEM-based Computational Mechanics code** (https://alya.gitlab.bsc.es)
- **Language:** Fortran 2008
- **Parallization strategies:**
  - MPI (130K CPU-cores) + OpenMP
  - Accelerators: OpenACC-CUDA
  - Co-execution on heterogeneous systems
- **Fully parallel workflow:**
  - Dynamic load balance (DLB)
  - Adaptative mesh refinement (AMR)
  - Parallel multiphysics/multi-code coupling
- **Alya is regularly run on PRACE Tier 0 systems** and part of the European Applications Benchmark Suite (**EUABSC**)

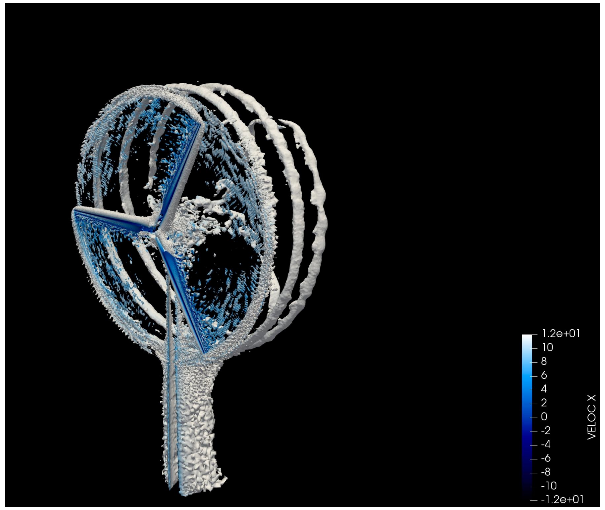




Alya Towards Multiphysics





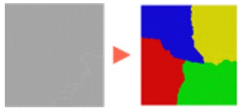


Accelerating the performance

Speed-up & Complexity Implementation

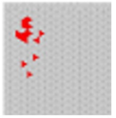
Algorithm Optimisation

Node - Cluster



Chip

Superscalar core Accelerators



Coarse-grained activities

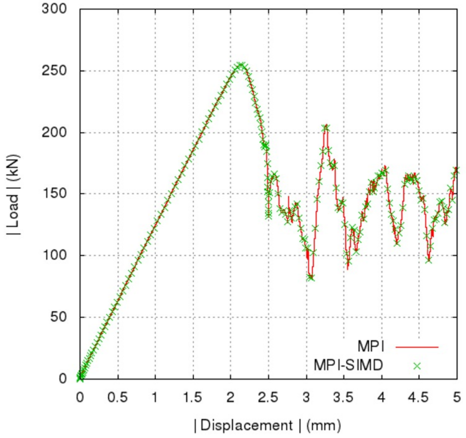
- Taskification / coloring
- Synchronous to asynchronous communication
- Mesh partitioning, advanced solvers
- Quantifying uncertainty on simulation
- Algorithm recovery from core/thread failures

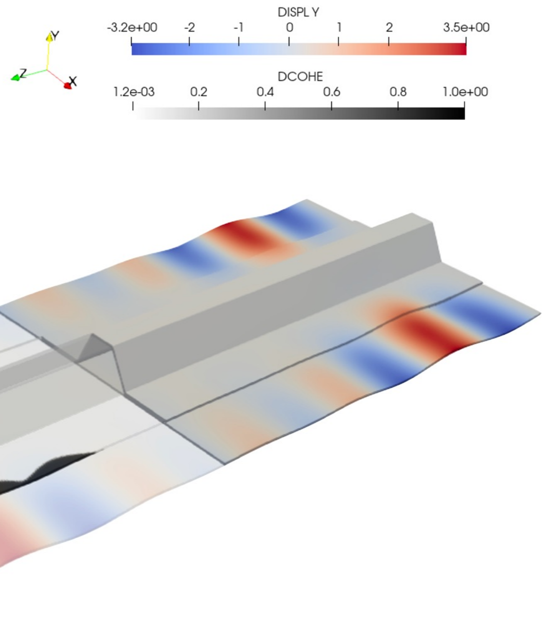
Fine-grained activities

- Task-based Dynamic Load Balancing (DLB)
- Single Instruction Multiple Data (SIMD)
- Use of accelerator directives (GPU)

Example

Compression After Impact (CAI) of a MONOSTRINGER structure





Case	Elem. Asse.(us)	Speed Up	Total Sim. (s)	Speed Up
MPI	12.95	1	22282.36	1
MPI + SIMD	2.96	**4.4**	6824.59	**3.3**

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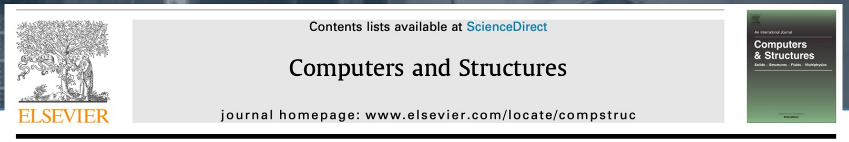
Advances in solid mechanics and application examples

A parallel contact algorithm for HPC systems


Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

A parallel algorithm for unilateral contact problems

G. Guillamet [a,*], M. Rivero [a], M. Zavala-Aké [a], M. Vázquez [a], G. Houzeaux [a], S. Oller [b,c]

[a] Barcelona Supercomputing Center (BSC), Plaça Eusebi Güell, 1-3, 08034 Barcelona, Spain

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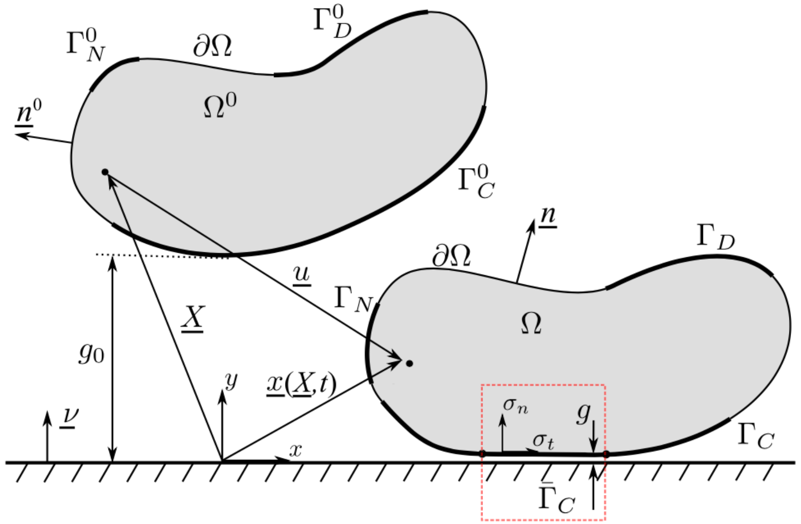
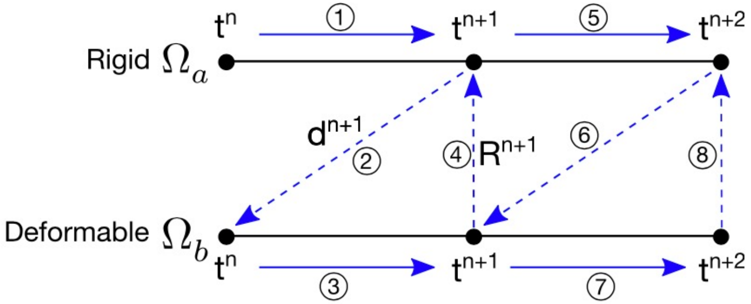
Non-linear contact problem

(Hertz-Signorini-Moreau law)

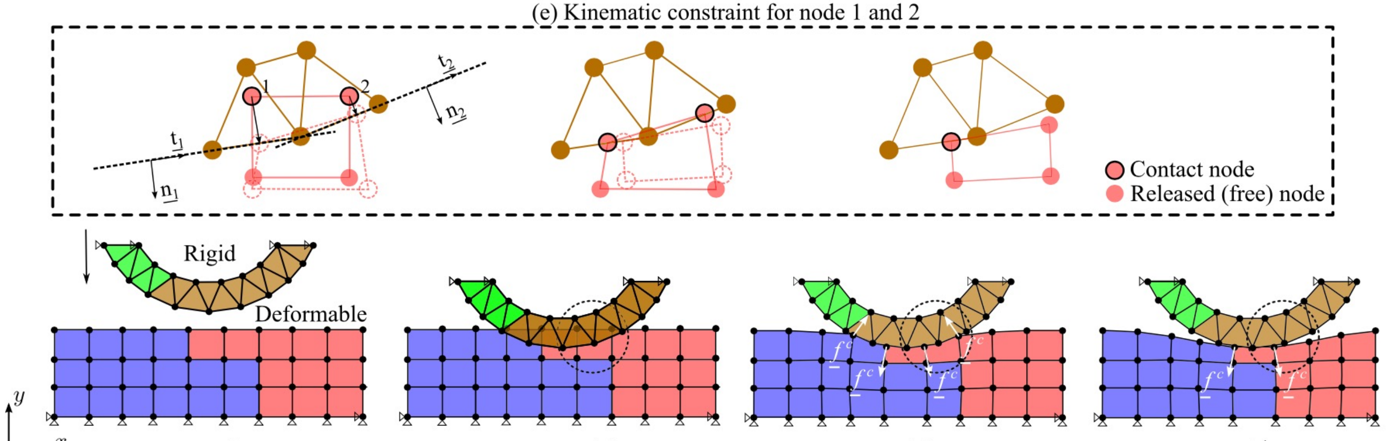
$$\nabla \cdot \underline{\boldsymbol{\sigma}} + \underline{\boldsymbol{f}}_v = 0 \quad \text{in}\, \Omega$$
$$\underline{\boldsymbol{\sigma}} \cdot \underline{\boldsymbol{n}} = \underline{\boldsymbol{\sigma}}_0 \quad \text{on}\, \Gamma_N$$
$$\underline{\boldsymbol{u}} = \underline{\boldsymbol{u}}_0 \quad \text{on}\, \Gamma_D$$
$$g \geqslant 0,\ \sigma_n \leqslant 0,\ \sigma_n g = 0,\ \underline{\boldsymbol{\sigma}}_t = 0 \quad \text{on}\, \Gamma_C$$



Method of Partial Dirichlet-Boundary conditions

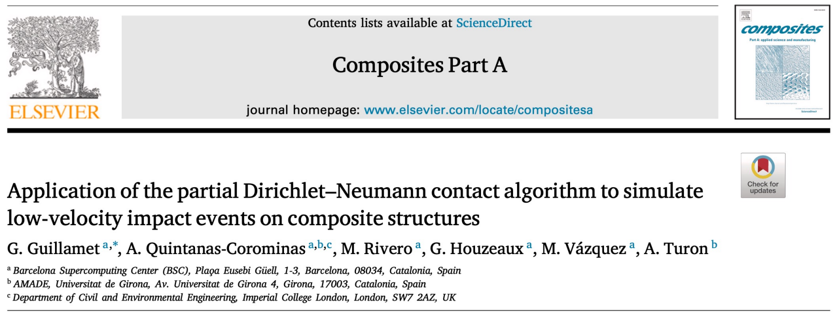


Gauss-Seidel algorithm



(a) t^n (b) t^{n+1} (c) $t^{n+1};\ i=1$ (d) $t^{n+1};\ i=2$

A parallel contact algorithm


Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Application of the partial Dirichlet–Neumann contact algorithm to simulate low-velocity impact events on composite structures

G. Guillamet [a,*], A. Quintanas-Corominas [a,b,c], M. Rivero [a], G. Houzeaux [a], M. Vázquez [a], A. Turon [b]

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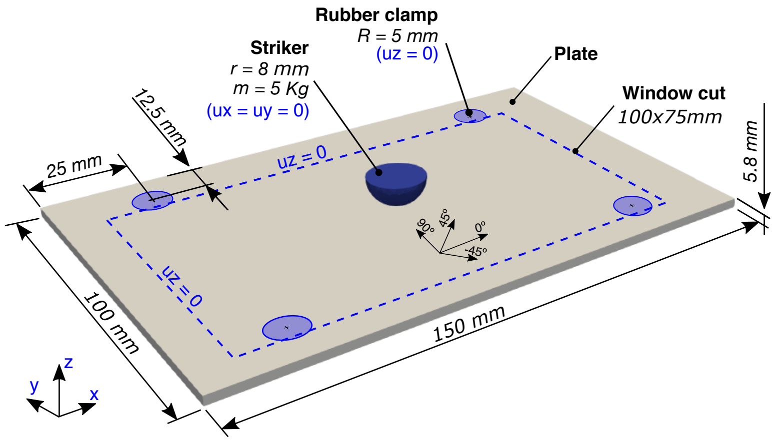
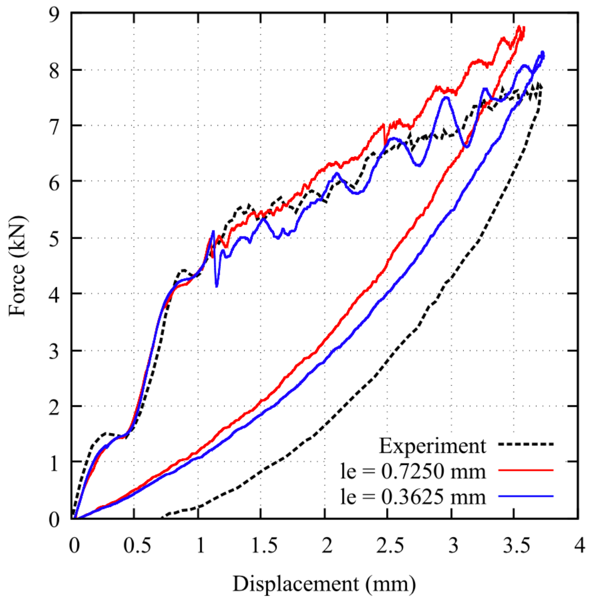
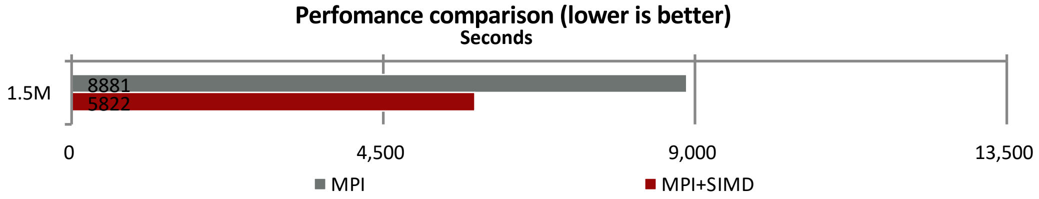
[b] AMADE, Universitat de Girona, Av. Universitat de Girona 4, Girona, 17003, Catalonia, Spain
[c] Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK

Benchmark test

ASTM D7136/D7136M-20 standard



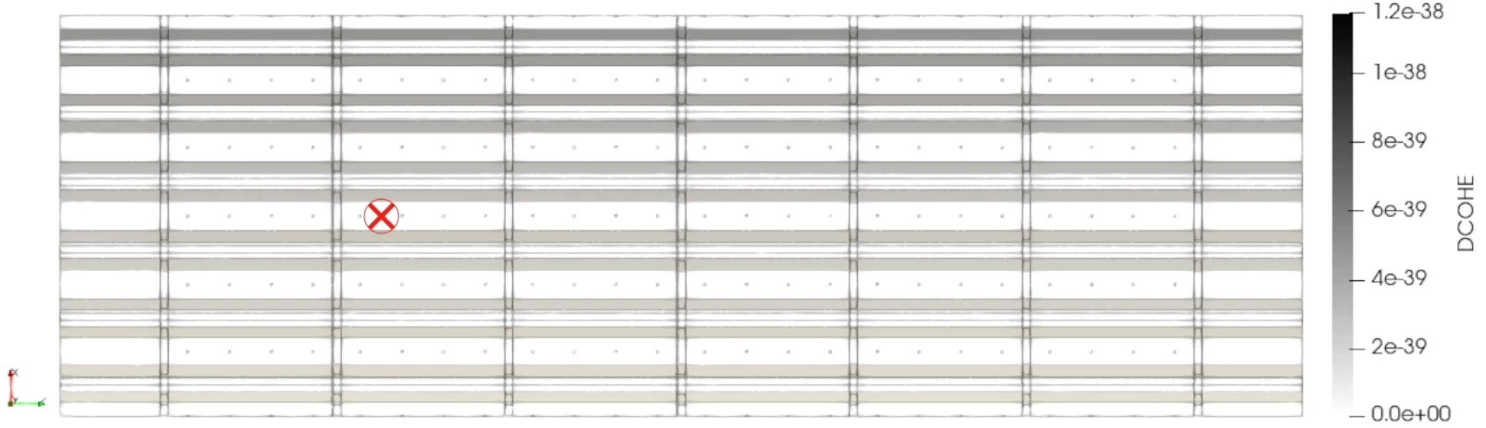


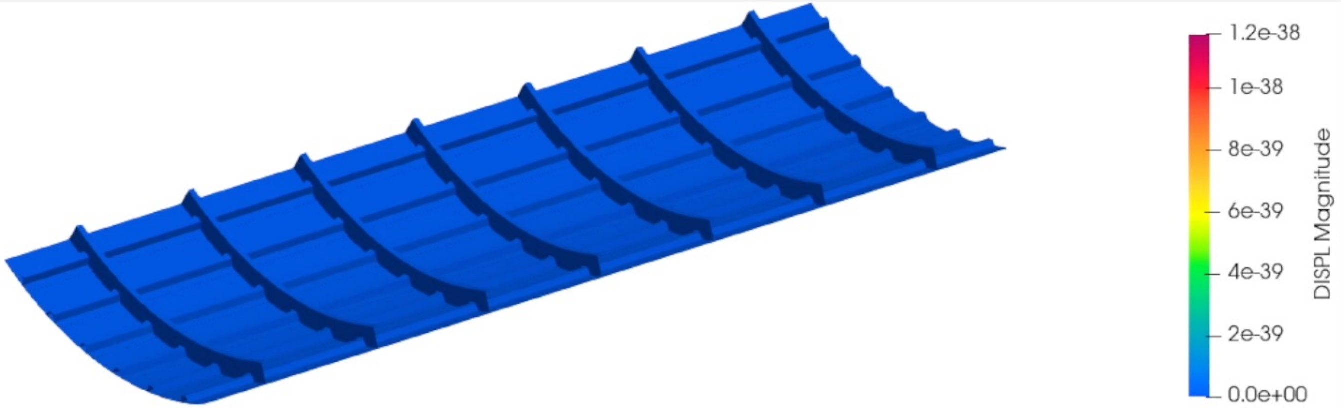


Multi-impact on a 5m curved panel from a passengers aircraft

Work in collaboration with Imperial College of London (ICL)

● Sensor ⊗ Impact from inside (skin/stringer's foot 23~31J) ⊙ Impact from fuselage-skin side 20~25J





- 17 consecutive impacts
- Inter- and Intra-laminar damage models
- No. of cells: 6M
- Computatinal time: ~4h
- No. of CPUs: 2400

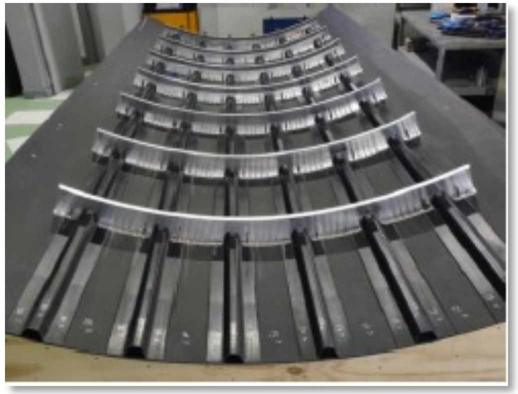
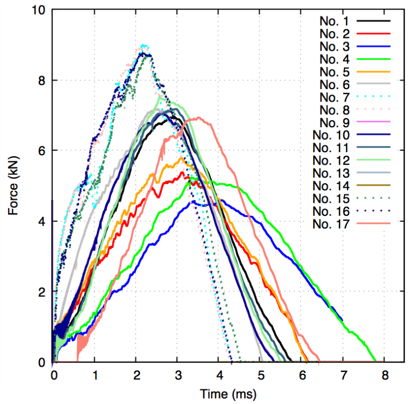


Image courtesy of ELEMENT Seville

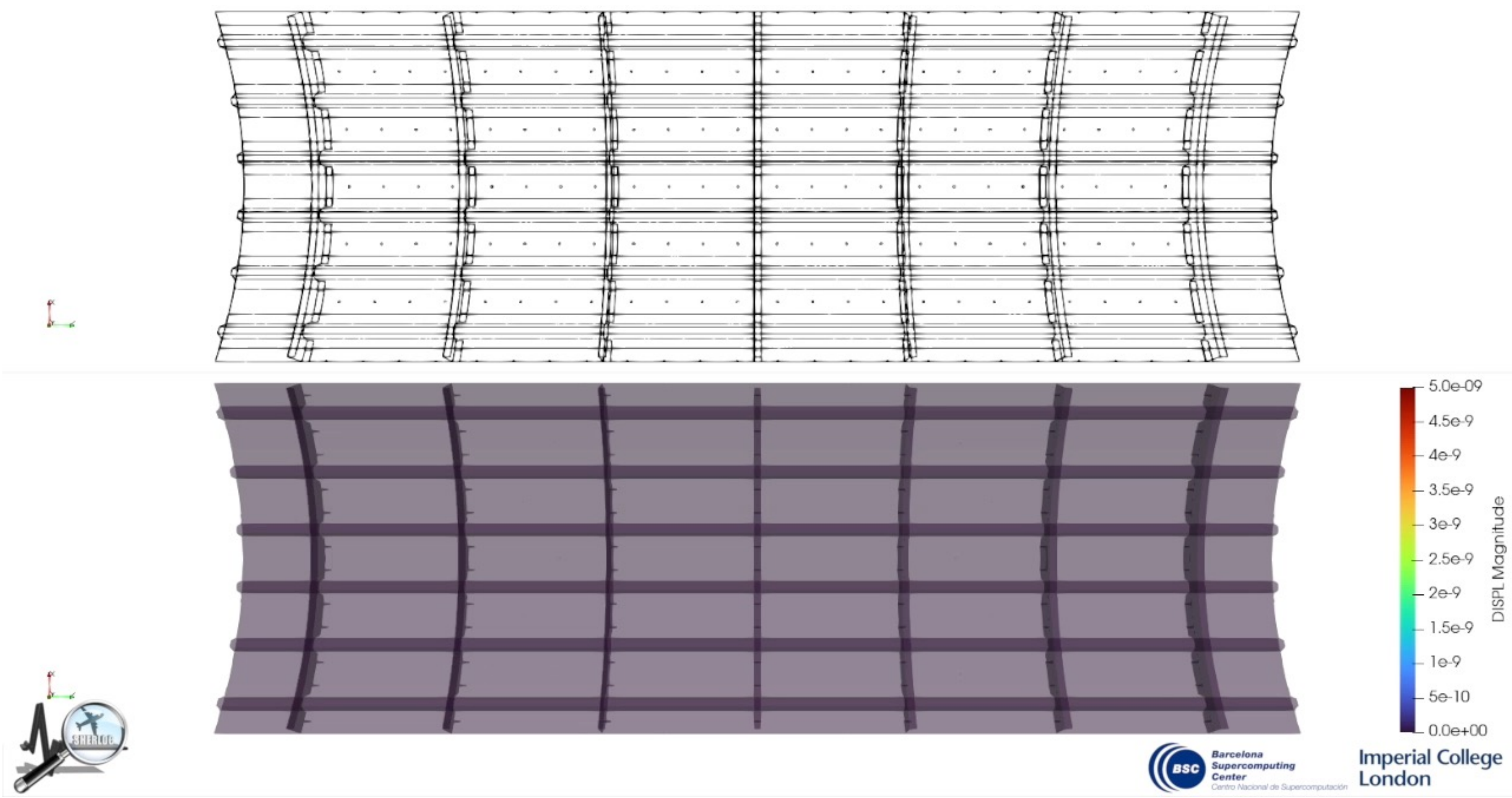


Barcelona Supercomputing Center
Imperial College London
Clean Sky 2

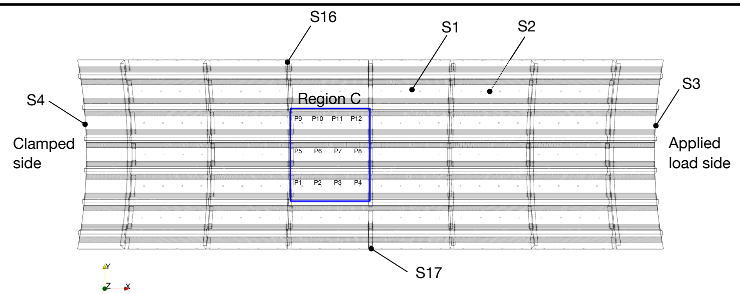
Active sensing on a 5m panel representative of passengers aircraft

Work in collaboration with Imperial College of London (ICL)

- Sensor



- Active sensing on Bay-C
- 12 excitation signals
- No. of cells: 6M
- Computatinal time: ~13min
- No. of CPUs: 768



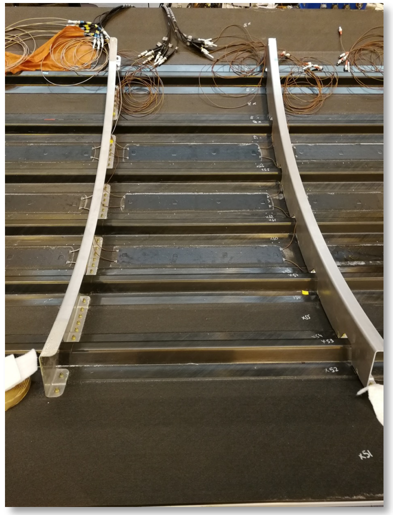


Image courtesy of FIDAMC and ELEMENT Seville

Smart virtual Fuselage representative of passengers aircraft

Work in collaboration with Imperial College of London (ICL)

Geometry details (based on curved panel)

- D=3.4m; L=4.466m
- Pitch: 250mm
- Distance between frames: 620mm
- Height frame: 100 mm
- 7 frames (6bays), 43 stringers

SHM system

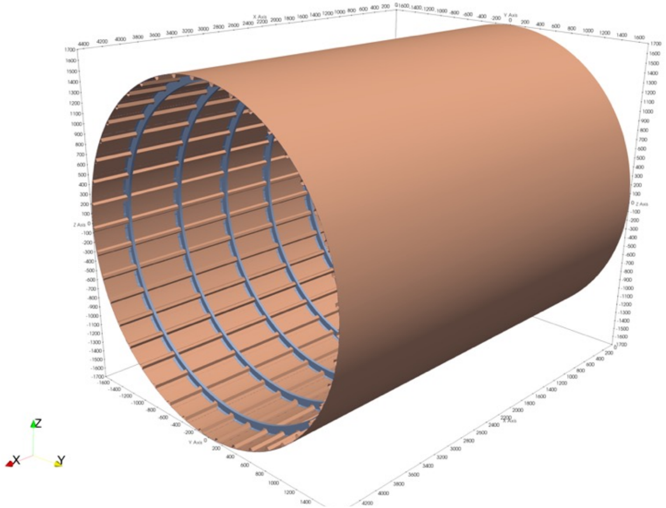
- Sensors ref. PI P-876.SP1 (Circular)
- 1032 sensors (4 x 6 x 43)
- R=5mm, h=0.5mm

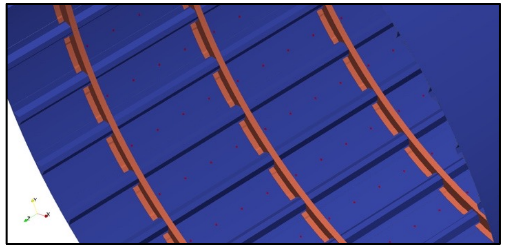
Materials

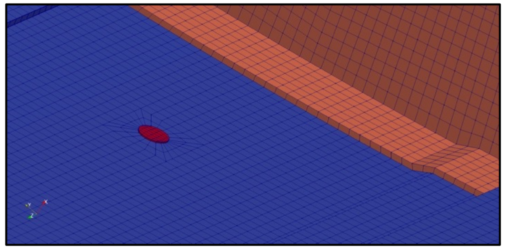
- *Skin/stringers (T800S/M21):*
  - tply = 0.194mm; tcoh=0.0mm
  - Lay-up skin/stringer: [45/-45/0_2/90/0]s
- *Frames (Aluminum)*
- *Sensors (Ceramic)*

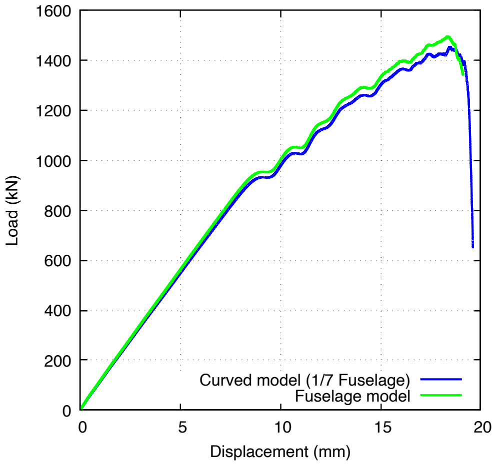
Mesh details

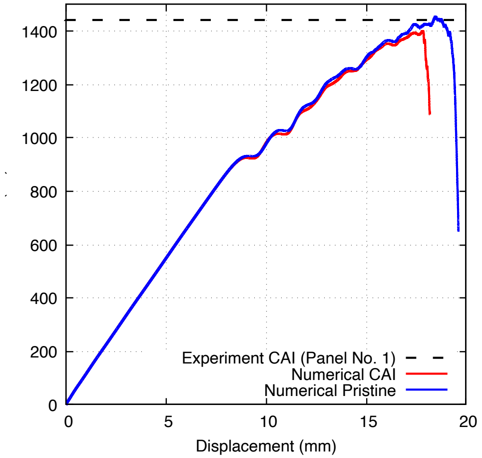
- 46,393,066 elements
- 155 x 10^6 DoF
- Structured mesh of HEX08 and COH08
- Averaged in-plane element size: 4mm
- Averaged thickness element size: 0.194 mm

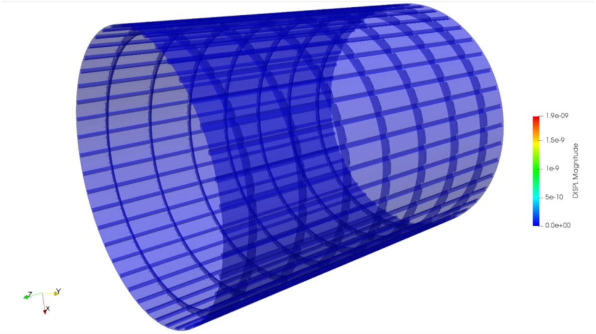












Fluid-Structure-Interaction

Fluid Structure Interaction framework

Computational Fluid Dynamics (CFD)

[Lehmkuhl et al. 2018, Owen et al. 2019 (WM)]

- Eulerian formulation
- Navier-stokes equations

$$\rho_f \frac{\partial \boldsymbol{u}_f}{\partial t} + \rho_f(\boldsymbol{u}_f \cdot \nabla)\boldsymbol{u}_f - \nabla \cdot [2\mu_f \boldsymbol{\varepsilon}(\boldsymbol{u}_f)] + \nabla p = \rho_f \boldsymbol{f}, \tag{1}$$

$$\nabla \cdot \boldsymbol{u}_f = 0, \tag{2}$$

Arbitrary Lagrangian-Eulerian (ALE)

[Calderer and Masud. 2010]

- Mesh movement is solved through a Laplacian equation.

Computational Solid Mechanics (CSM)

[Belytscho et al. 2007 (2n edition)]

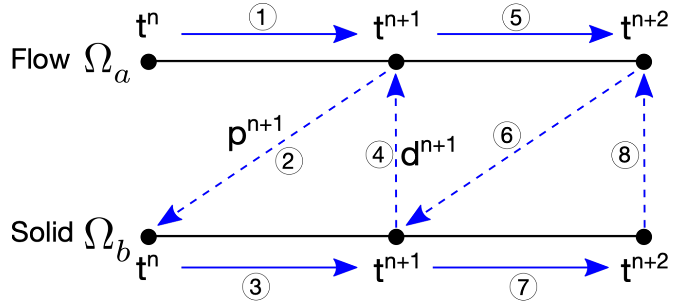
$$\rho_s \frac{\partial \boldsymbol{d}_s}{\partial t} = \nabla \cdot \boldsymbol{P} + \boldsymbol{b},$$

- Total Lagrange formulation in finite strains.
- Equation of the linear momentum balance.
- Newmark-Beta integration scheme.

FSI coupling algorithm

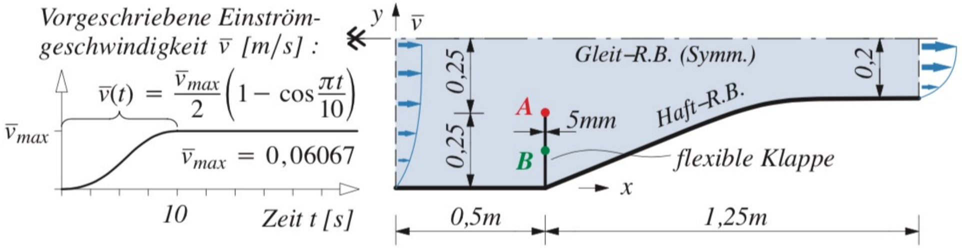
- Coupling conditions

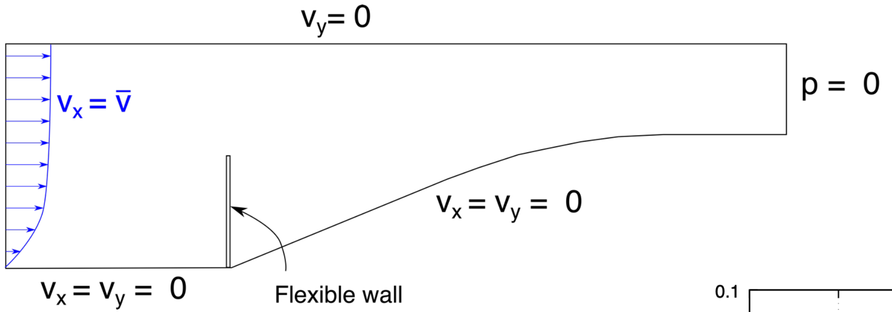
$$\begin{aligned} \boldsymbol{d}_f &= \boldsymbol{d}_s, \\ \boldsymbol{t}_f &= -\boldsymbol{t}_s, \\ \boldsymbol{u}_f &= \frac{\partial \boldsymbol{d}_f}{\partial t}, \end{aligned}$$

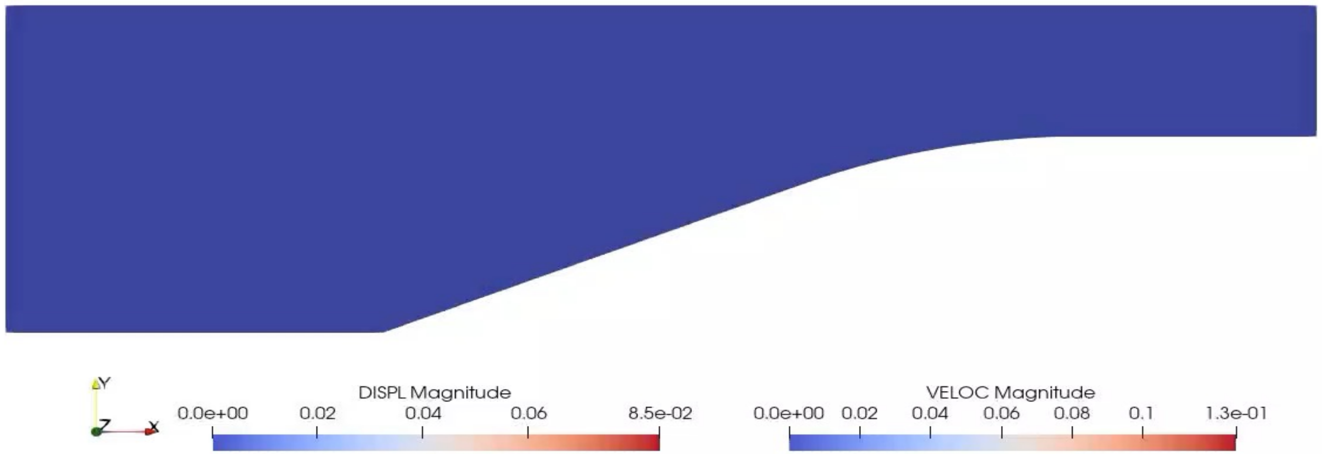


- Partitioned approach (multi-code)
- Gauss-Seidel algorithm
- Staggered Explicit/Implicit coupling algorithm
- One-way / two way coupling
- Data transfer: on the boundary

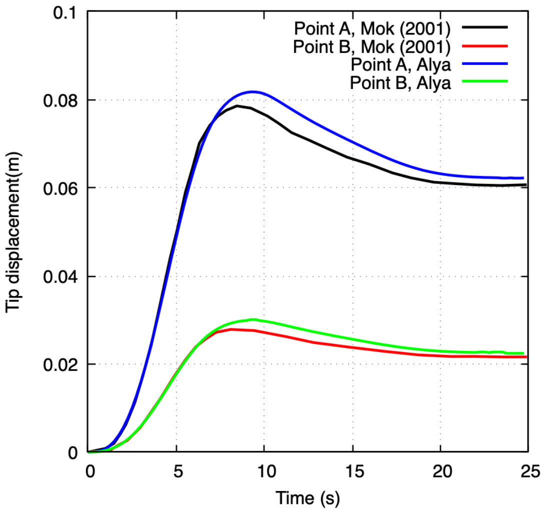
Benchmark test: 2-d channel with flexible wall (Mok 2001)

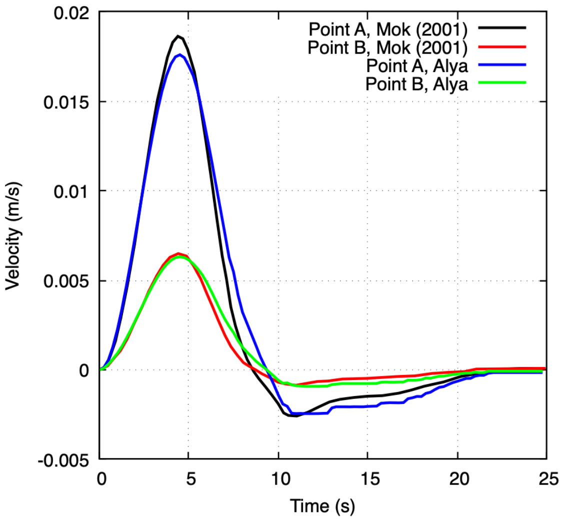


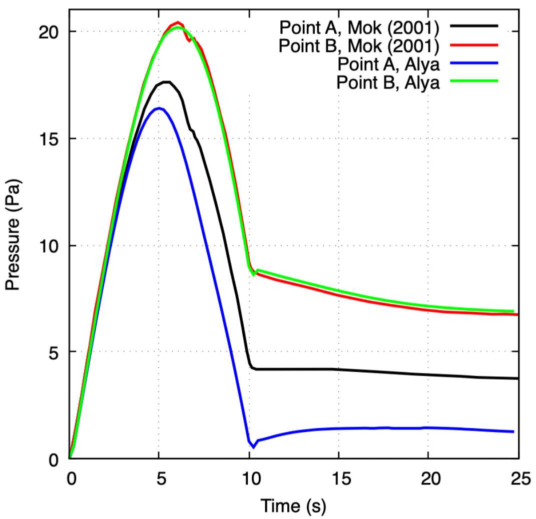




Solid	Fluid
rho =1500 kg/m3	rho = 956 kg/m3
E = 2.3e6 N/m2	mu = 0.145 kg/(m·s)
v = 0.45	







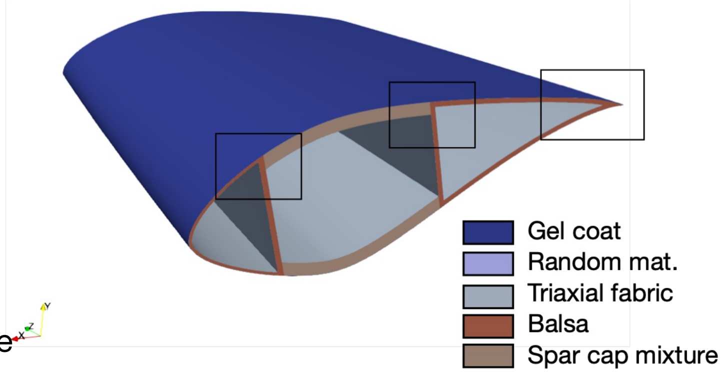
Fluid-Structure Interaction

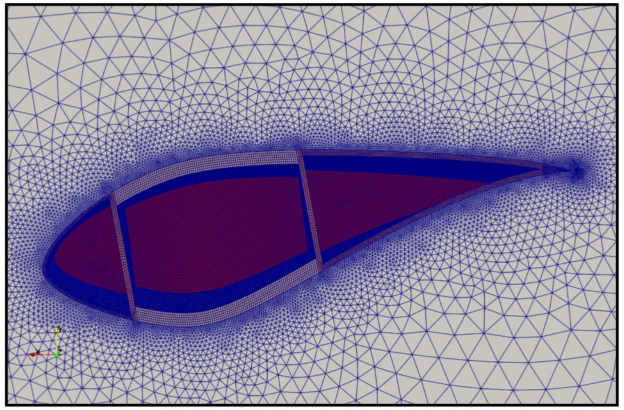
Description

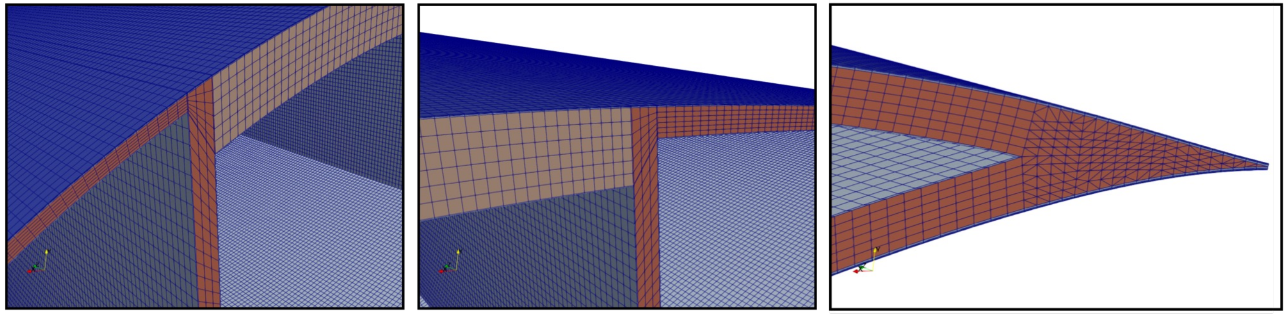
- Ref: WindPACT 1.5MW horizontal wind turbine blade from NREL (Malcolm and Hansen, 2002)
- It is a conventional 3-d bladed upwind horizontal-axis wind turbine
- It is a 33m long blade (70m rotor diameter) - Mid-large scale wind turbine

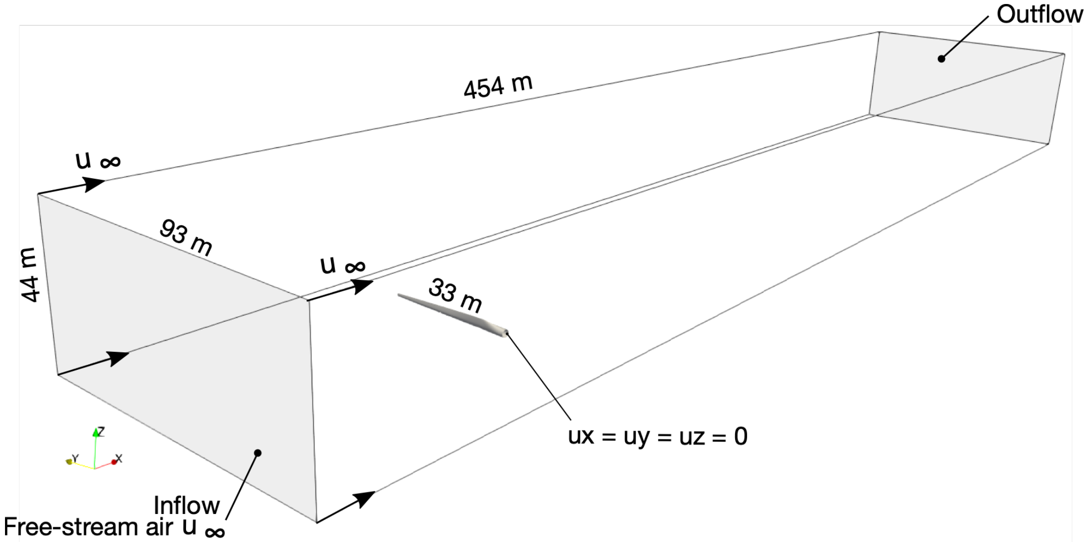
Mesh discretitzation

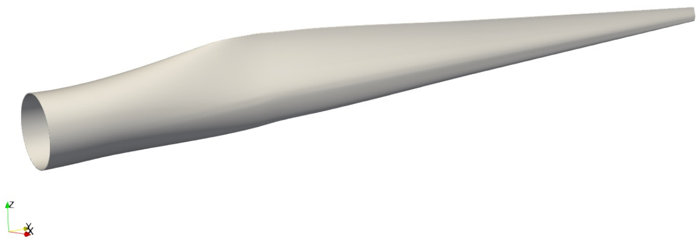
- Flow domain: Full integration linear 4-node (Tetra), 5-node (Pyr) and 6-node (Wedge)
- Flow domain: 18,011,043 elements (21.5M DoF)
- Solid domain: Full integration linear 8-node (Hexa) and 6-node (Wedge)
- Solid domain: 4,303,554 elements (14.6M DoF)

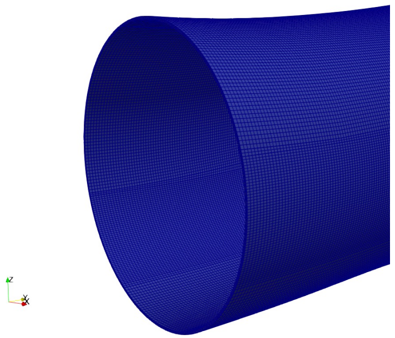








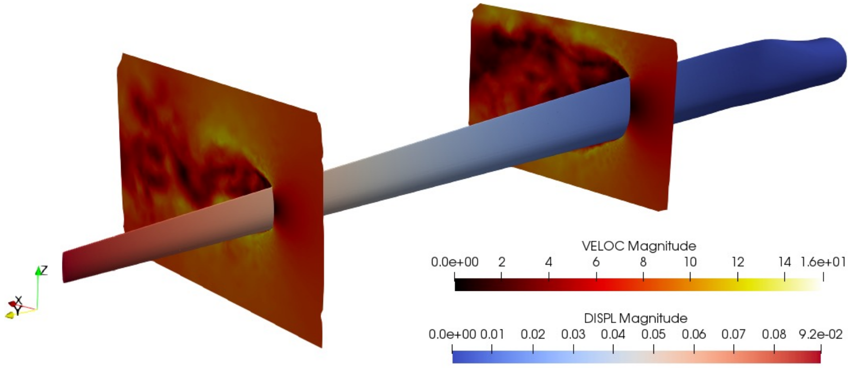




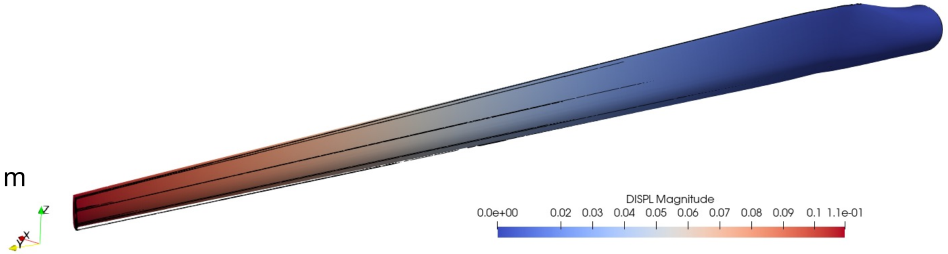
Horizon 2020
European Union Funding
for Research & Innovation

Benchmark test: 2-d channel with flexible wall (Mok 2001)

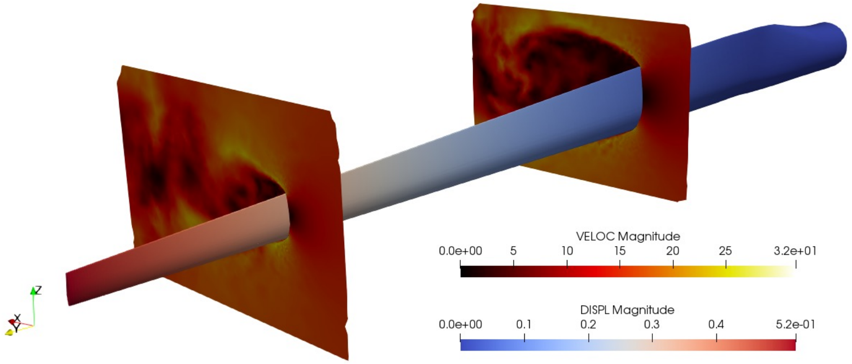
8 m/s



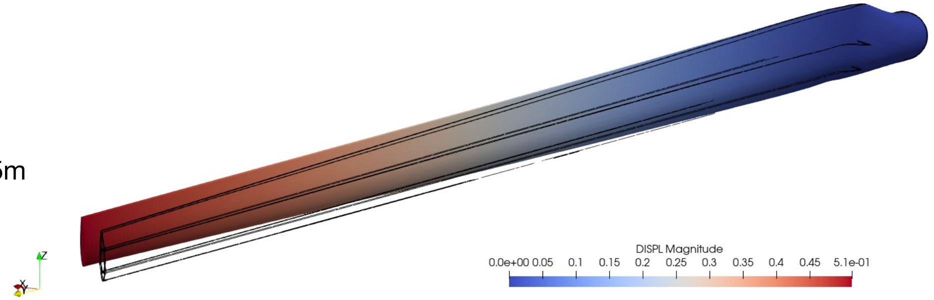
dmax = 0.11m



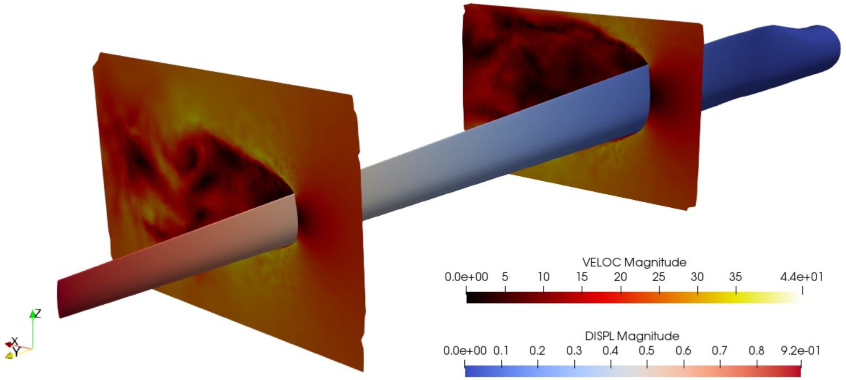
16 m/s



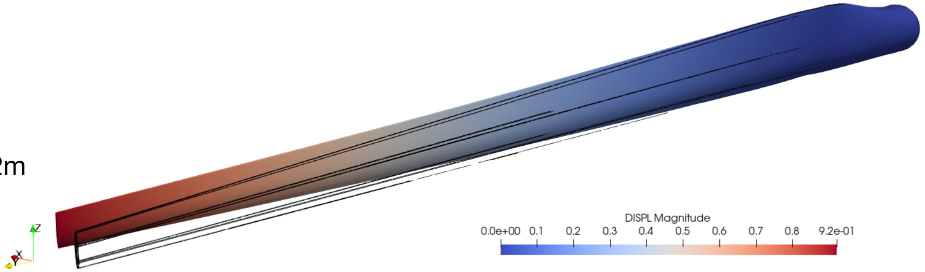
dmax = 0.5m



24 m/s



dmax = 0.92m



Scale factor x1

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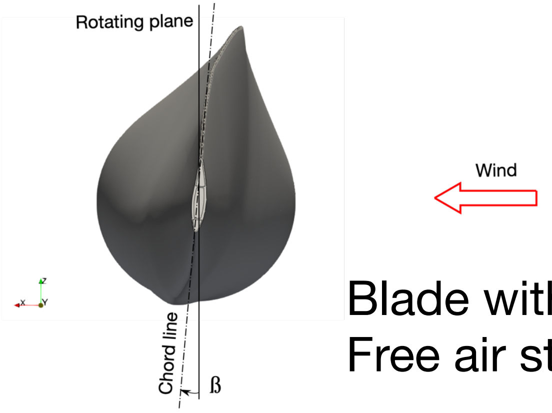
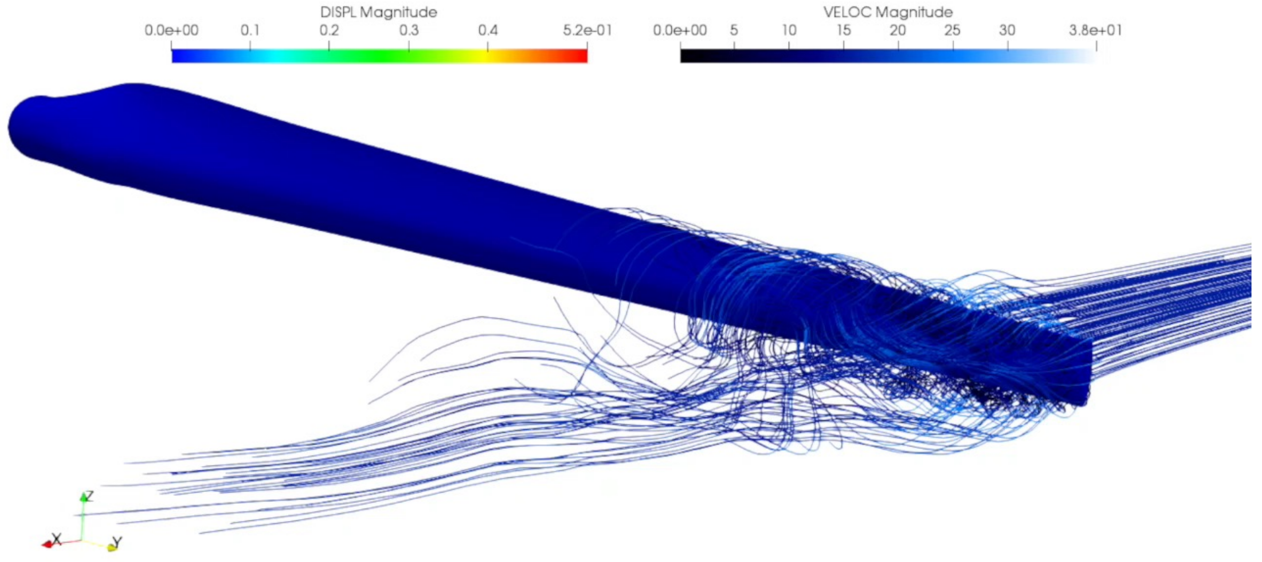
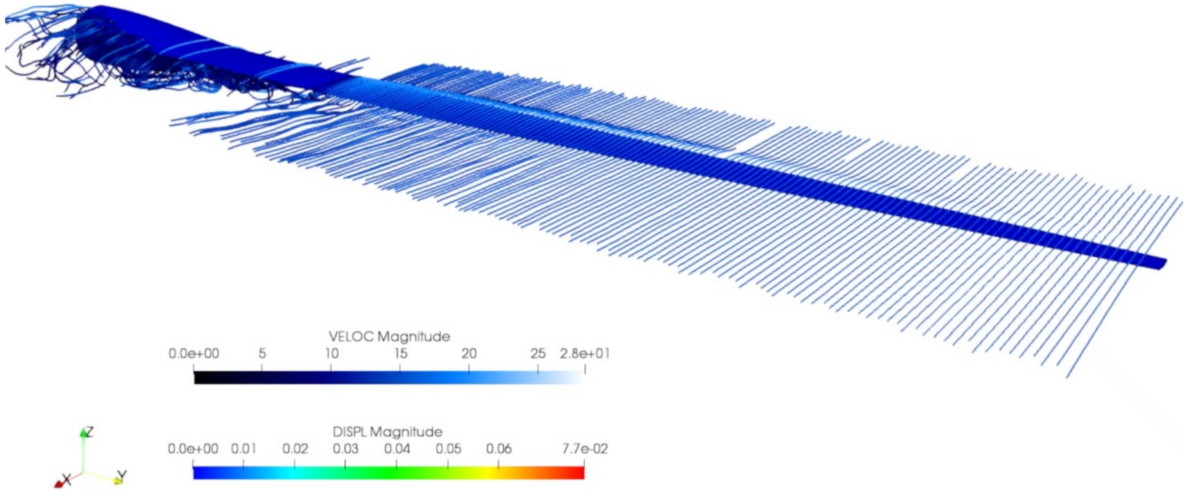
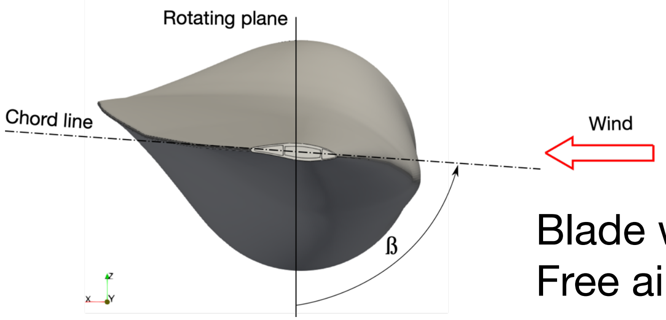
Turbulent flow past wind turbine blade



Blade with a pitch angle of -2.6º
Free air stream of 16 m/s







Blade with a pitch angle of +87.4º
Free air stream of 16 m/s

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Thank you very much for your attention!

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