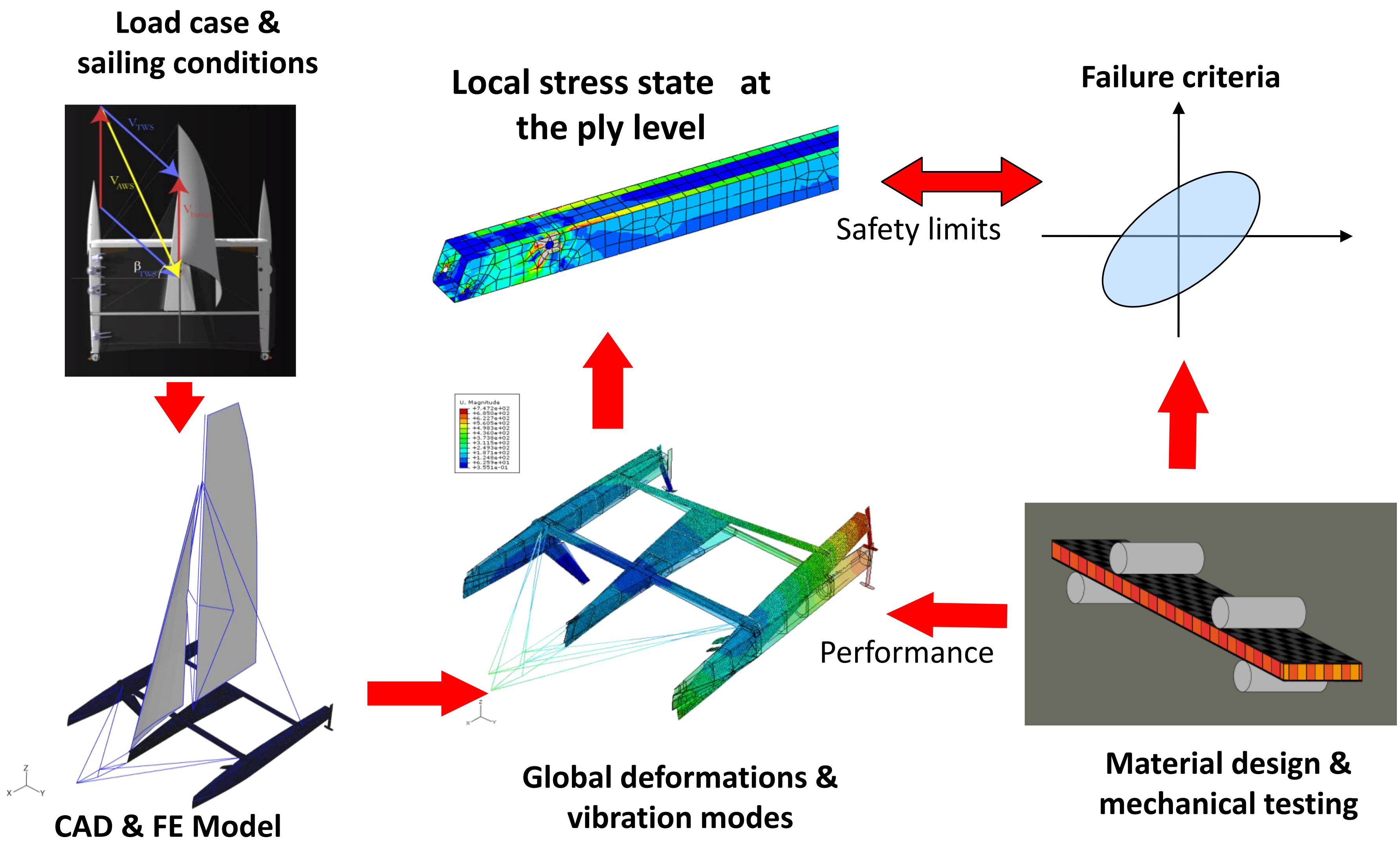
OFFICIAL SCIENTIFIC ADVISOR

Innov'Sail 2010, Lorient, July 1st

HOW MULTIDISCIPLINARY SCIENTIFIC RESEARCH MAY HELP BREAK THE SAILING SPEED RECORD

M. Calmon & al., EPFL
Hydroptère Design Team

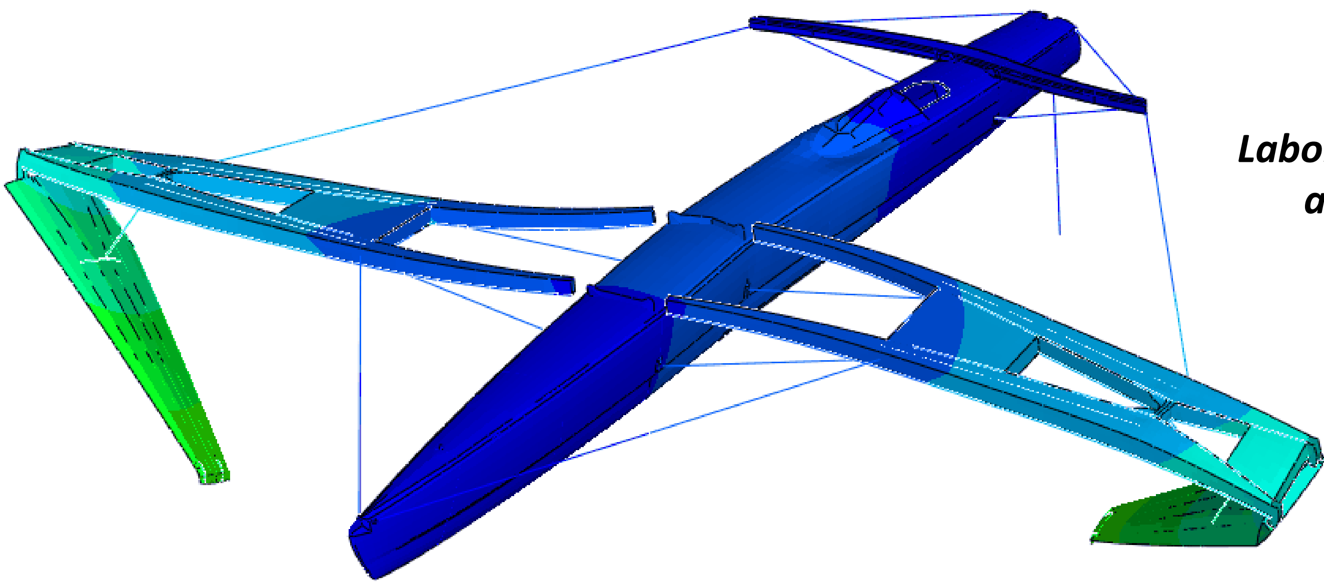
- l'Hydroptère
  - Lift of hydrofoils, complete balance of weight
  - Drag reduction, high performances
- Sailing speed records
  - Channel, 2005
  - Outright 500m & 1NM
  - Back to offshore
- Complex problems to solve
  - Trans-disciplinary project
  - EPFL scientific partnership
- New challenges
  - Versatility
  - Reliability
- Future projects
  - l'Hydroptère.ch
  - l'Hydroptère Maxi


Load case &
sailing conditions
Local stress state at
the ply level
Failure criteria
Safety limits
CAD & FE Model
Global deformations &
vibration modes
Performance
Material design &
mechanical testing

LMAF
Laboratory of Applied Mechanics and Reliability Analysis

l'Hydroptère Design Team

LTC
Laboratory of Polymer and Composite Technology



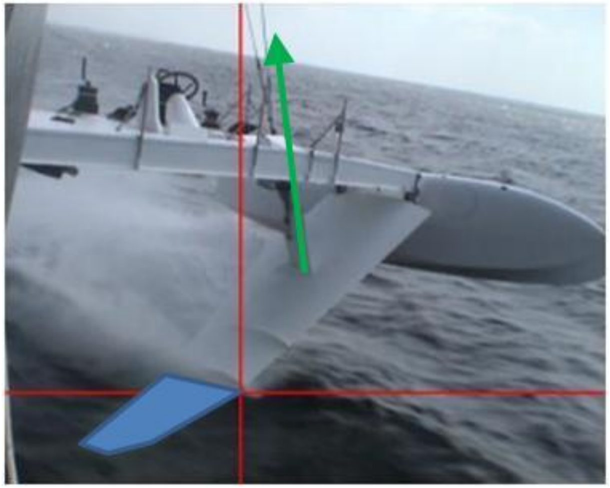
CVLab
Computer Vision Laboratory

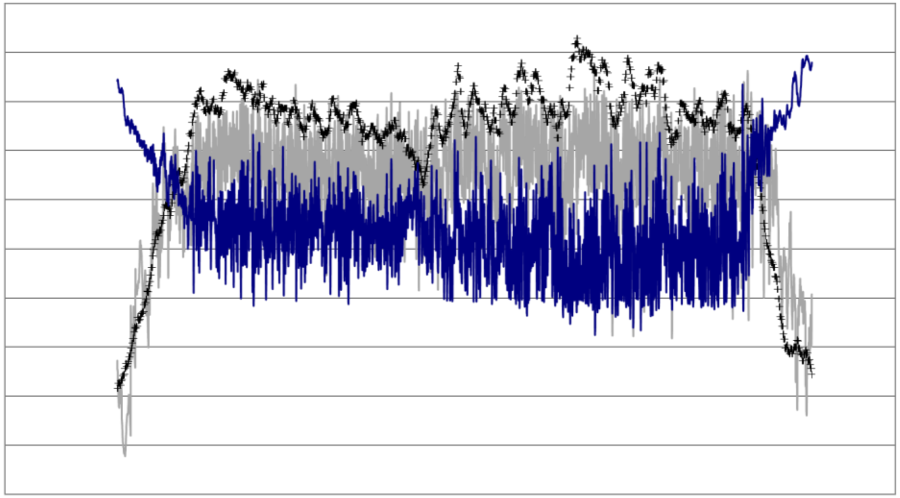
LMH
Hydraulic Machines Laboratory

- 4 sub-systems:
  - Stress & positioning sensors (HBM digiCLIP)
  - Navigation unit (B&G WTP2)
  - Inertial unit (IXSEA Octans)
  - Video system (Cosworth Pi VIDS2)
- CAN-bus
- Data logger & ruggedized computer
  - Cosworth Pi Sigma LLB
  - Lemer Pax Posibox
- Motivation
  - Real-time load analysis
  - Feedback on dynamic behavior

Foil Immersion Detection

- Motivation
  - Platform motions with reference to water surface
  - Refined foil loads
- Measurement system integration
  - Synchronization



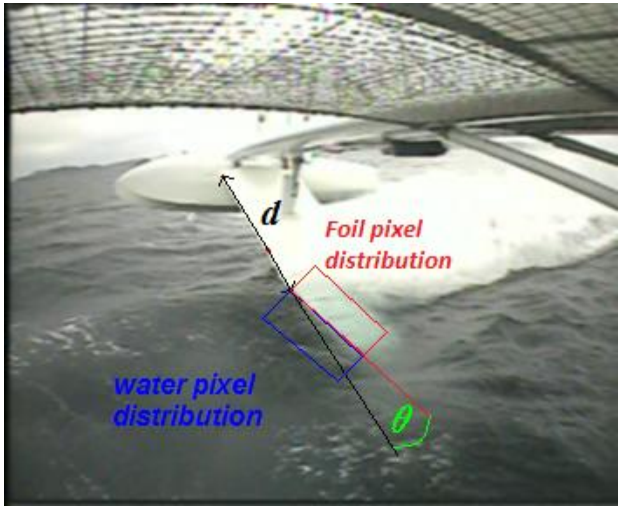


Foil Immersion Detection

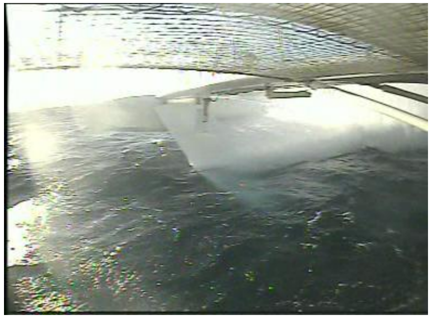
- Refraction-based principle
  - Move along the foil leading edge
  - Look for a change of slope
- Algorithm keypoints
  - Functional maximization
  - Kullback-Leibler divergence

$$F(d,\theta) = \frac{D_{KL}(P,Q) + D_{KL}(Q,P)}{2}$$

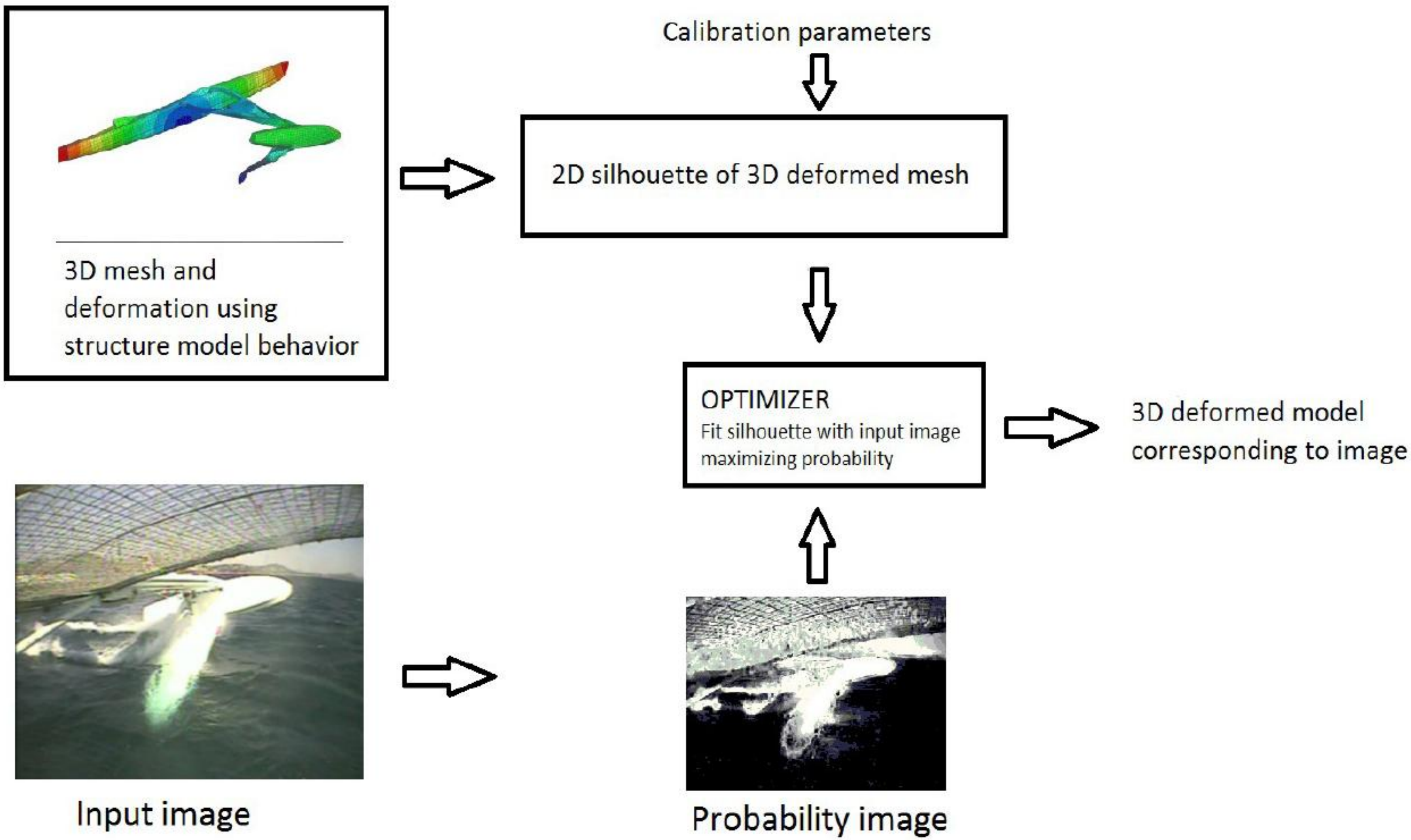
$$= \frac{1}{2}\sum_{0}^{255} P(i)\log\frac{P(i)}{Q(i)} + Q(i)\log\frac{Q(i)}{P(i)}$$



- Hazards
  - Changing light conditions
  - Reflections
  - Blurred images by spray drops



Cross-Beam Torsion

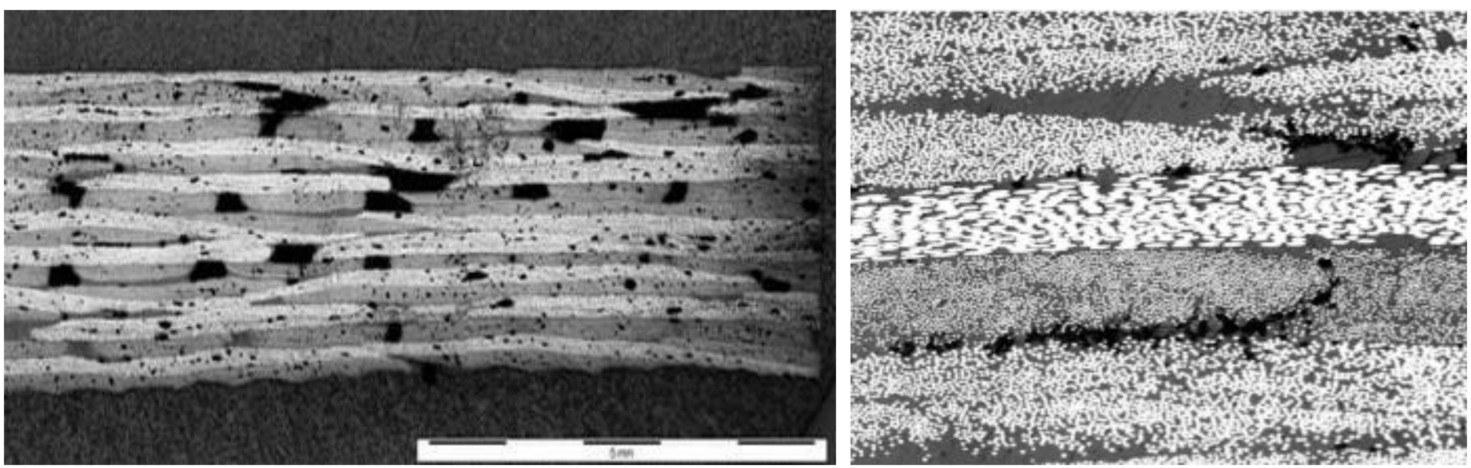


Manufacturing Processes

- Shipyard practice (Decision SA)
- Processing methods studies
  - Heating rate
  - Applied pressure
  - Draping sequence
- Part quality control
  - Micrographic visual inspection
  - Curing stage (DSC, DMA)

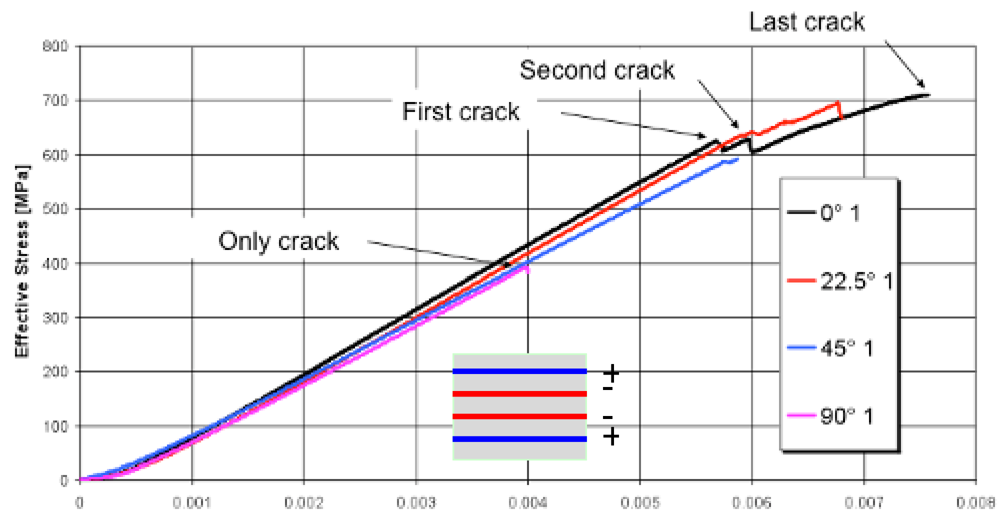
Sound composite

Process-induced porosity



Monolithic Parts

- Off-axis plies in thick laminates
- Role on failure mechanisms
- 4-pt bending
- Design rules



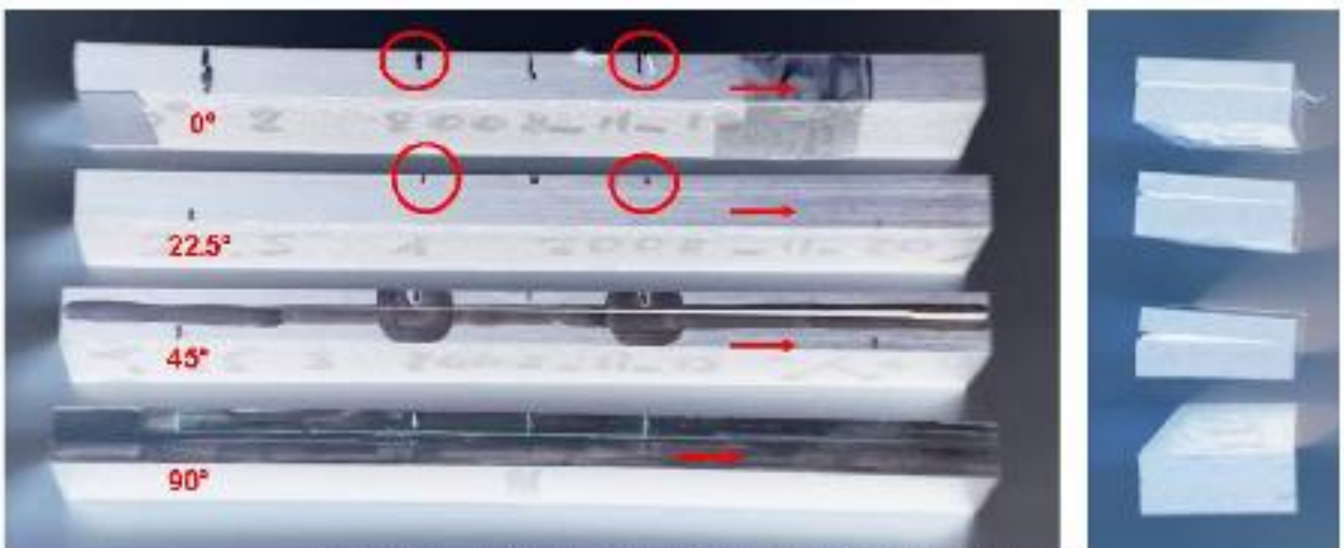
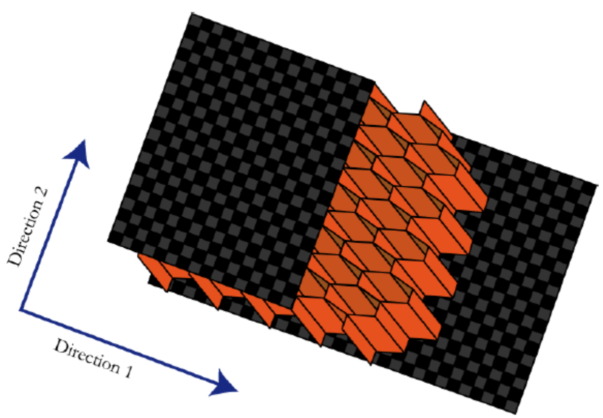
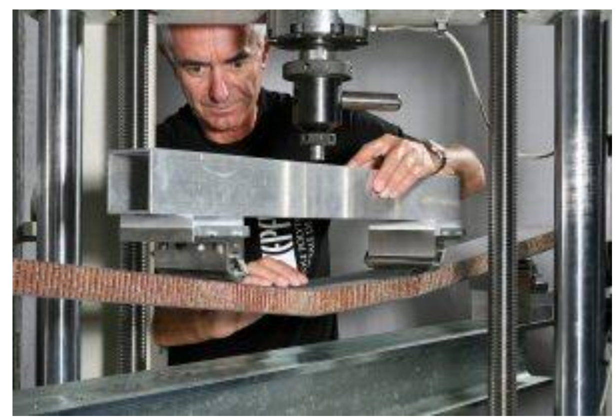


Figure 6-4 : Examples of some of the specimens tested. Front and side views.

Sandwich Structures

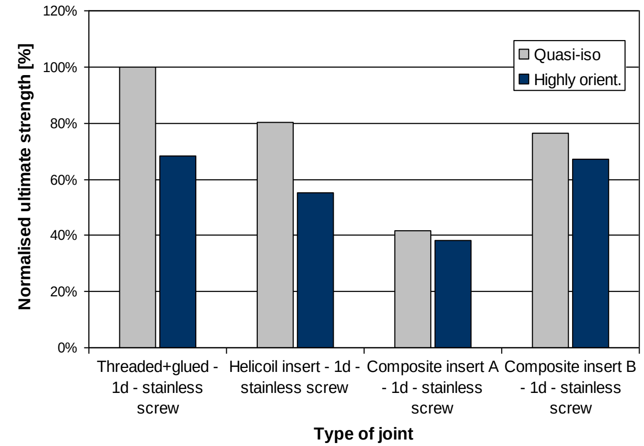
- Behaviour identification
- Anisotropic honeycomb (Nomex Flexcore)
- Preliminary tests
  - Tension, compression and shear for the skins
- 4-pt bending
  - Several span lengths
  - Core shear modulus
- Structural model updating

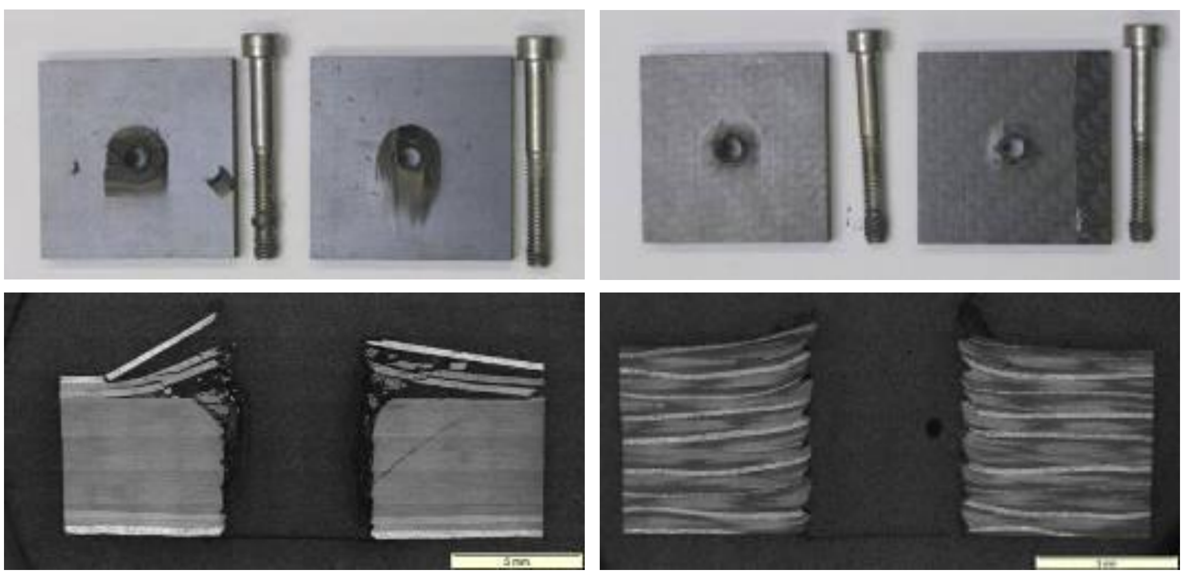


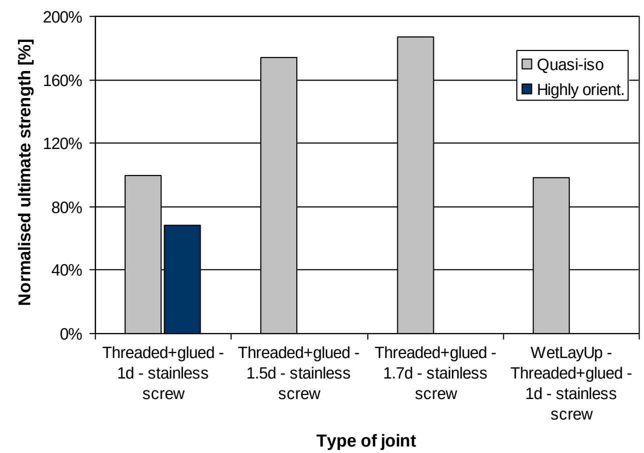


Threaded Joints

- Joining metallic to composite parts
- Joint strength influenced by:
  - Stacking sequence
  - Insert
  - Screw
  - Glue
  - Thread length
- Special testing device
  - Screw pulling-out

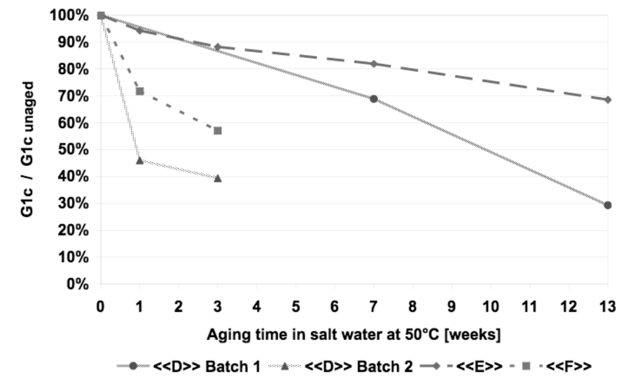


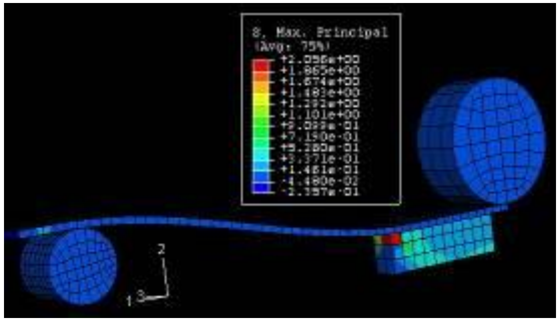


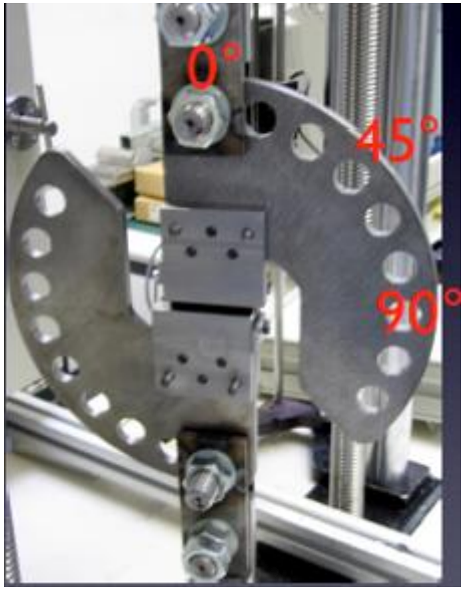


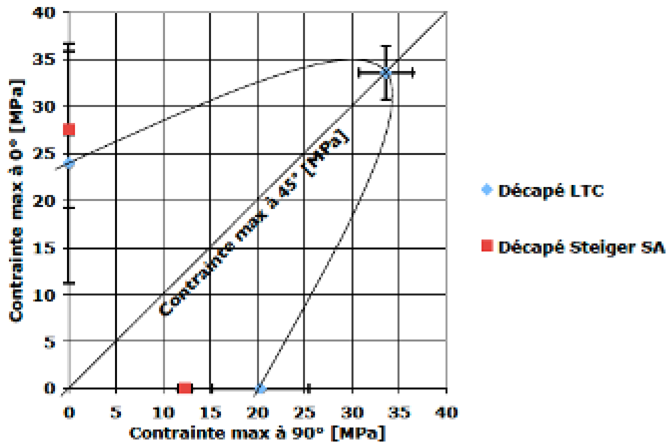
Bonding

- Joining Titanium to composite parts
- Surface treatment investigations
- Fracture strength measurements
    - Griffith's critical strain energy release rate G_{Ic}
- Accelerated aging tests
- Cohesive zone model in Abaqus
    - Previous fracture test
    - Extended failure criteria test



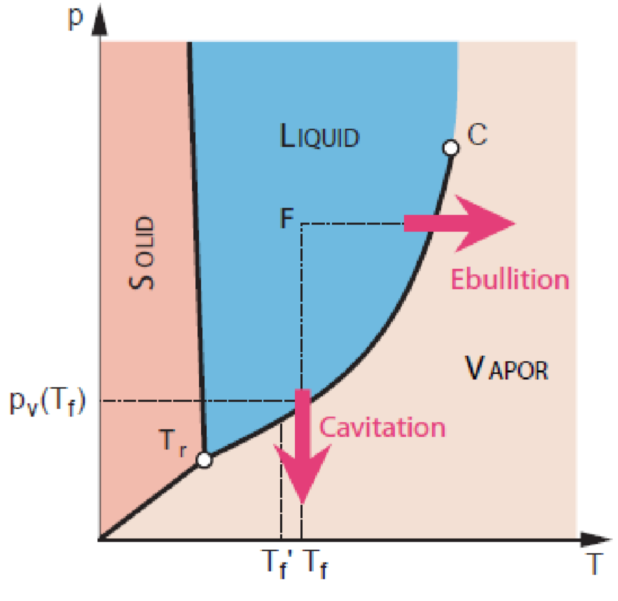


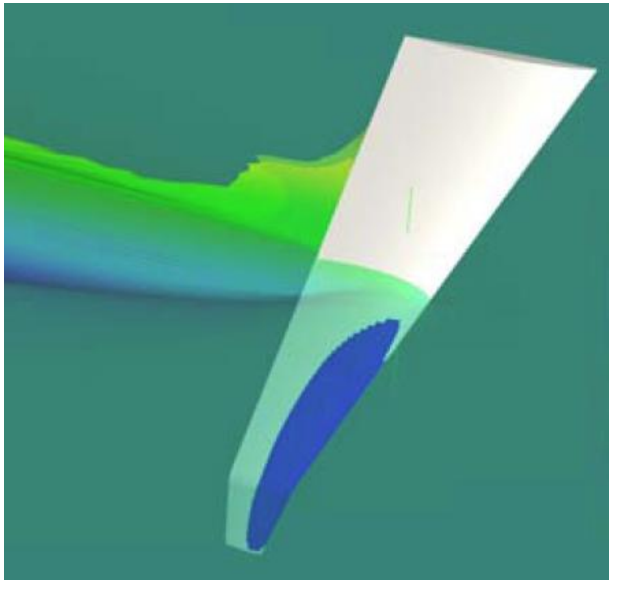




Hydrodynamic Phenomena

- Cavitation
  - Formation of vapour cavities in low pressure zones
  - Almost impossible to avoid with high speeds
  - Alteration of hydrodynamic performances
  - Vibrations
- Ventilation
  - Air from above the free surface sucked into low pressure zones below the surface
  - Drop in lift

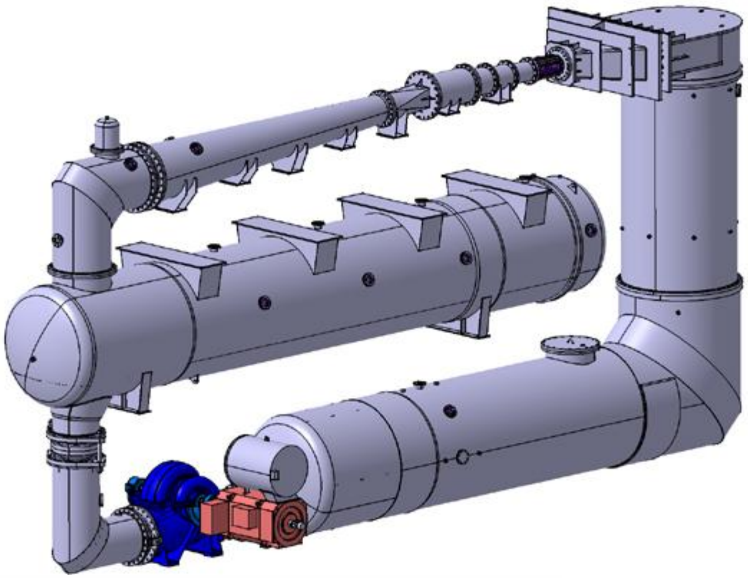


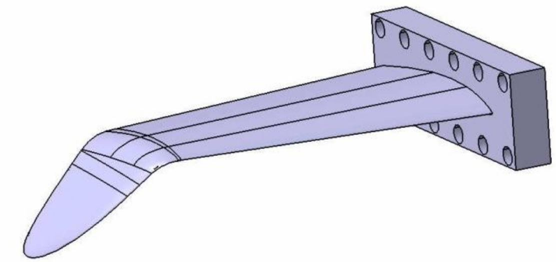


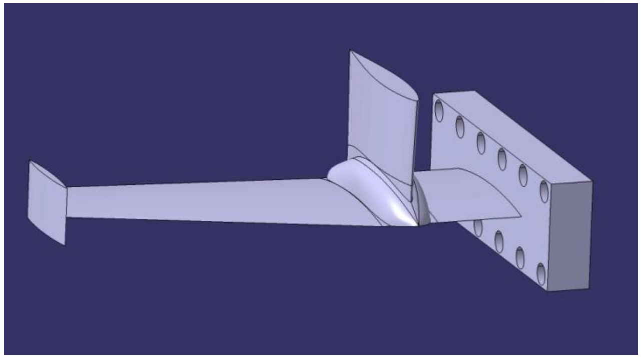
$$\sigma = \frac{p - p_v}{\frac{1}{2}\rho V^2}$$

Experimental Context

- EPFL high speed cavitation tunnel
  - 150mm square test section
  - Pressure controlled from 0.02 to 1.6MPa
  - Inlet flow velocity up to 50m/s
  - Angle of attack control
  - 5-axis balance for force measurement
  - Strobe, digital camera
  - Flash lamps, high speed video camera
- l'Hydroptère specific tests
  - 1/10th scaled models of foil and rudder/stabilizer
  - Developed turbulent boundary layer (V>15m/s)
  - σ adjustment for cavitation similitude above 50kt

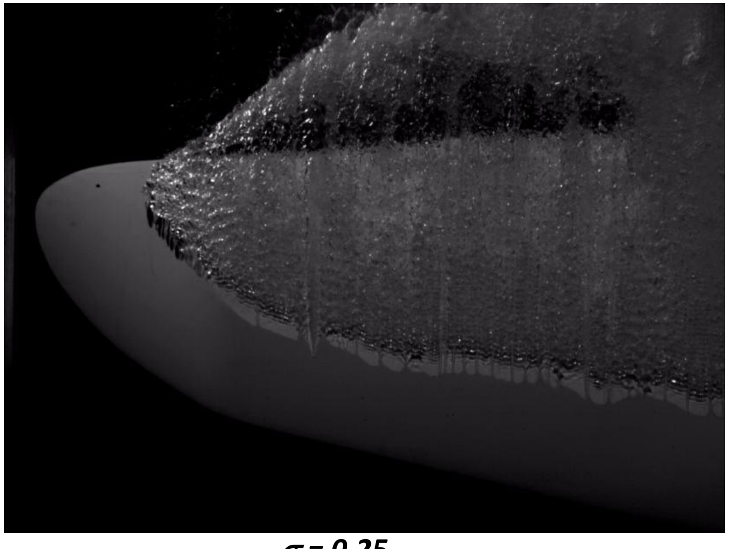




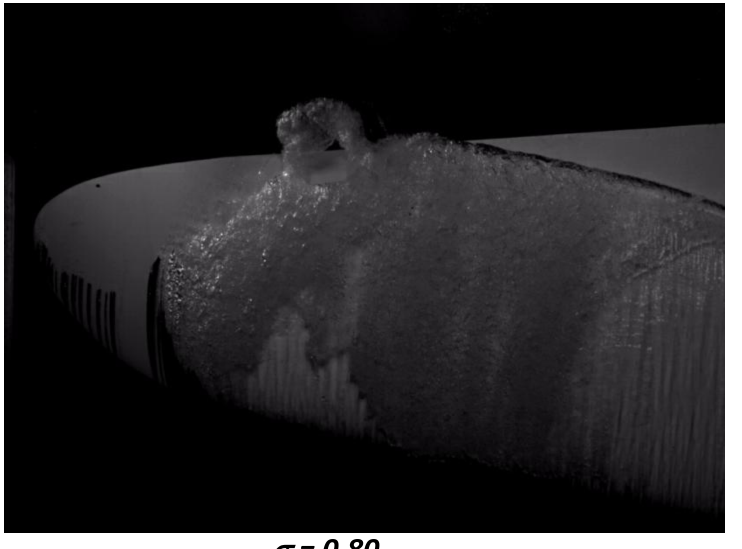


Experimental Cavitation

- Attached cavitation
- Angle of attack dependence
- Low angles (left):
  - Long thin cavity starting downstream leading edge (sheet cavitation)
  - "Smooth" flow, low vibrations
- High angles (right):
  - Cavitation inception even for higher σ
  - Cavity detachment moves upstream until leading edge
  - Pulsed cavities (cloud cavitation)
  - Lift fluctuations, high vibrations



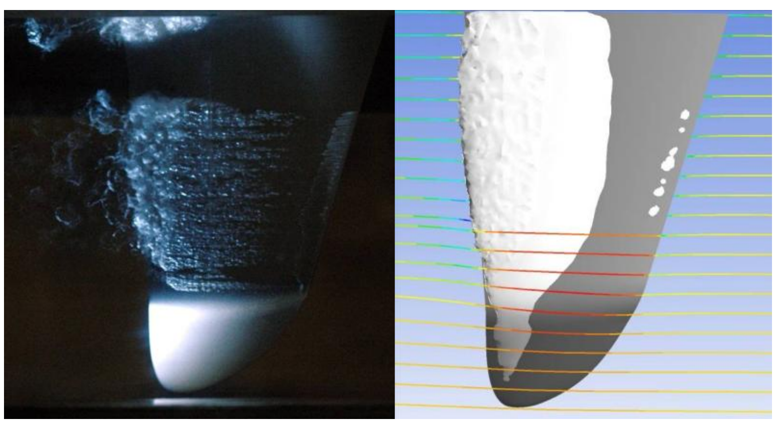
σ = 0.25

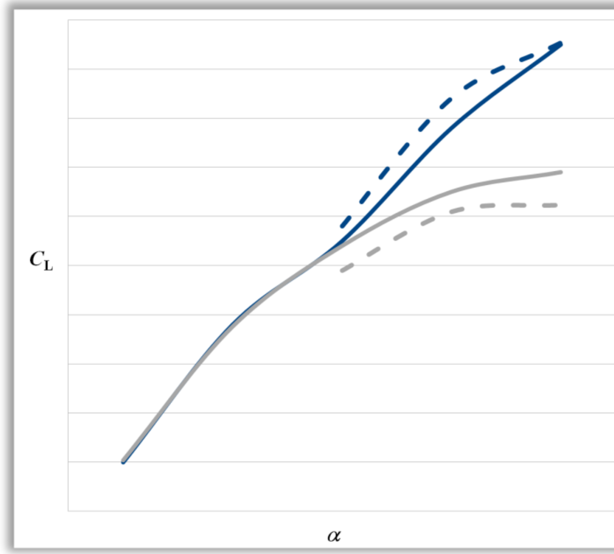


σ = 0.80

Simulated Cavitation

- Numerical context
  - 3D RANS solvers ANSYS FLUENT & CFX
  - Realizable *k*-ε turbulence model
  - Multi-phase simulation with VOF method
- Cavitation models
  - Low pressure "contouring"
  - FLUENT Mixture model
  - CFX three phase flow model
- Simulation validations
  - Experimental tests in EPFL cavitation tunnel
  - Visual comparisons
  - Hydrodynamic loads variations

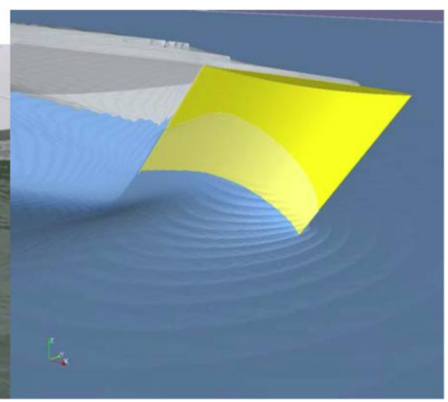


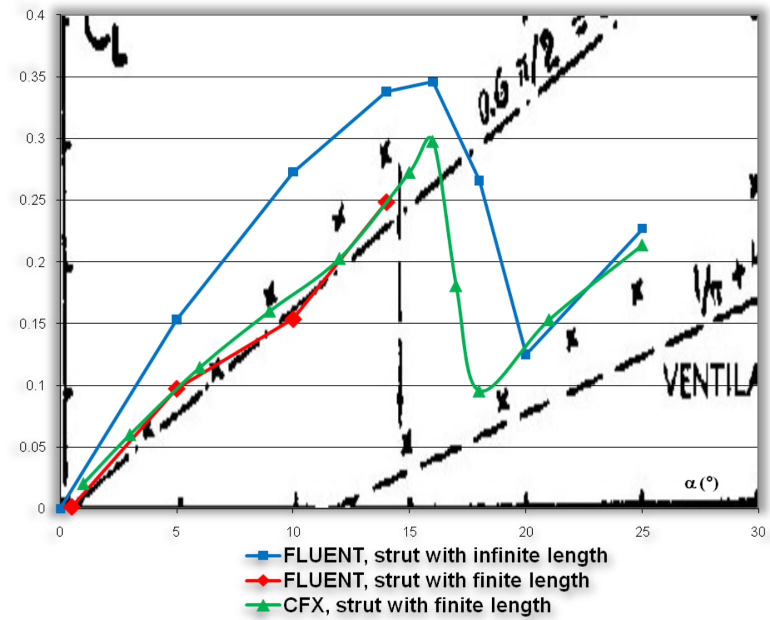


High σ=0.49 and low cavitation (—)
Low σ=0.31 and strong cavitation (—)
(- - - Simulation, — Experiments)

Simulated Ventilation

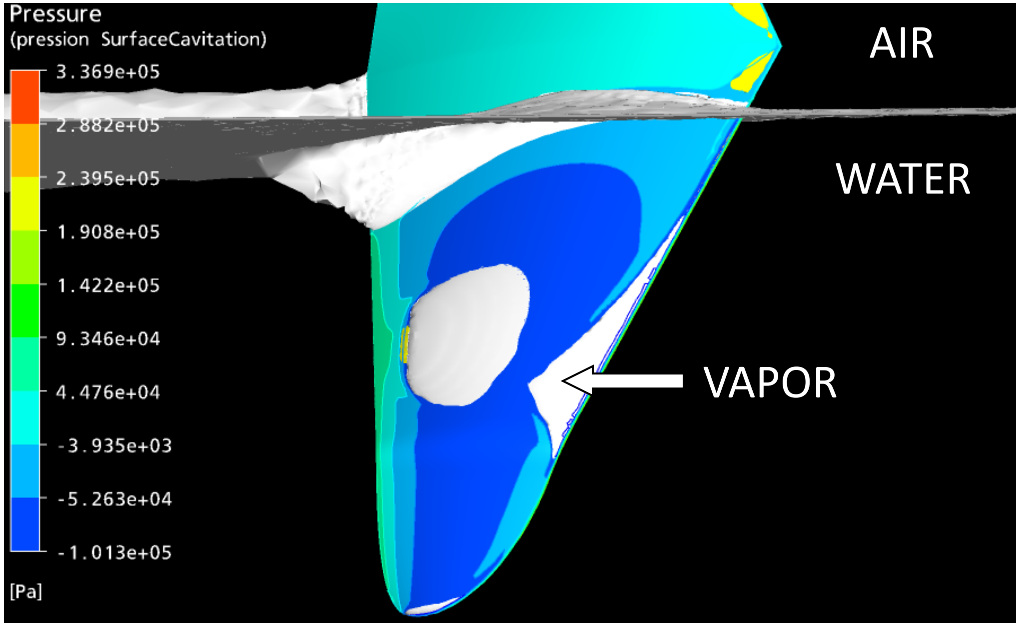
- Numerical context
  - 3D RANS solvers ANSYS FLUENT & CFX
  - Realizable k-ε turbulence model
  - Multi-phase simulation with VOF method
- Simulation validations
  - No new experimental tests
  - Visual comparisons during sea trials
  - Bibliography test case
- Hoerner, *Fluid-Dynamic Drag,* 1965
  - Dingee experiments, 1953
  - Davidson Laboratory, NJ, USA
  - Slender surface-piercing strut
  - Loads variation according to angle of yaw





Simulated Real Case

- Numerical context
  - 3D RANS solver ANSYS CFX
  - Realizable k-ε turbulence model
  - Multi-phase simulation with VOF method
- Three-phase simulations
  - Cavitation
  - Flat free surface (ventilation)
  - Steady state conditions
- Optimization process
  - Manual iterations
  - High lift/drag ratio
  - Low tendency to ventilation
  - Low tendency to cavitation

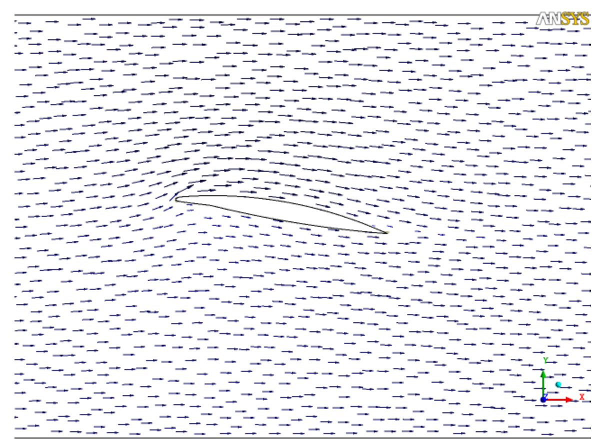


Foil shape optimization

- Optimization process
  - Multi-objective procedure
  - Evolutionary algorithms
  - Towards a more tolerant design
- Numerical context
  - 3D URANS solver ANSYS CFX
  - Single phase flow
  - SST turbulence model
- Test case
  - 2D hydrofoil in tunnel test section
  - Constant upstream velocity
  - Pitch motion
- Optimization parameters
  - Lift/drag ratio in nominal conditions
  - Tendency to separation
  - Tendency to cavitation

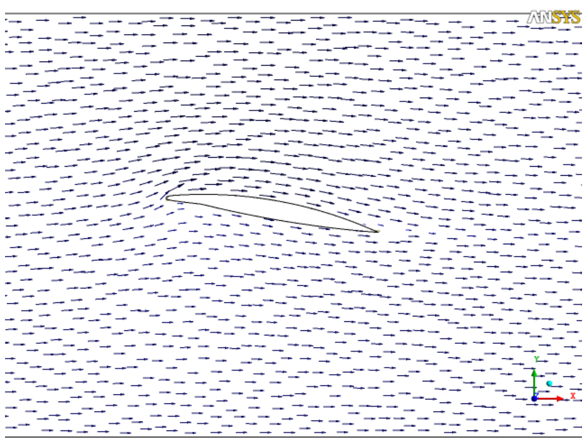
EASY The Evolutionary Algorithms SYstem

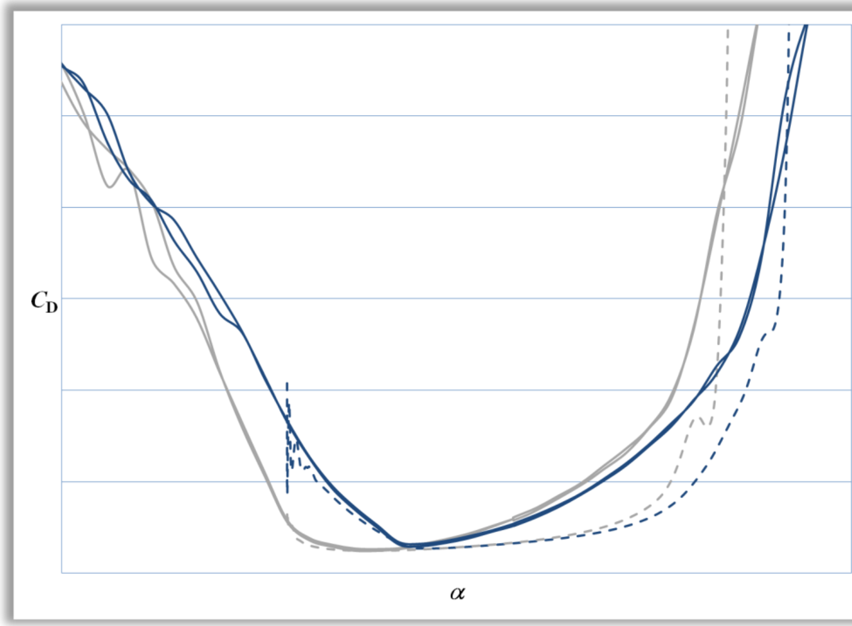
NTUA, Giannakoglou



Optimization Validations

- Experimental validation
  - Lift and drag measurements
  - 2 profiles: initial, Pareto-optimal solution
- Observations
  - Qualitative agreement
  - Drag increase postponed to higher α
  - Quantitative discrepancies
  - Drag underestimated
  - Too late stall
- Further tests
  - RANS/exp. comparisons
  - NACA0009 profile
  - Same observations

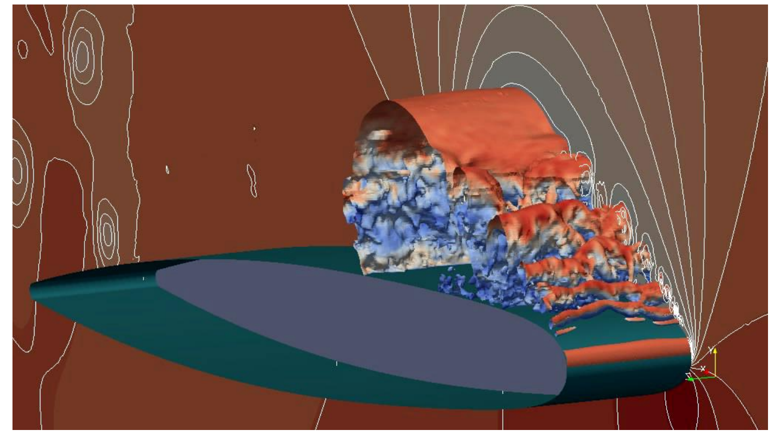


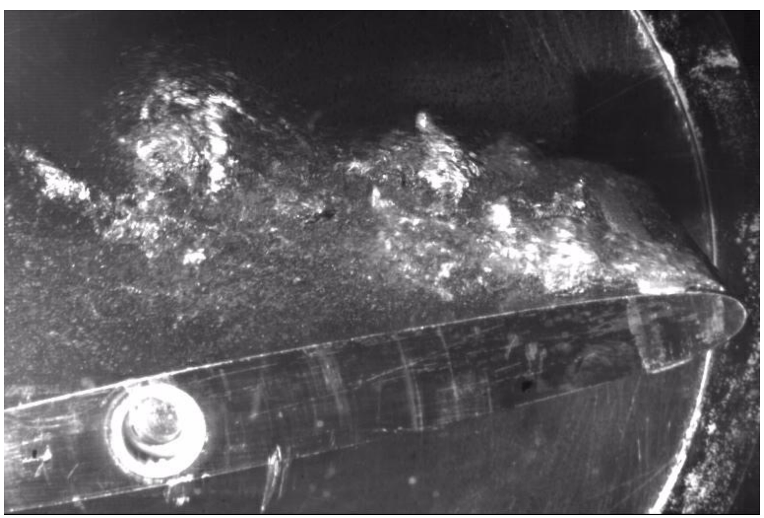


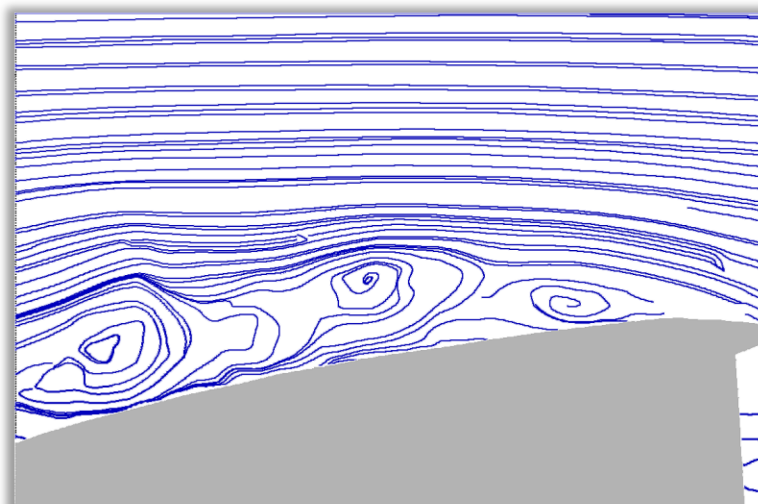
Profile drag coefficient; comparison between initial profile (▬) and Pareto-optimal profile (▬)
(- - - URANS simulation, ▬ experiment)

Large Eddy Simulation (LES)

- Numerical context
  - ❑OpenFOAM solver
  - ❑Large scales of the flow
  - ❑α=11°, V=5m/s
- Observations
  - ❑Unsteady detached flow and vortex streets
  - ❑From the leading edge and far before stall
- Validation
  - ❑Cavitation visualization
  - ❑PIV
  - ❑Drag value







- Optimization simulations with HPC
  - Licensing constraints
  - Open-source software solutions (OpenFOAM...)
- Fluid-structure interaction
  - Dynamic behaviour of sandwich structures in waves (slamming)
- Fluid-structure instabilities (divergence, flutter)
  - Foil alone
  - Whole platform
- Advanced Measurements systems
  - Visual cross beam torsion finalization
  - FBGS use investigations
  - Identification and monitoring developments
  - Dynamic stability visual alarms

LOMBARD ODIER
LOMBARD ODIER DARIER HENTSCH

AP
AUDEMARS PIGUET
Le maître de l'horlogerie depuis 1875

l'Hydroptère

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