Need for Speed:
The Known Unknown of Fluid Structure Interactions

SSPA Your Maritime Solution Partner

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Outline

- What do we need to understand about foils?
- What's Fluid Structure interaction
- Design challenge for One Design classes
- Experimental setup
- Passive Adaptive Composites
- Numerical model
- Results
- Summary

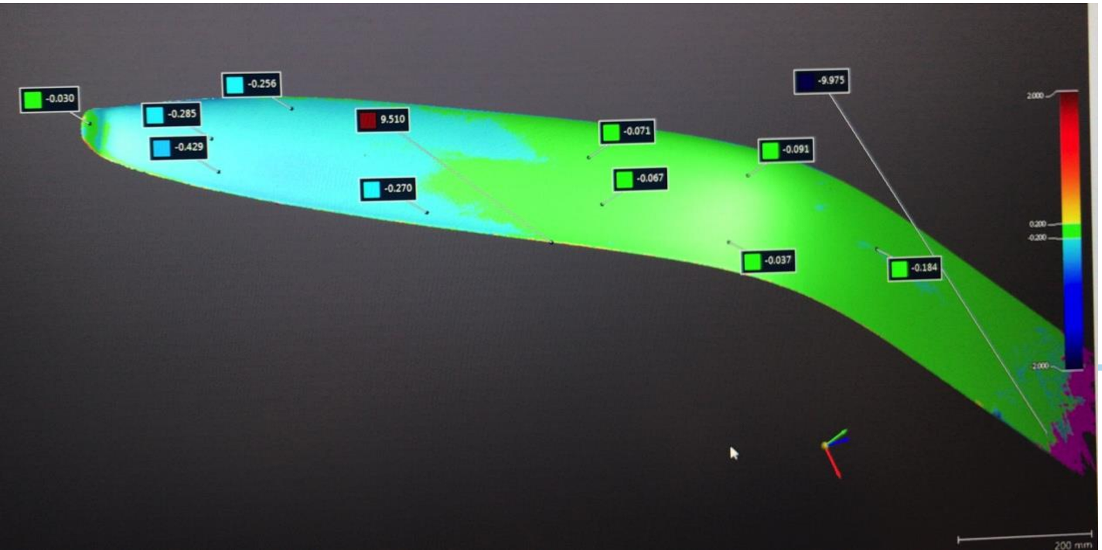
Boats' evolution: from sailing to flying

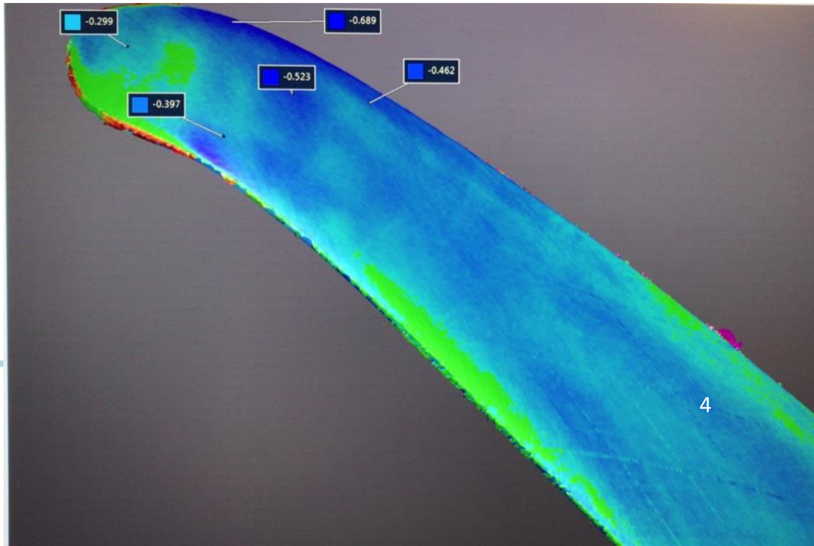
- The America's Cup is the oldest trophy in sporting history
- It has always **pushed** the **boundaries of sailing and its technology** up to extreme levels
- America's Cup research and development teams are not only composed of naval architects but also extremely competent engineers from aeronautics, F1, advance material industries etc…
- Boats and technologies are in constant evolution.

Why do we need an Experimental Methodology?

- **Foils bending and torsion**
  - How can we measure it?
  - Is there consistency between different foils?

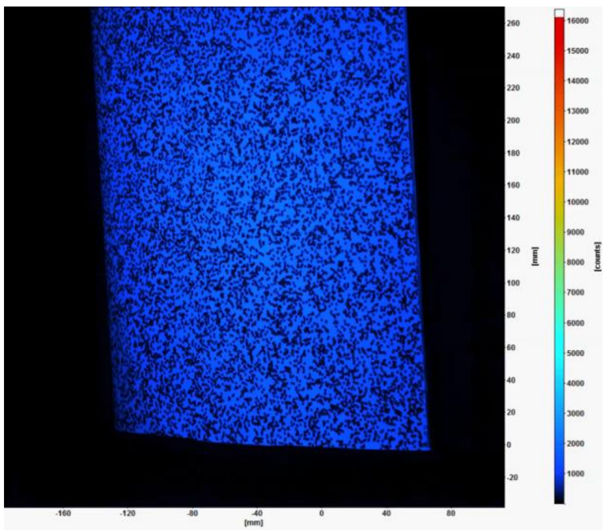
- **Foils shape**
  - Are there differences between design and built shapes?
  - How can we assess correct shape?



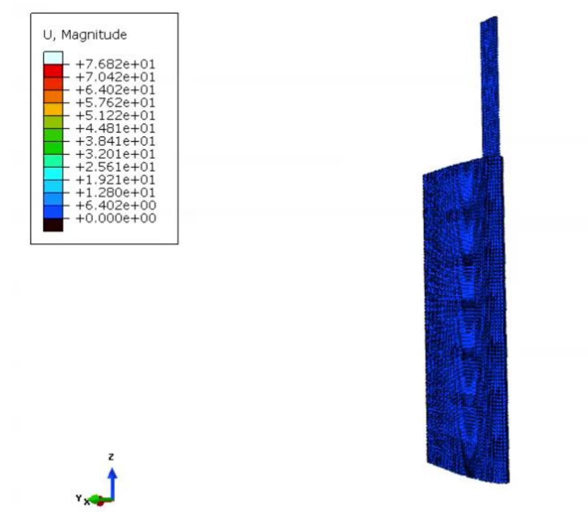


Fluid Structure Interaction

- To develop an **experimental methodology** capable of accurately describing the **structural response** of a full-scale foil **under fluid-load** together with the flow features that are affected by the deformation and twist of the foil
- To design and develop a foil structure tailored to decrease its lift coefficient by means of increased flow speed



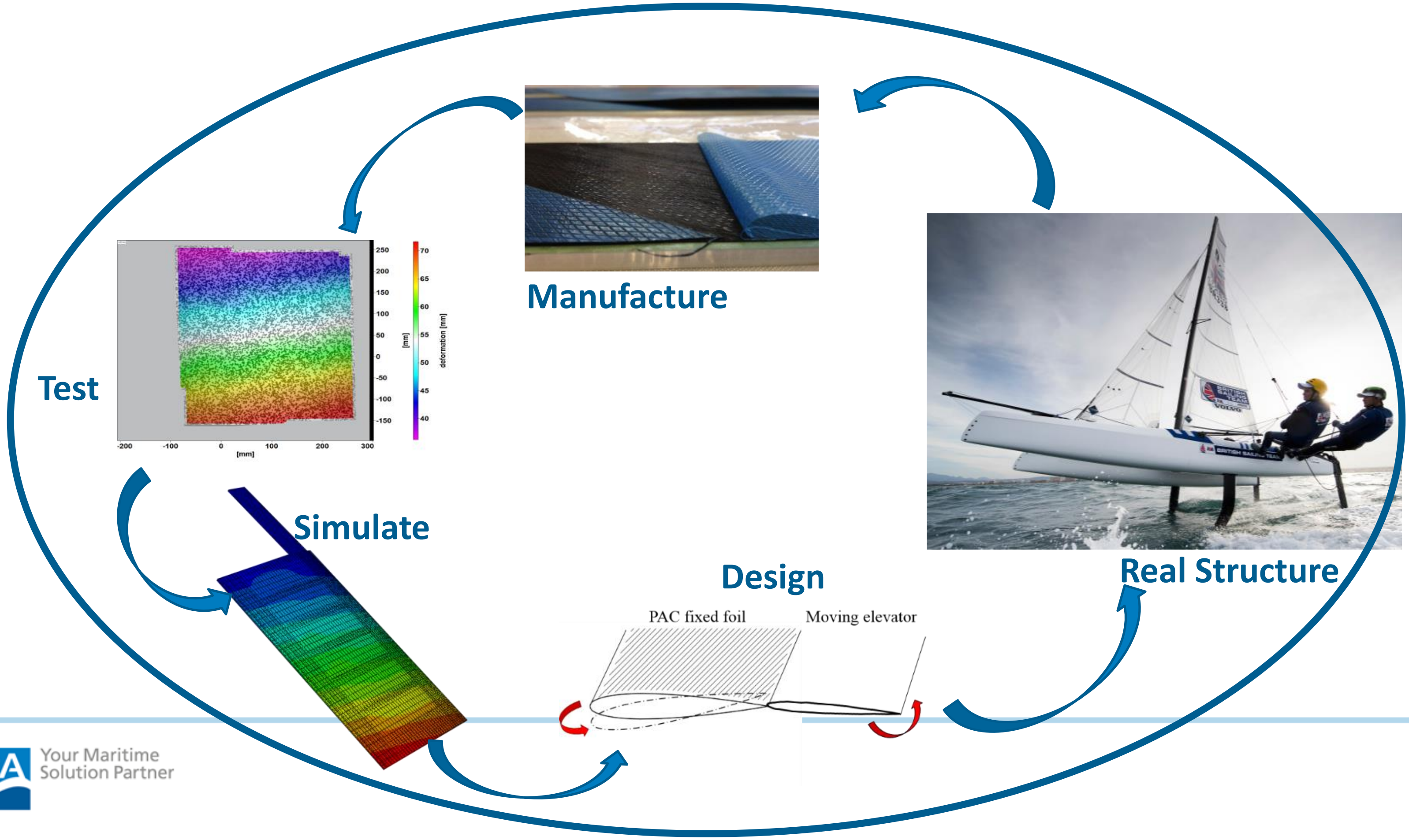
Digital Image Correlation high-speed camera recording under wind load



Finite Element Analysis Model under Computational Fluid Dynamic load

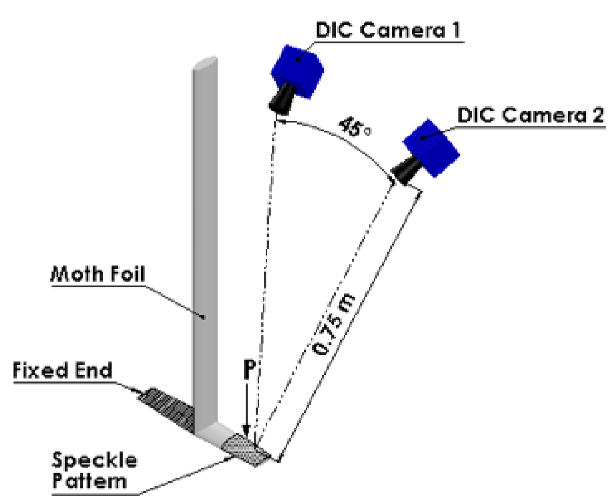
Background & Motivation

- Develop a validated design methodology for flexible composite structures to improve the performance range of foil sections

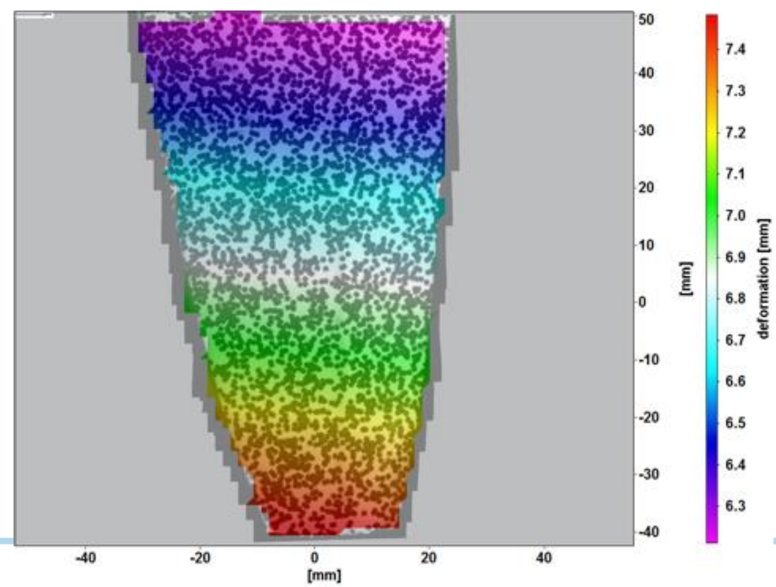


Measuring stiffness and shape

- Use of Digital Image Correlation (DIC) cameras in stereo configuration to capture out-of-plane deformation of specimen
- Apply known static load representative of sailing condition at estimated centre of pressure
- Estimate deflection and twist of the foil in laboratory environment under static load
- Apply load at different positions along the chord to assess torsional stiffness
- For **quasi-isotropic** foils: effective angle of attack reduced by 0.23 deg + deflection of horizontal tips → 5% decrease in generated lift force [1]



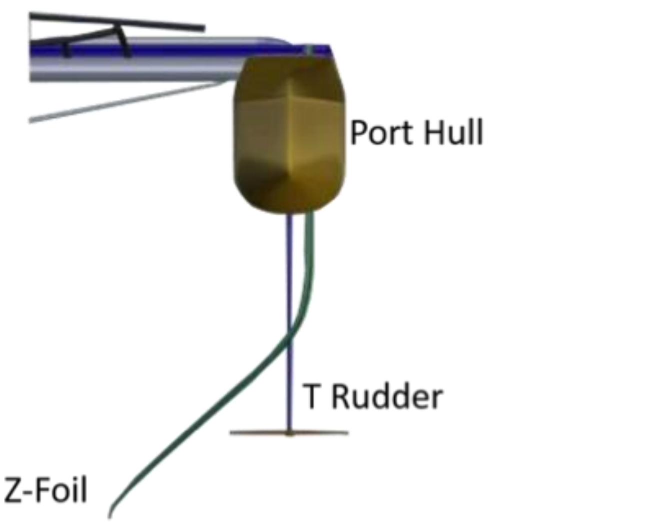
Digital Image Correlation setup in laboratory environment



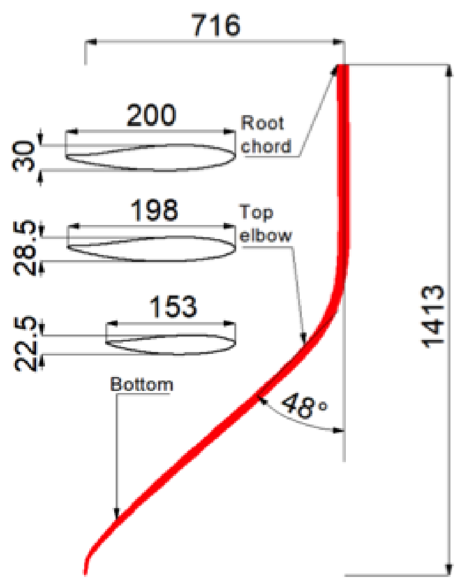
Example of the DIC deformation field for 177.82 N applied 14mm behind the leading edge

One-design?

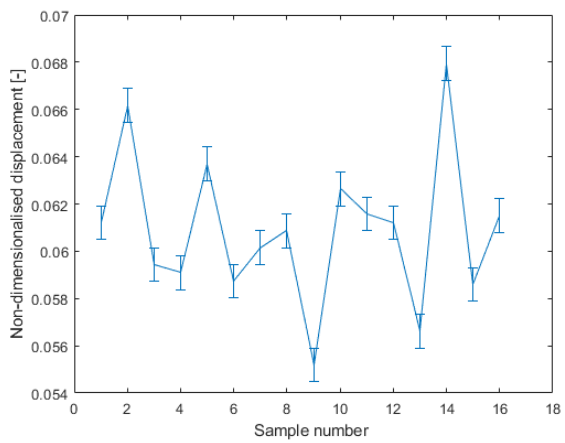
- The NACRA17 uses a passive system Z-foil that needs to be immersed at all times – 4 lifting points.
- Rake is adjusted constantly by crews using the provided rake controls
- Pitch moment is also adjusted by crews that move longitudinally across the boat to maintain a constant ride height and trim.
- Heeling moment is kept constant by leeward T-rudder and Z-daggerboard, by crew weight and adjusting sails – Gennaker and Mainsail.



Configuration of the NACRA17 T-rudder and Z-daggerboard (Foiling week, 2018)

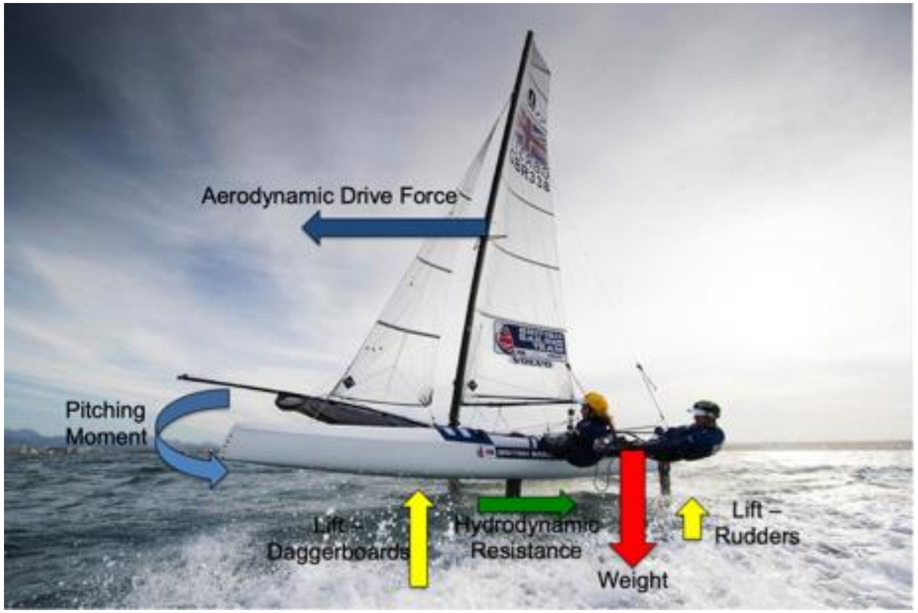


Dimensions and sections of the underwater part of the NACRA17 daggerboard – 3D scanned

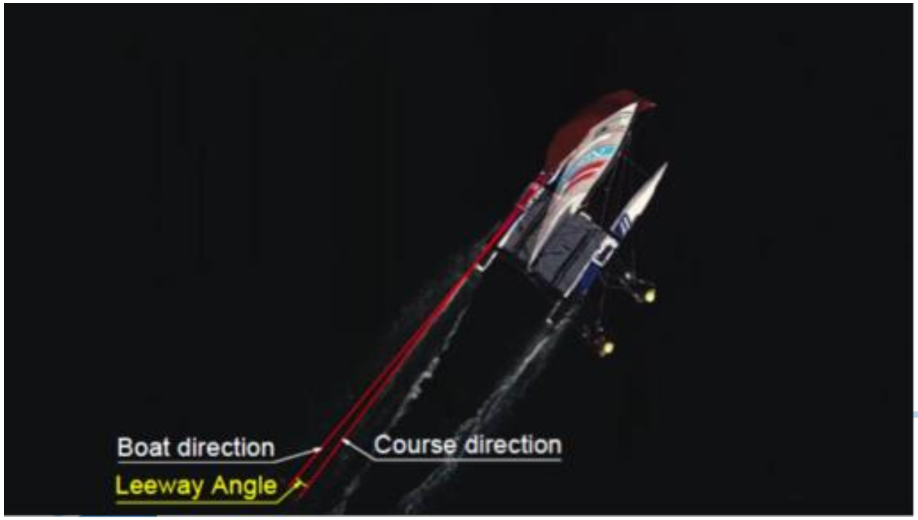


Non-dimensionalised displacement resulting from structural testing.

Balance of forces

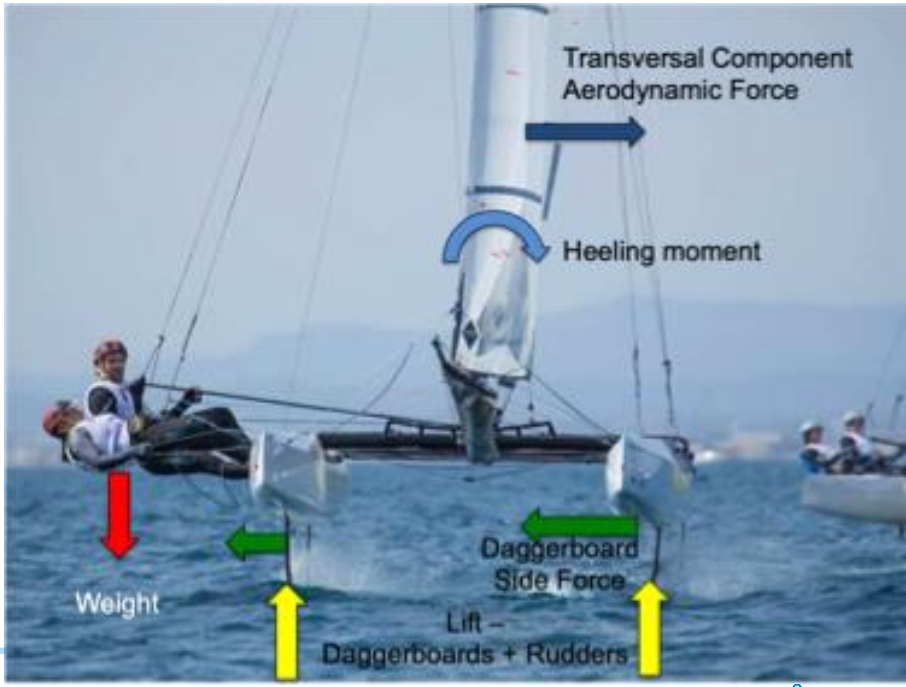


Longitudinal balance of forces



Leeway angle!!!

Transverse balance of forces

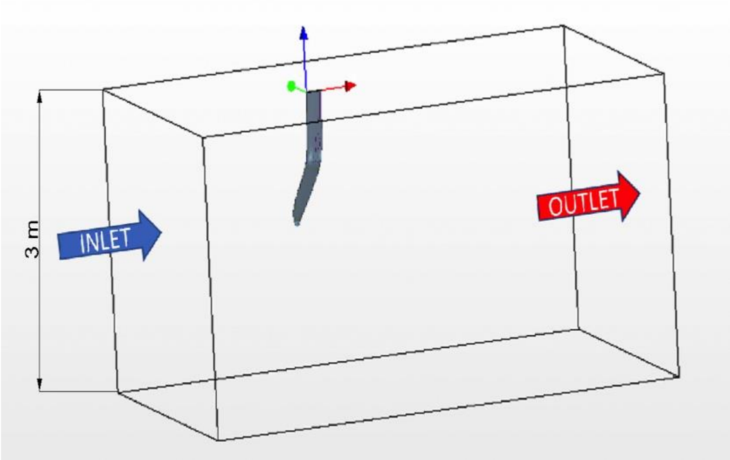


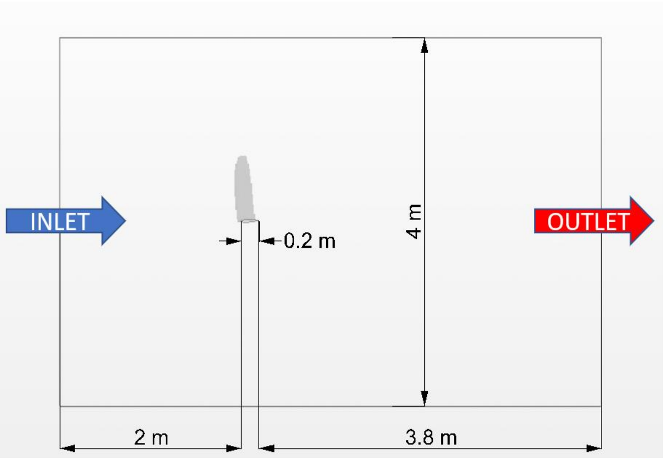
Foiling problems: Ventilation

- Ventilation occurs near free-surface
  - Thick cambered section (as the NACRA 17 one) is prone to generating spray when piercing free surface, leading air ventilation to be initiated in suction side.

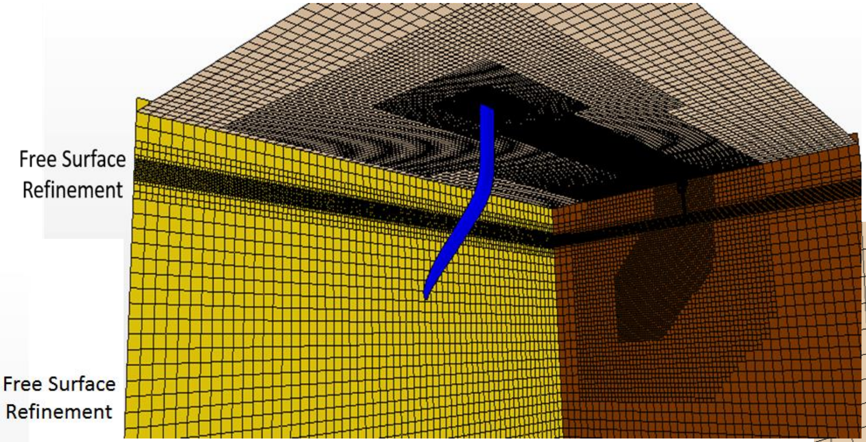
- Reynolds number dependent on water temperature
  - If speed and profile don’t change, but temperature changes, kinematic viscosity value changes and therefore flow regime changes – at low temperature like in Sweden the kinematic viscosity is larger therefore the Reynolds number is smaller

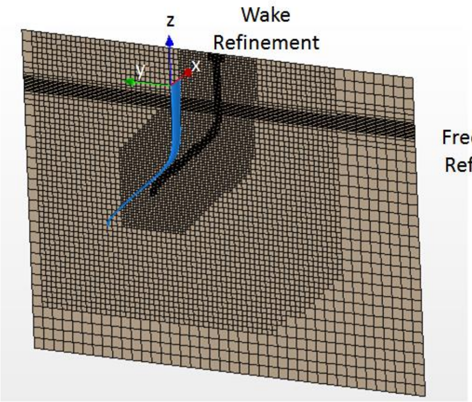
CFD computations

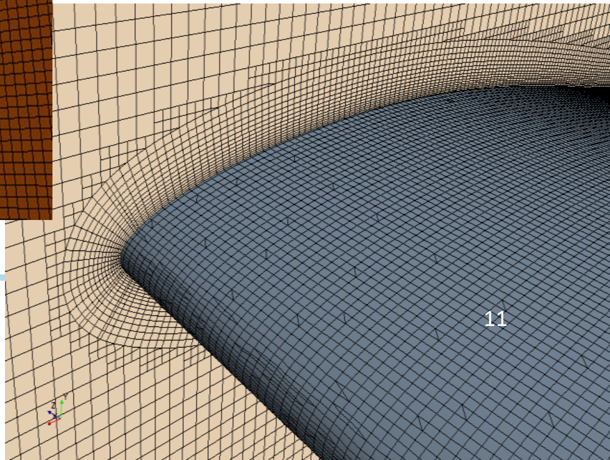




Computational Fluid Dynamics domain







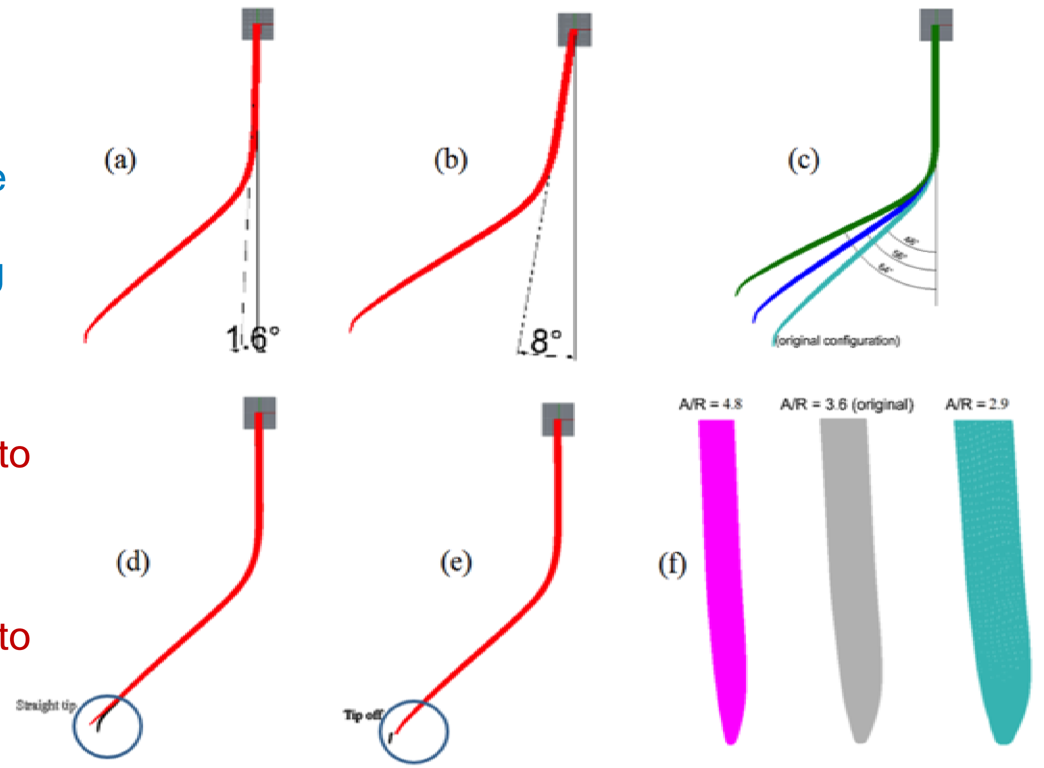
Mesh in domain and around foil

CFD simulations and Results from MSc student

Foil configuration has a large impact on performance…

Maintain the possibility of inserting the daggerboard from above the hull:

- Cant-in 1.6° : change of the foil inclination towards the inner side of the boat (a)
- Heeling 8° : example of a boat heeling condition (b)
- Elbow 56° : angle comprised between the z axis direction and the diagonal section of the foil increased from 48° to 56° (c)
- Elbow 64° : angle comprised between the z axis direction and the diagonal section of the foil increased from 48° to 64° (c)
- Straight tip: foil tip straightened (d)
- No tip: foil tip cut off (e)
- Aspect Ratio 2.9: span to chord length ratio decreased from 3.6 to 2.9 (f)
- Aspect ratio 4.8: span to chord length ratio increased from 3.6 to 4.8 (f)

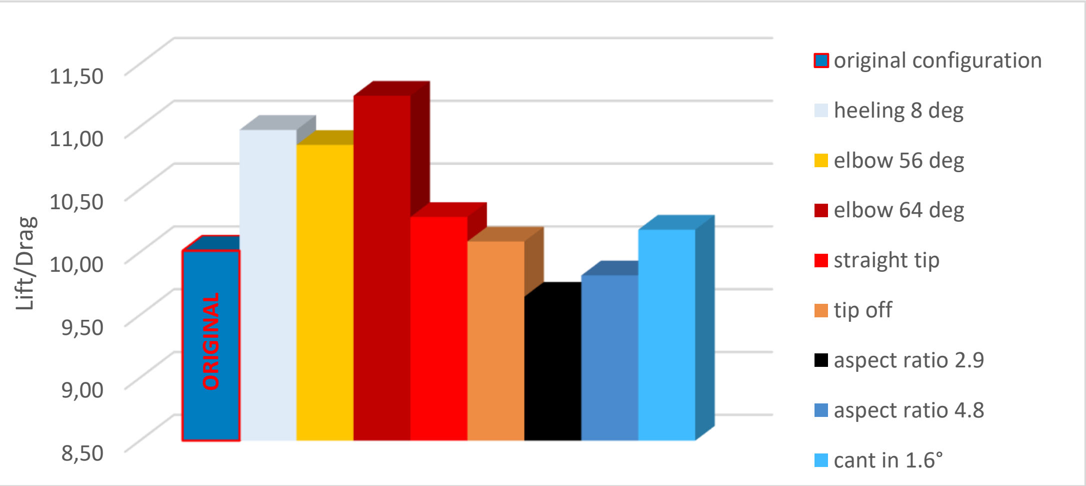


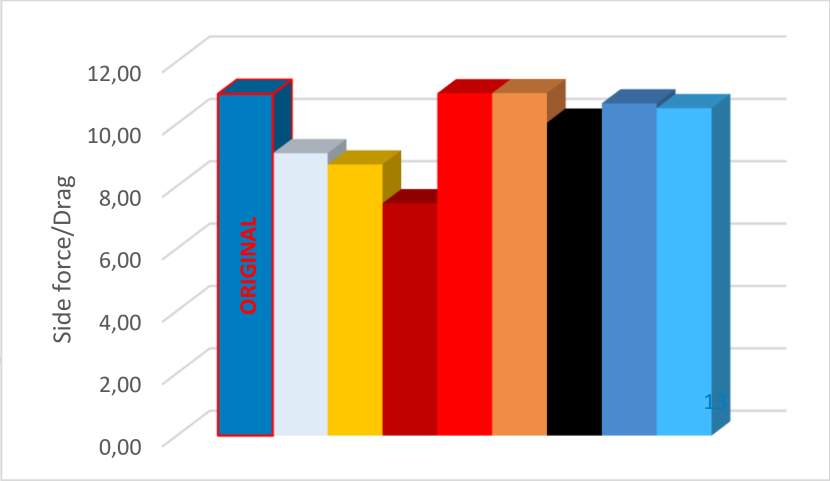
Different foil configurations to assess differences in performances from the design standard

A change in foil

Leeward NACRA 17 Z-foil with a rake of 3; boat speed of 10 m/s and ride height of 0.5m above the free surface

- Elbow 64º: highest lift to drag and lowest side force to drag ratios. This configuration is ideal to sail the boat foiling downwind where boat would lift in lighter wind and would not need to counteract so much the side force to sail closer to target mark.
- AR 2.9: lowest Lift to Drag ratio. Low on Side Force to Drag ratio too. Cambered section shape of the foil affects the results as always increases the drag value.
- "Straight tip" and the "Tip off" configurations provide slightly better performances than the original configuration. Think more about simplifying construction and investigate shape optimisation in that area.
- "Cant-in" and "Heeled" configurations achieve similar results, with an increase in Lift to Drag ratio (+ 1.66 cant-in; + 9.61 heeling) and a decrease in Side Force to Drag ratio (- 4.21 cant-in; - 17.4 heeling). Downwind mode.

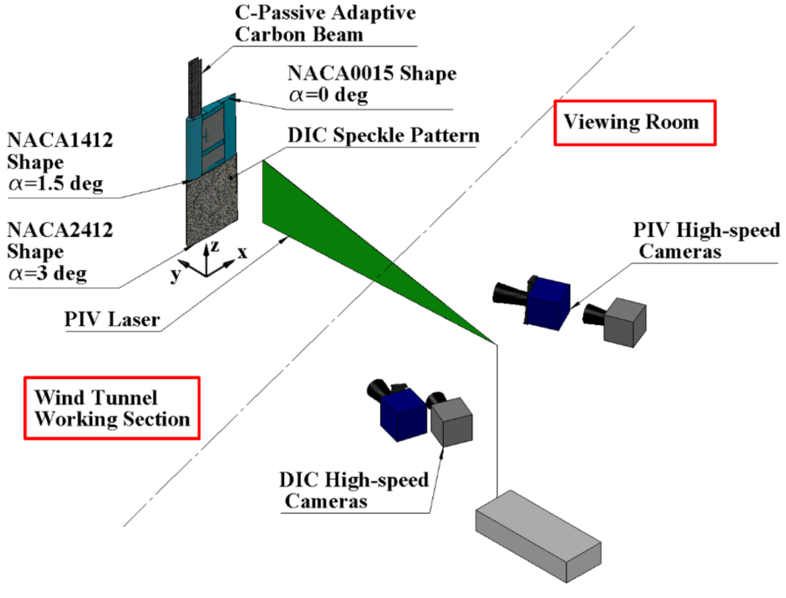




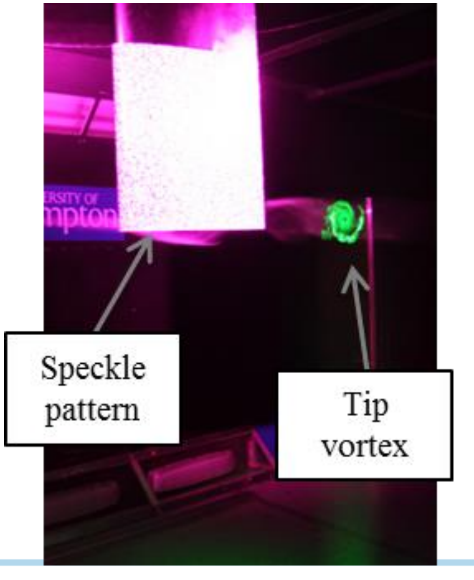
Lift to Drag and Side Force to Drag ratios for the different design cases

The Experimental Methodology

- To measure the **structural deformation** of the foil with Digital Image Correlation
- To measure the **forces and moments** acting on the foil with balance
- To measure the **position and structure of tip vortex** with Particle Image Velocimetry



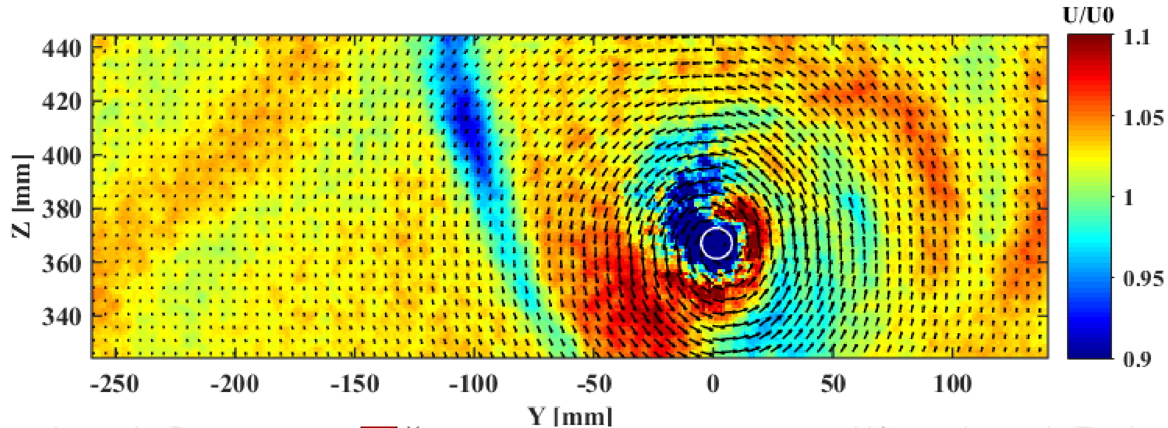
University of Southampton R. J. Mitchell Wind Tunnel Working Section

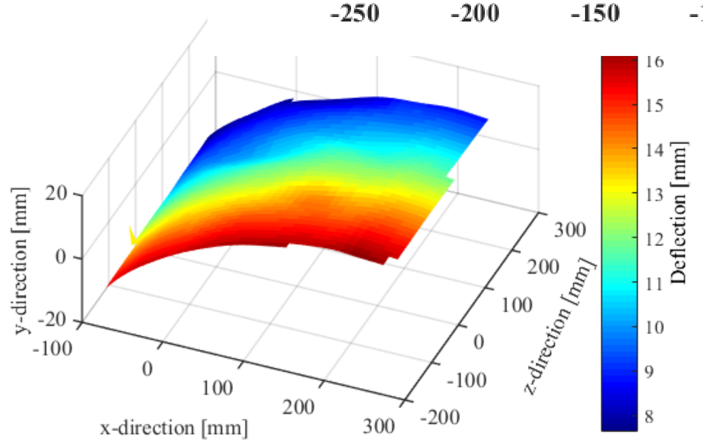


Experimental Model

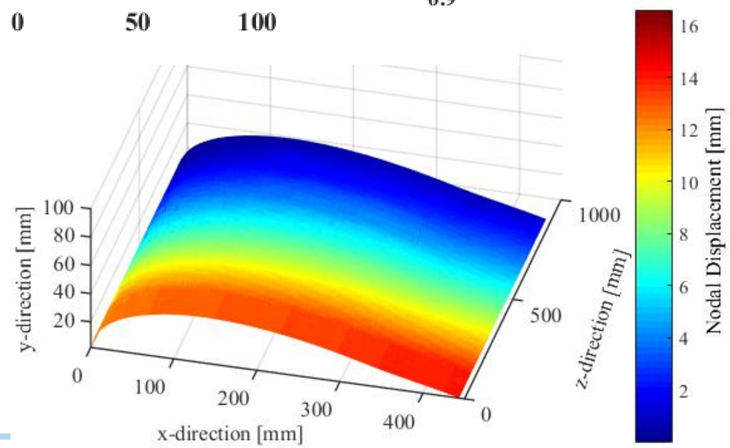
Full-Field Measuring Techniques

- DIC and PIV are capable of recording the data necessary to describe the surface's structural behaviour and the flow surrounding an object without modifying the nature of the structure or the flow itself





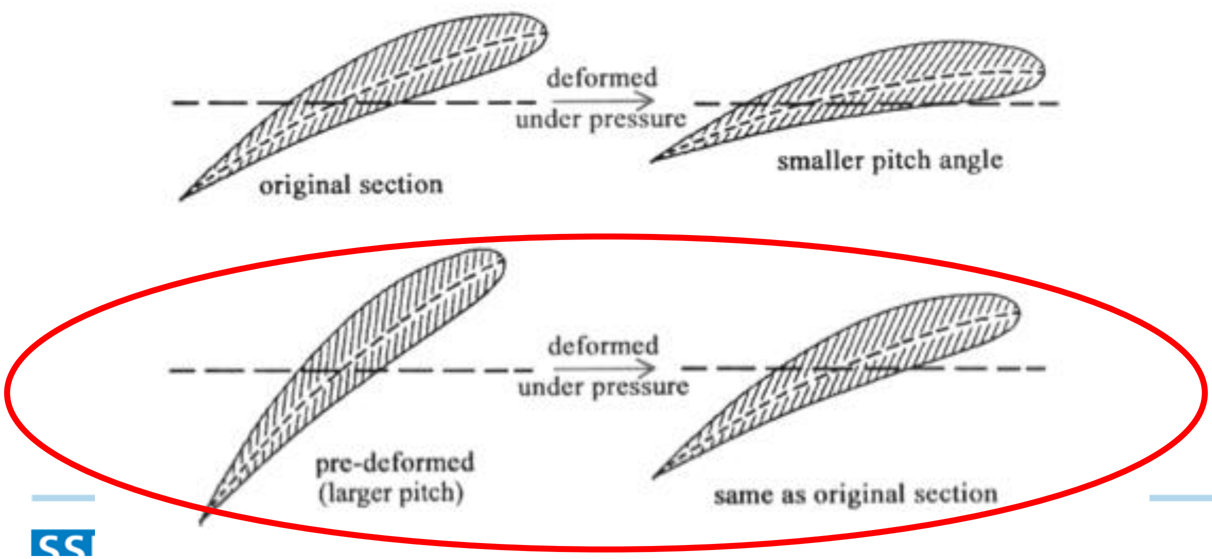
Experimental aerofoil: aerofoil shape/deflection measured with DIC. DIC coordinate system



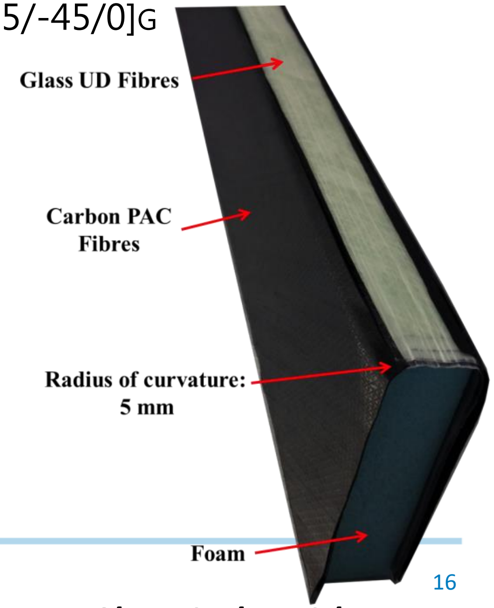
Numerical aerofoil: aerofoil deflection measured with FEA. Aerofoil coordinate system.

The Concept: Passive Adaptive Composites

- Composite aerofoil structures
  - High stiffness to weight ratio & better fatigue resistance
- Design components with elastic couplings to enhance the performance of the whole structure
  - Aircraft wings, wind and tidal turbines, propeller and helicopter blades and **High-performance sailing boats**
  - C-Beam made of pre-preg UD quasi-isotropic E-Glass plies and PAC carbon plies : in top and bottom faces $\phi=[0/45/-45/0]_G+[30/30]_C$ in transverse web $\phi=[0/45/-45/0]_G$



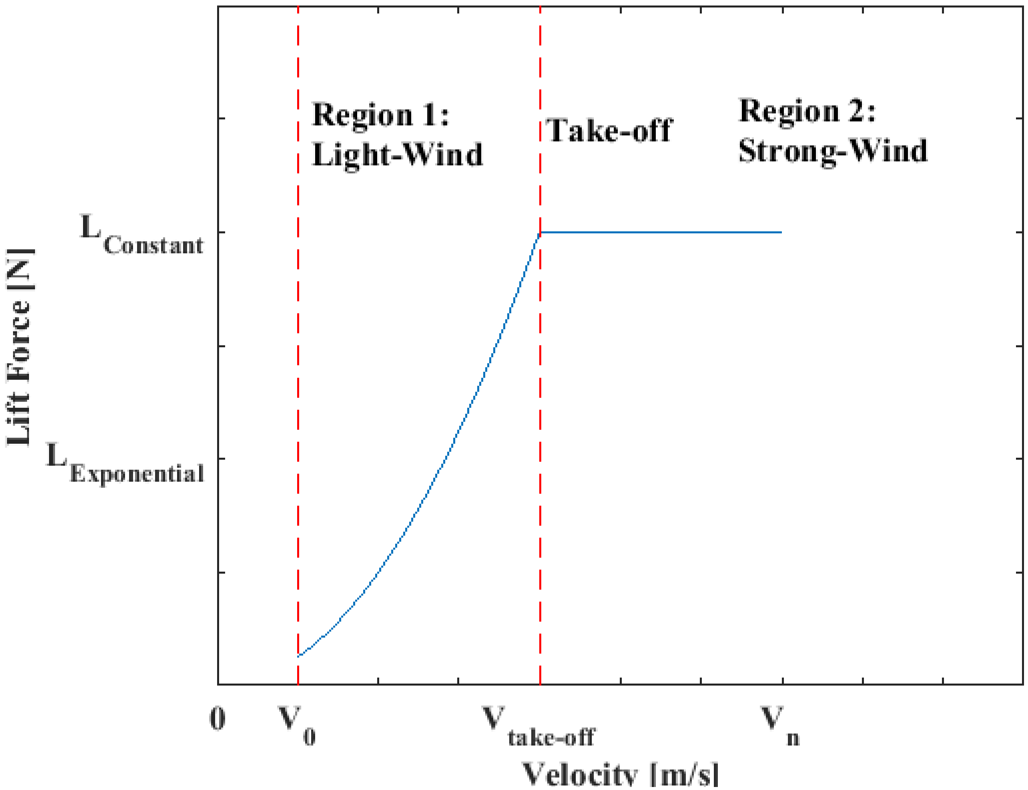
Quasi-isotropic (top) and PAC aerofoil (bottom) under increased pressure load



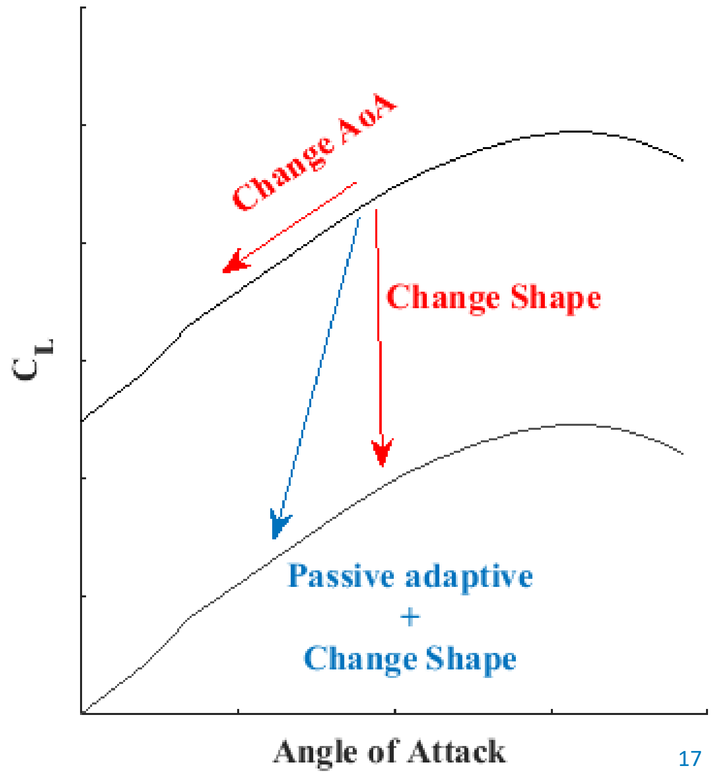
Glass-Carbon C-beam

The Design Development

- Bend-twist coupling deriving from the oriented plies in the laminate gives the possibility to achieve tailored designs for an expected load, inducing a twist on an aerofoil-shaped section
- Reduction in induced drag (reduction in effective angle of attack) and reduction in skin friction (constant change in shape)

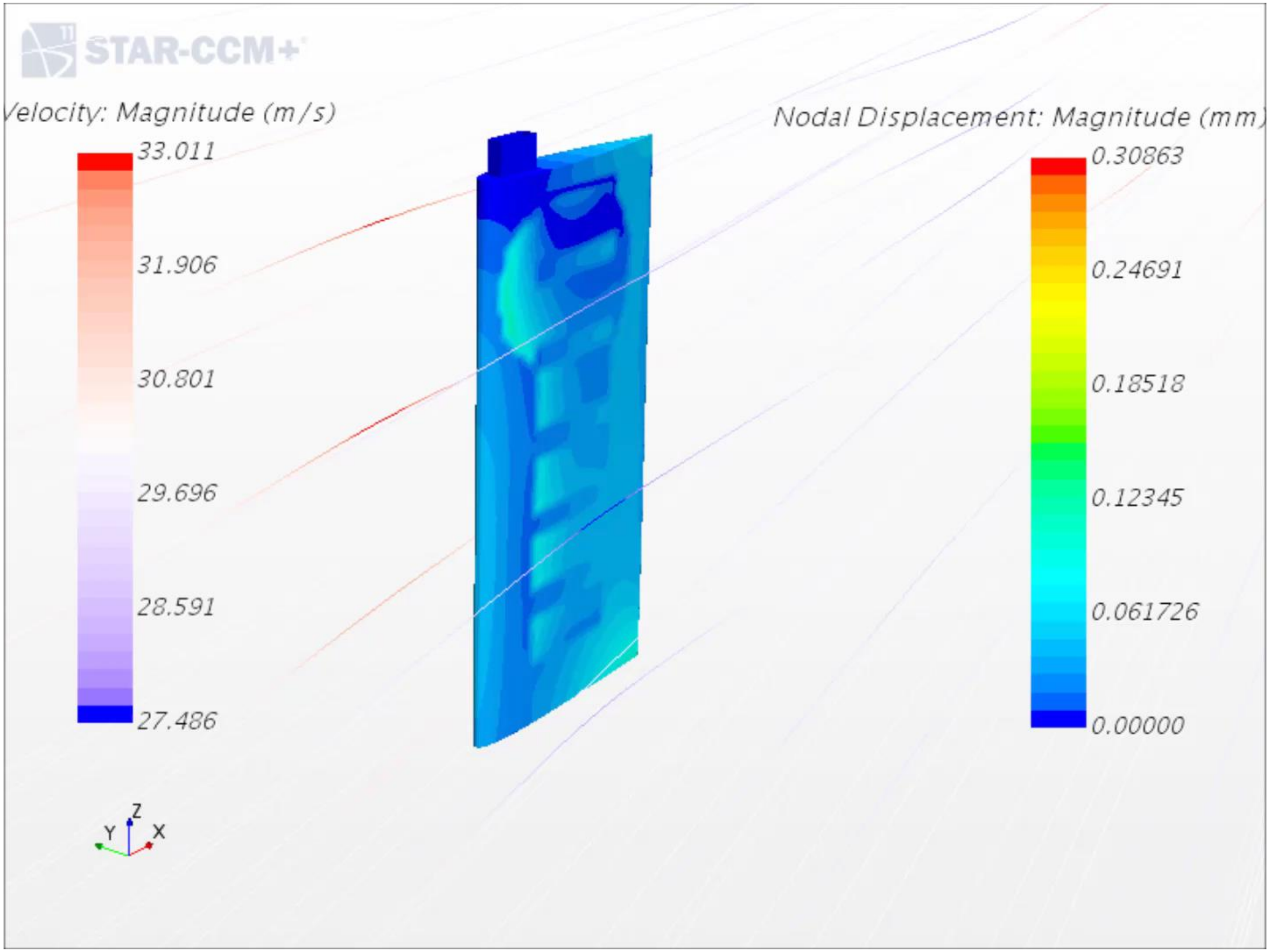


Ideal lift over velocity profile for an hydrofoil section



Lift coefficient curves for cambered and symmetric sections

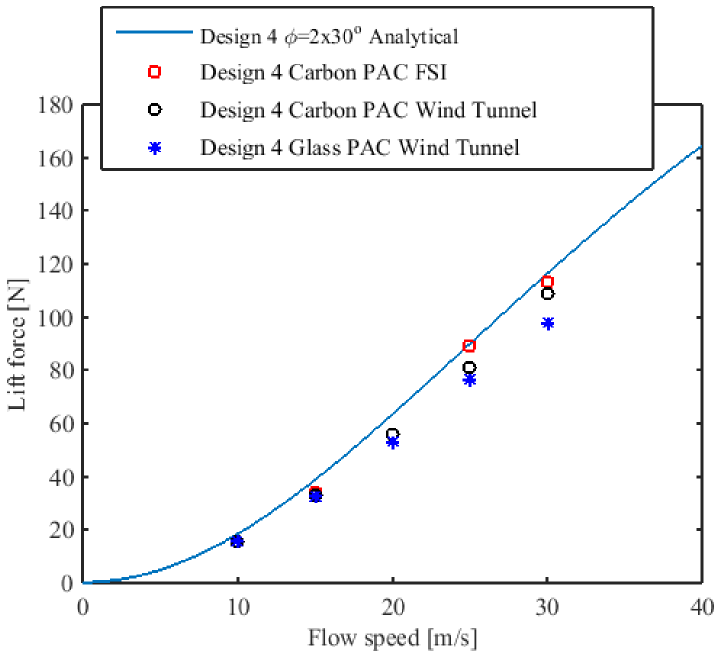
The Fluid Structure Interaction Numerical Method



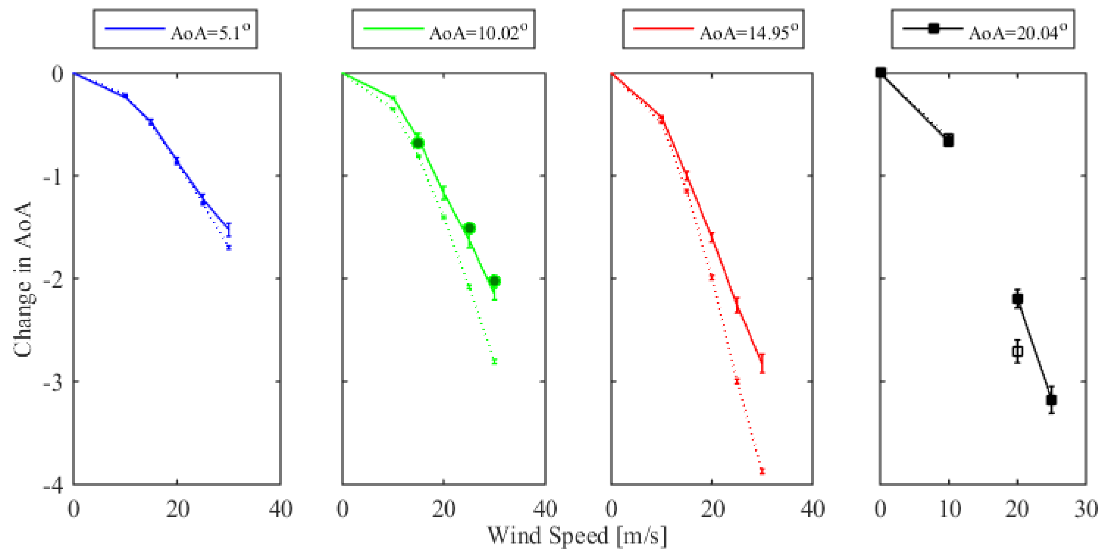
Full Fluid-Structure-Interaction simulation from CFD

Numerical & Wind Tunnel Results 1/2

- Both the numerical and wind tunnel measures show that is possible to design a structure tailored to a design goal controlling the level of bend-twist coupling: proportionality of $L \propto V^2$ reduced to $L \propto V^{1.65}$
- Quasi-isotropic glass-fibres with PAC carbon plies have a lower strength and torsional rigidity compared to the carbon-only beam, therefore the response presents higher deflections and twist values that helps to reduce the lift coefficient for a given wind speed and angle of attack



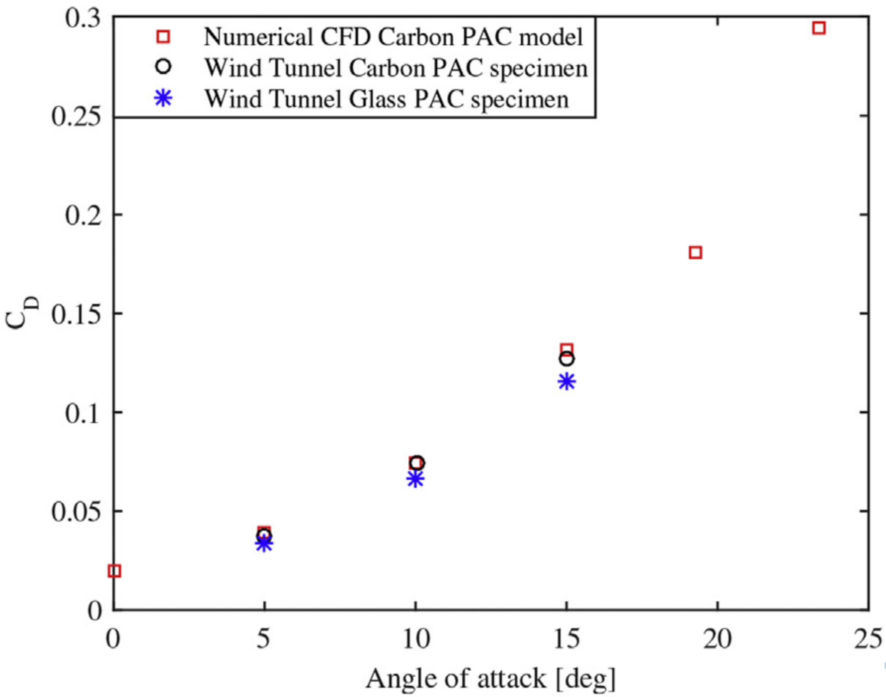
Lift force over wind speed for AoA=10deg



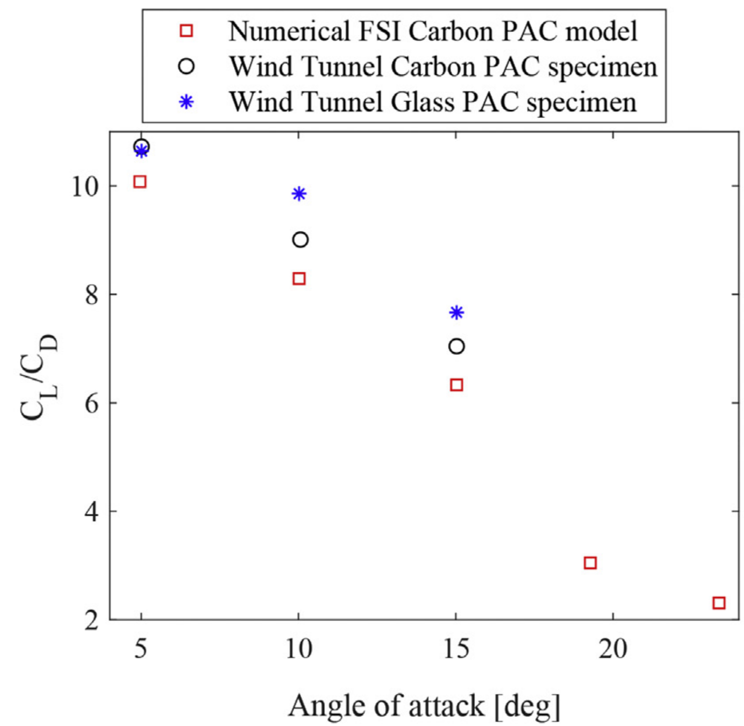
Change in angle of attack for a range of wind speeds and angles of attack

Numerical & Wind Tunnel Results 2/2

- The foil with the internal Carbon-Glass spar has a **lower drag coefficient** due to the change in angle of attack that results in a **decrease in induced drag**.
- The foil with the internal Carbon-Glass spar presents a higher CL/CD meaning that the **reduction in induced drag has more impact than the reduction in lift due to deflection**. This leads to a reduction of ≈ 13% on the drag and an increase in CL/CD ratio.



Drag coefficient over angle of attack



C_L/C_D over angle of attack

Conclusions…

- ✓ We need to properly assess bend-torsion properties and shape of built foils to be able to sail with consistent appendages

- ✓ The possibility of tailoring a design to a certain load is extremely important in foil design sections, especially when investigating high-performance foiling catamarans

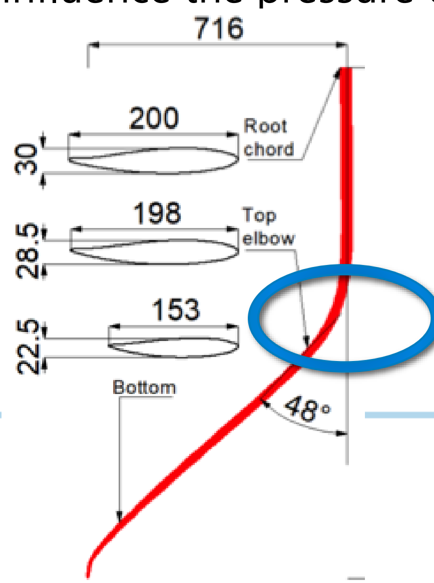
- ✓ A **new experimental technique** was developed and used to describe the structural response as well as the fluid behaviour and the aerodynamic response of a flexible PAC foil simultaneously under wind load
  - ✓ **This can be used in static or dynamic conditions to assess foils for foiling boats**

- ✓ A **numerical FSI methodology** was **validated** against the wind tunnel measures and the numerical set-up was used as a **design tool** to improve the performances of a foil section
- ✓ Having developed the new design it was proved that it is possible to substantially **decrease the lift coefficient value with increased wind speed**
  - ✓ This can be used in the development of new foils for high performance boats

… Ideas for future works: How can PAC be used?

- Developing an experimental set-up able to measure the structural deformation and flow features in a towing tank
  - Describing the structural response in water allows stiffer structures to be tested (as in water the forces experienced by the specimen will be five times larger than in air). This methodology would be suitable to test in a towing tank real-hydrofoil structures
- To manufacture and test a passive-adaptive internal structure of a foil that **changes its shape** (with multi-element foils or flaps) to **achieve a constant lift force with increased speed (renewable energy)-** Possibility of using a passive adaptive layup in elbow region (L or Z foils) to influence the pressure distribution and avoid ventilation?

Change pitch at difference advance speed!



Change in layup to PAC to reduce drag and "increase" pressure near free-surface to avoid ventilation

THE END
Any Questions?

Special thanks:

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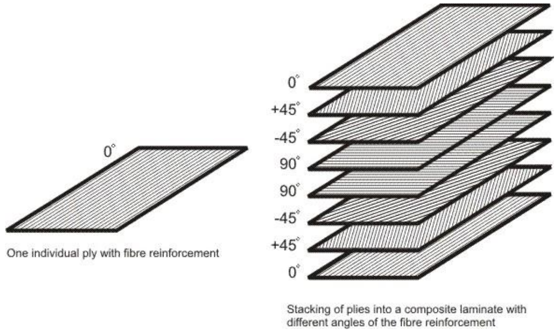
LAVISION We count on Photons

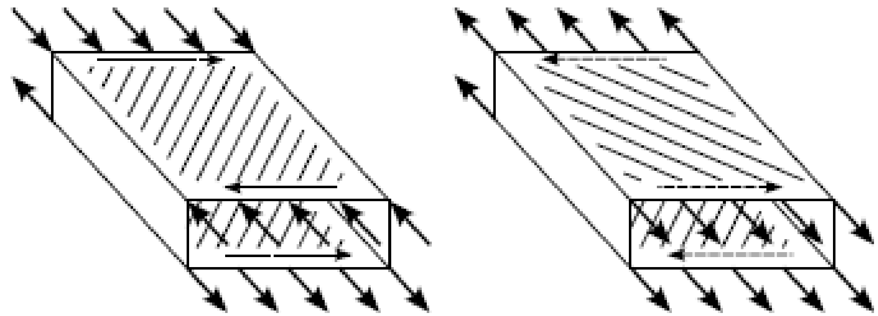
What happens in composite materials

1. Composite materials present a very high to stiffness ratio

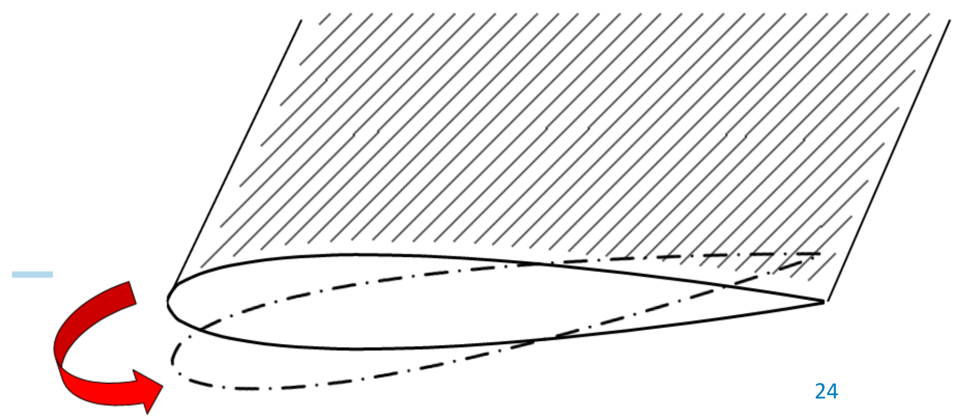
2. It is possible to use composites to improve performances of structures changing the plies orientation: from a microscopic level the effects are seen in the macroscopic level.

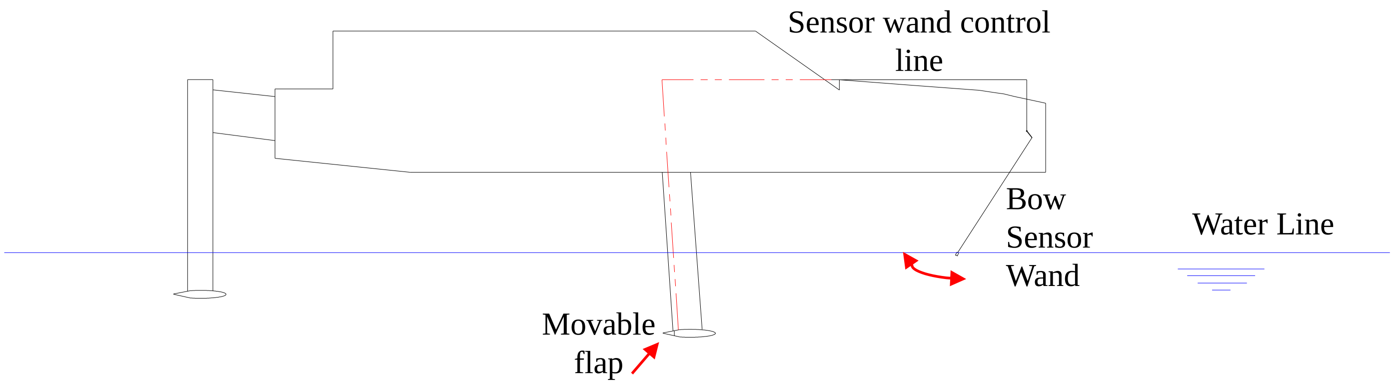


$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \\ k_x \\ k_y \\ k_{xy} \end{bmatrix}$$



Nx, Ny, Nxy forces of the fluid,
Mx, My, Mxy moments of the fluid,
εx, εy, εxy inner strain in material
kx, ky, kxy laminate curvature
A, B & D laminate properties and depend on the fibres orientation





Sensor wand control line
Bow Sensor Wand
Water Line
Movable flap