STRUCTURAL AND FLUID DESIGN EXPLORATION TO ENHANCE THE PERFORMANCE OF A FINN MAST FOR THE OLYMPICS GAMES

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Abstract. FINN is a dinghy boat used for the Olympics Games. Unlike most of the series involved in Olympics, which are one-design boats, the FINN offers class rules system which allow to propose design enhancements to target specific requirements from sailors. Structural design has been performed using the **3D**EXPERIENCE Platform by Dassault-Systèmes. Trade-off between structural design (composites) and fluid performance (external shape) have been performed over 10000 virtual models and imagine seven different masts to be manufactured by Heol Composites. Each manufactured mast was used for training and competition by the sailors of French National Federation in various conditions, in different sailing areas (France, Italy, Greece, Spain, ...). Advanced tests have been performed on one particular mast to mesure the strains and mast deformation from optical fibre measurements in collaboration with Pixel-Sur-Mer. Those experiments were then used to develop and validate accurate simulation with the mast, boom and sail all modeled in a single Fluid-structural simulation. All this engineering work has been performed from 2018 to 2021. This project leaded to enhancement the performance of sailors in various conditions and helped them to get a better understanding on the way the combination mast and sail were contributing to the performance, especially in transition as tacking, gybing.

1 INTRODUCTION

Racing yachts have been a pioneer in composites design for various reasons mainly related to their high stiffness and strength but also this ability to build complex shaped structures. Structural design was then massively required to ensure reliability of structures for offshore racing (Vendée Globe, former Volvo Ocean Race) or inshore racing (America's Cup, TP52, TF35, ...). Such structures were mainly driven according stiffness, strength and stability criteria. As sailing remains a mechanical sport, over the last two years, a project has been performed by **Dassault Systèmes** (engineering), the **Fédération Française de Voile** - FFV (Customer), **HEOL Composites** (Builder), **Ecole Nationale de Voile et Sport nautique** - ENVSN (Performance) and **WB Sails** (Sailmaker) to design and manufacture a new composites mast to improve the global performance of FINN boat (See Fig. 1), a dinghy olympic boat used for next Olympics (Tokyo 2020 delayed to 2021). Some previous studies and developments were conducted by various national federations and Olympics sailors with no specific success or result [Fin(2017)]. Most of the sailors are using an equivalent mast provided by the same supplier in Switzerland (More than 100 mast per year), demonstrating the complexity to propose major innovation on such structures without a large experimental campaign.

Figure 1: Finn boat along tests of mast n°4 in La Rochelle.

Actually, the mast is dropped on the keel and guided by the deck with the ability to rotate around the axis of the mast. Therefore the mast is a cantilever beam with double fixed point. The deformation of the mast is only due to sail (hoisted along the mast) which can be tune (using sheet) according to external pressure (wind) applied on the surface. Therefore, there are no capabilities to control the deformation of mast in various conditions (using standing rigging). The mast must be designed in agreement with real sail pressure applied on the mast for the various sailing conditions. To improve FINN mast, it has been highlighted the need to enhance the dynamic response. In fact, the better the dynamic, the lower sailor will consume energy and will be able to have better decisions the race. Moreover, as requested from sailors, a specific stiffness target for the mast need to be reached. According to the manufacturing process and variability of the material, the ability to reach the target is already a challenging work requesting advance tools to share precisely the design definition to the mast builder.

All those objectives have been taken into account to conduct a large study described below. First, the development of the design process to be able te optimized the various parameters (shape, composites layups) according to constraints (manufacturing, plies shape, ...) is presented. Several masts have been manufactured and were tested with Olympic sailors. Analysis has been performed for each based on the feedbacks of sailors and were taken into account to drive the design of the next mast. Second, experiments performed on the masts are detailed, including some experiments using optical fibre on mast while sailing. Third, mast deformation from experiments are compared to advanced fluid-structural simulations.

2 MAST DESIGN AND OPTIMIZATION

The composites mast is a hollow tube layup with composites plies. To reach the targeted stiffness, right balance between external (drag) and material (weight of mast) must be found. Using the **3D**EXPERIENCE, the following process is implemented (See Fig. 2) :

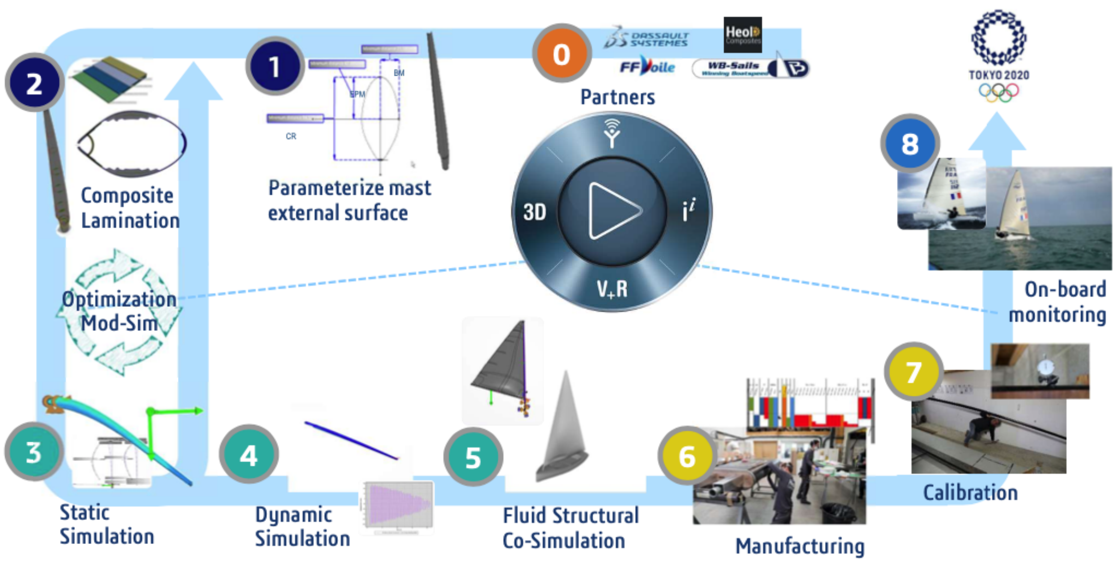

Figure 2: Workflow for the development of FINN mast: Partners are working in collaboration on **3D**EXPERIENCE Platform (0), Parametric definition of the mast's shape is proposed for several sections along the shape (1), Parametric surface is discretized to define composites layups over the shape (2), Loads cases to qualify the the structure are defined (3), optimization is performed between steps 2 and 3, Dynamic simulation from optimized model (4), Fluid-structure simulation using designed mast, sail and boom (5), Manufacturing of the mast (6), Static and dynamic validation at ENSVN (7), comparative sailing tests (8).

2.1 Conceptual parametric model

Mast shape is defined with 8 sections over the height of mast. Each section is defined with 3 parameters : Length of profile, Width of profile, Position of the max width. The aft part of the profile is setup in a different way as the sail track is part of the mast profile. Composites layup is defined inside. Global lamination is define with a minimum thickness to ensure stability of the skin. Some reinforcements are introduced at the maximum distance from neutral axis for maximum contribution to the stiffness or the structure (See Fig. 3).

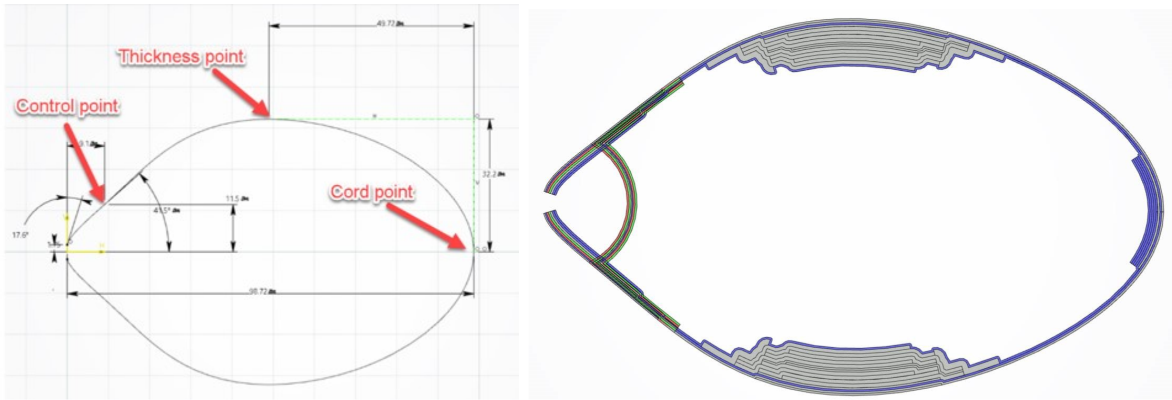

Figure 3: Parametric definition of mast shape (left) and composite layup definition per section (right).

Global laminate over the whole is set as a stacking sequence sequence with the proportions of plies per direction fixed. Only the thickness laminate is set as a parameter for the exploration. The local reinforcements are layers at 0°and and the number of plies per section is the parameters.

There are 24 parameters for the shape control (8 sections x 3 parameters). For the composites definition, there are 2 parameters (number of plies at 0°) per section and the thickness of the global lamination.

Material properties have been computed both using physical tests using flexural tests [Méchin(2017), Mechin et al.(2018)Mechin, Keryvin, Grandidier and Glehen, Keryvin et al.(2020)Keryvin, Marchandise, Mechin

2.2 Load-cases abstraction for design process

Tests of mast has been normalized with the definition of two static load-cases to validate the global stiffness of the mast along lateral and longitudinal bending (See Fig. 4.

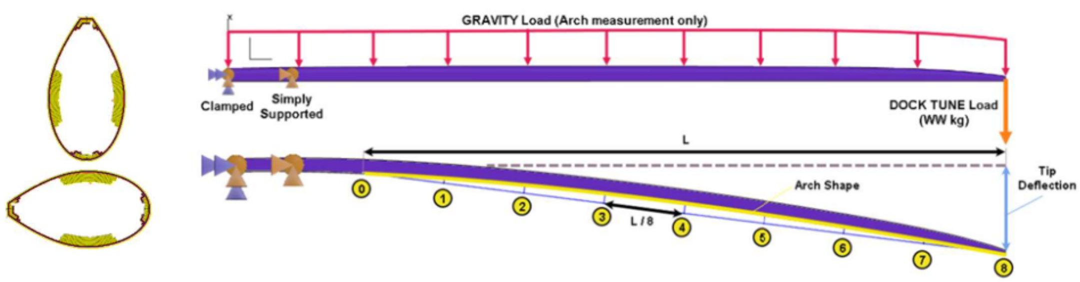

Figure 4: Static load-cases defined for the stiffness validation of the mast.

The stiffness must be carefully considered at the bottom part of the mast as the dynamic response of the tube would be massively affected by that. Forces applied for each load case (WW kg - the value is confidential) have been defined in agreement with standard sailing conditions at 10 knots.

2.3 Trade-off and optimization

Using the parametric model previously defined two separated trade-off are performed. The first one is performed using iSight to link CATIA and XFlow (all Dassault Systèmes products). CATIA is controlling the parameters of the shape according to the set chosen. XFlow is running fluid analysis to measure the drag of the mast (See Fig. 5). Deformation of the mast is fixed to match the shape of the sail. This deformation remains constant whatever the external shape of the mast as there is a specific stiffness to target. Various profiles were compared from the reference shape (the one define from previous FINN mast campaign, 2013-2016) using the 24 parameters defined previously for the shape.

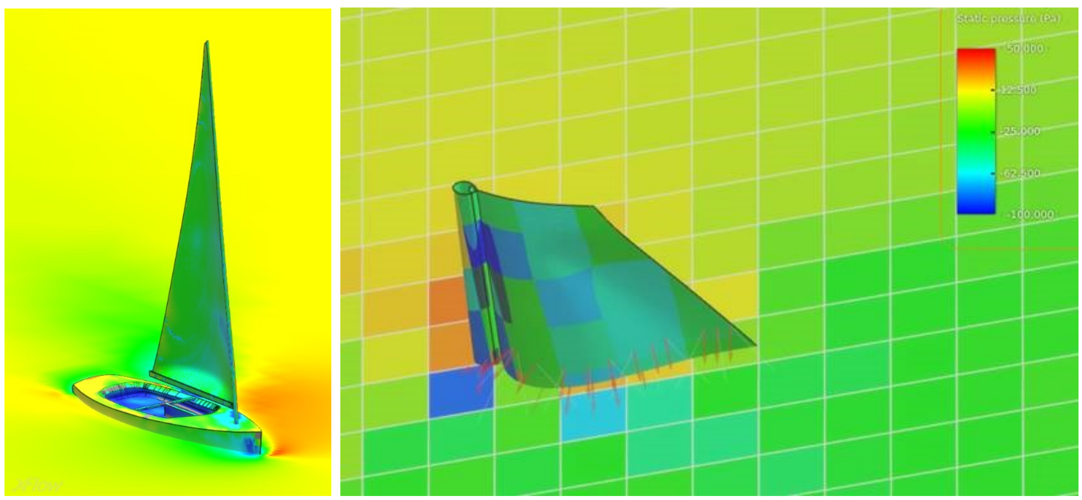

Figure 5: Fluid simulation result are shown for velocity around the mast and sails. Various mast shape are considered and the performance is compared through a parameter mixing drag and contributing force for the speed of the boat.

It was demonstrated slight difference regarding the profile on the performance of the boat. But according to the global improvement expected, it was decided to not continue using the existing mould which offer a significant range of solution from a structural point of view.

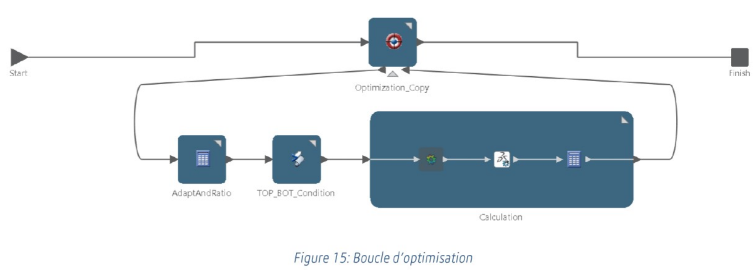

Figure 6: Process Composer App offers the ability to optimized physic simulation using the various inputs of the plies (thickness of global laminate & number of plies at 0°per section).

The second one study is performed using Process Composer App (**3D**EXPERIENCE). Using the 17 parameters previously listed (2 per number of ply pre section + thickness of global laminate), a design of experiments (DOE) is proposed to trade-off of composites configuration (See Fig. 6). Some constraints are added to this DOE definition to ensure a minimum thickness on the whole structure, or a maximum number of consecutive plies at 0°without off-axis plies. The optimisation's constraints have been suggested in various papers [Irisarri et al.(2013)Irisarri, Lasseigne, Leroy and Le]. All the results matching requirements were then considered in details according to stability computation and strength analysis. Such DOE was performed several times changing baseline of composites lamination and materials involved. Such explorations were used for all the masts manufactured.

2.4 Design criteria validation

Displacements are targeting sailors expectations. Actually, the composites layup extracted from most of the optimisations leaded to a large number of plies at the bottom of the mast which are highly driving the final displacement observed on the mast (See Fig. 7 - left). Therefore, those plies should be carefully layup to avoid some difference between virtual model and physical tests.

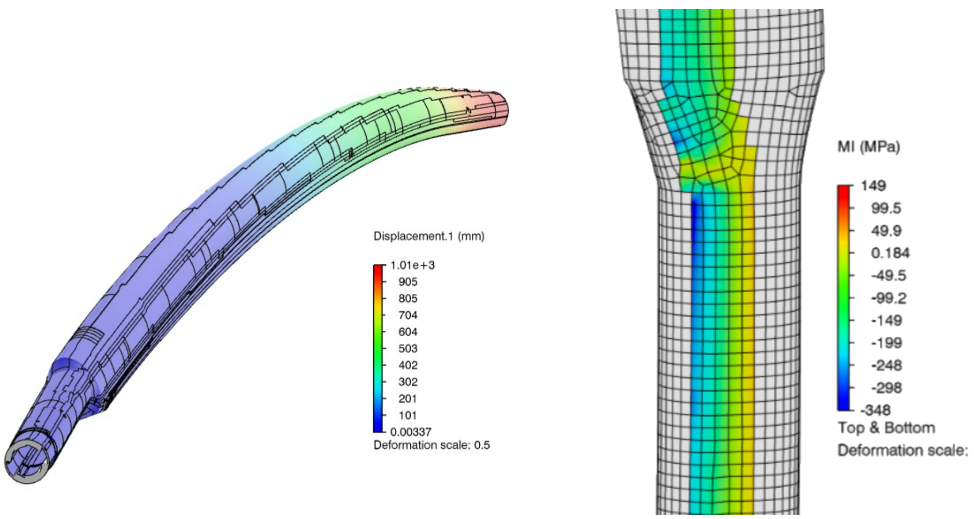

Figure 7: Results for mast design are given : Displacements given for a sailing case with the mapping of thickness distribution (left), Stress concentration at the deck point under compression (right).

From a stress point of view, stresses concentration are observed at the level of the deck (See Fig. 7 - right). Those stresses concentration are due to the double bending longitudinal and lateral. As the compressive strength properties for considered plies is higher than 1200 MPa, the margin of safety for the static sailing case is in agreement with the expectations. According to the geometry of the mast section considered and the lamination, the margin of safety for local buckling is sufficient to avoid any instability.

3 EXPERIMENTS AND MONITORING ON WATER

In the previous section, a way to build the parametric model for the composites was proposed with the ability to trade-off on parameters. This model was used to design 7 mast which have been manufactured from May 2018 to February 2021. Each mast was qualified using a testing protocol set by the ENVSN (static and dynamic protocol).

On mast n°4, the opportunity came to monitor the mast with optical fiber along the height of the mast. Optical fibers were dropped on the mast on each side (Portside & Starboard) and on the fore face of the mast. Each optical fibre has 4 sensors at specific heights (See Fig. 8).

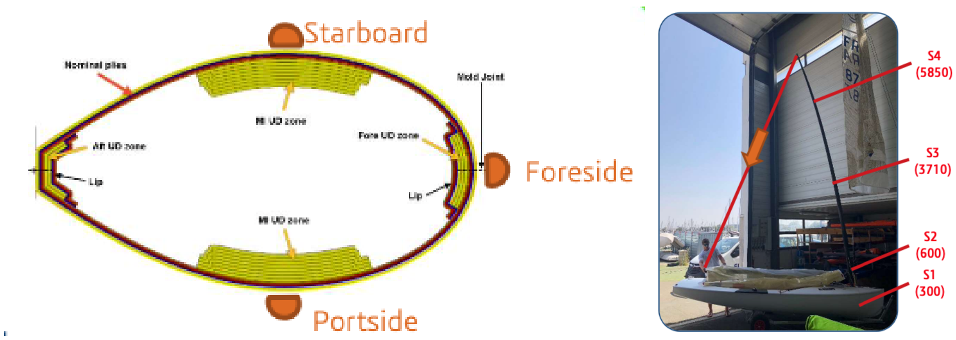

Figure 8: Optical fibres definition mast n°4 : Sensors position on the section (left), Sensors position along the height of the mast (right).

Tests were performed in La Rochelle over the summer 2019. Various wind conditions were observed from 5 to 20 knots with various waves conditions (large waves vs. shoppy conditions). Some brief analysis of the recorded data are proposed below (See Fig. 11):

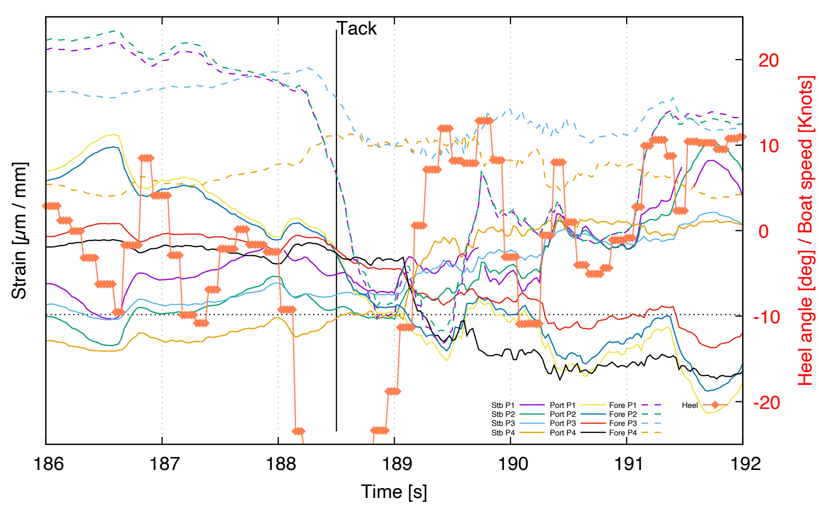

Figure 9: Strain results per sensor along de mast are plot over the upwind configuration. Horizontal dashed black line is the reference value for null strain (Strains values have been hidden for confidential reasons).

Sensors are named from 1 to 4 from the bottom to the top (See Fig. 8). Maximum strains in tension both the lateral and longitudinal is observed on sensor S1 meaning that the maximum bending occur at the bottom (in agreement with beam theory). On compression, the values observed are really low compared to the ones in tension. This is due to the bending of the mast which is a combination of lateral and longitudinal due to sheet tension and boom reaction on the mast. The max compressive value is then located closer fro the aft section of mast.

On the fore face, the strains remain important while sailing upwind. The highest values form the strains are similar for sensors S1, S2 and S3. This is related to the sail in tension along the mast. 60% of the bending of the mast is due to the sheet tension tuning the sail. For this reason, the tension is massively decreasing on sensors S1 and S2 for the fore face while tacking (188.5s). the bottom of the mast is relaxed as the sheet is trimmed. On the other side, as the sail remains tuned (Outhaul, Vang and Cunningham), tension on the mast for sensors S3 and S4 is remaining important.

In the same way, analysis have been performed for downwind conditions (pumping and gybes), repair (720), upwind pumping. Moreover, sensitivities of Vang, Outhaul & Cunningham tension have been done. Three configurations were considered (Reference tension, -10%, +10%). This helped to define better tuning leading to more homogenized strain values along the mast due to tune of the sail.

To be able to validate the loadings conditions in the virtual models, few tests were done at the shed with identified tensions to get the relationship between strain measured and forces introduced (See Fig. 8 - right). The force introduced is not communicated for confidential reasons but was done in agreement with the works from Devaux [Devaux et al.(2003)Devaux, Casari, Choqueuse and Davies, Casari et al.(2004)Casari, Choqueuse, Davies and Devaux]. The difference observed on the top part of the mast were due to: first, the way boundary conditions are introduced at the bottom of the mast, second, the definition of plies at the top of the mast which were not in agreement with manufacturing process. The virtual boundary conditions were constraining too much the bottom leading to higher deformation on the top. Some corrections and enhancements were added to the virtual model to match the experiments.

Table 1: Strains measured for the tests at the shed. Tension is introduced accordingly to Fig. 8. Results are compared to virtual model.

Sensor	Experimental strain (%)	Virtual strain (%)
S1	0.146	0.142
S2	0.150	0.140
S3	0.193	0.185
S4	0.152	0.03

The relationship between strain and introduced forces was used to identify the load cases (forces from the sail and righting moment) occurring while sailing. The identified values were in agreement with previously estimated ones (maximum 5% difference).

4 FLUID-STRUCTURAL SIMULATION

According to experimental work, the virtual mast model was enrich with the design of boom, sail and gooseneck to virtually get the really assembly of the whole FINN performance part (See Fig. 8). The material of the sail is defined according to data provided by the sailmaker. Gooseneck is glued to he mast (merging mesh nodes). Coupling is created between gooseneck and boom axis. Only the rotation around boom fitting axis is allowed.

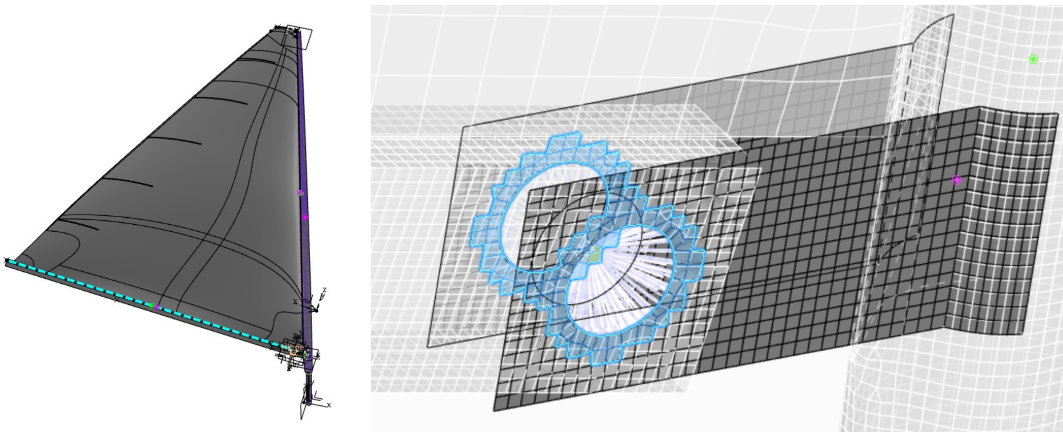

Figure 10: Model of the whole FINN upper deck model: Assembly of mast, boom and sail to perform advanced analysis (left). Details of the gooseneck model with axis for vertical rotation (right).

The preload of the sail must be introduced with the sheet tension on the boom to bend the mast. This simulation is performed with explicit simulation in Abaqus solver. Stability of the simulation is complex and mass scaling is used to stabilize it.

The preload step is used for a restart to run the co-simulation. The co-simulation is a fluid-structure simulation between Abaqus and XFlow (See Fig. 13). The iterative process is working as follow: mesh from preload is provided to fluid simulation to get a pressure field which is used for structural simulation, leading to new deformed mesh provided again for another fluid simulation. This iterative process is performed until we get convergence (equilibrium between structural deformation and fluid pressure). The fluid simulation is modeled with the following conditions: True Wind Speed (TWS) is set to 12 knots, True wind angle (TWA) is set to 40°. Boat speed is set to 5 knots accordingly to measured values along the experiments. This simulation provided the ability to compare the strain measured on the virtual mast to the experiments using optical fibre. Results are in the same order of magnitude.

To improve the realistic behavior of the virtual model, some additional information were needed. In fact the composites plies have various contribution to the damping of the structure (observed while running the explicit simulation). Therefore, the way the mast is responding to the dynamic loading depends on the stacking sequence of composites and their individual contribution. Damping properties per ply should be identify to populate the Abaqus solver. Reviewing the literature [Mahmoudi et al.(2019)Mahmoudi, Kervoelen, Robin, Duigou, Daya and Cadou] suggested that the damping was changing according to the fibre and the resin used. Some advanced virtual models have been initiated according to Literature using multiscale approach

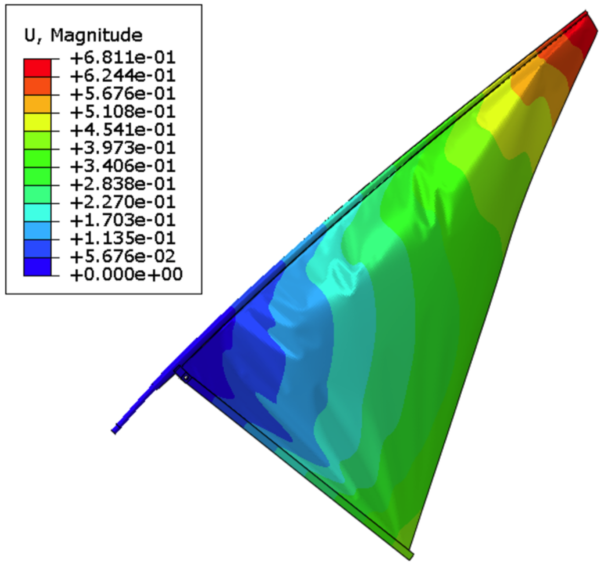

Figure 11: Result of displacements of mast and sail along the preload step.

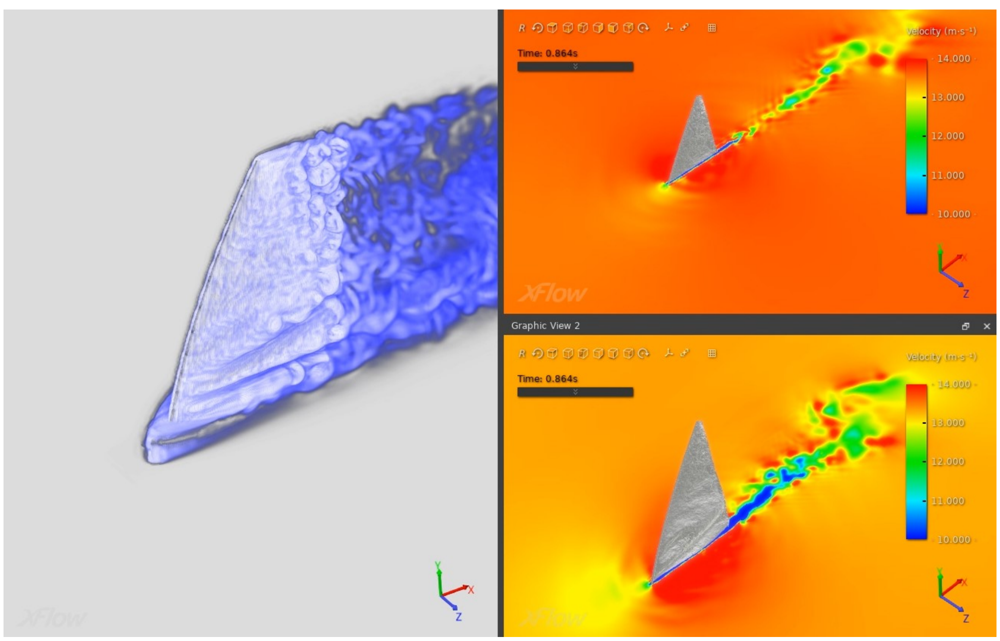

Figure 12: View of vortex in XFlow around the structural model according to the co-simulation under computation.

[Neagu et al.(2009)Neagu, Bourban and Månson] and it was finally performing physical tests which helped to validate some simulations. Few tests were performed to measure the effect of the angle on the same fibre/resin composite (See Fig. 13). The modal frequency is significantly different between plies at 0°and plies at 90°. From modal frequency, damping properties were extracted.

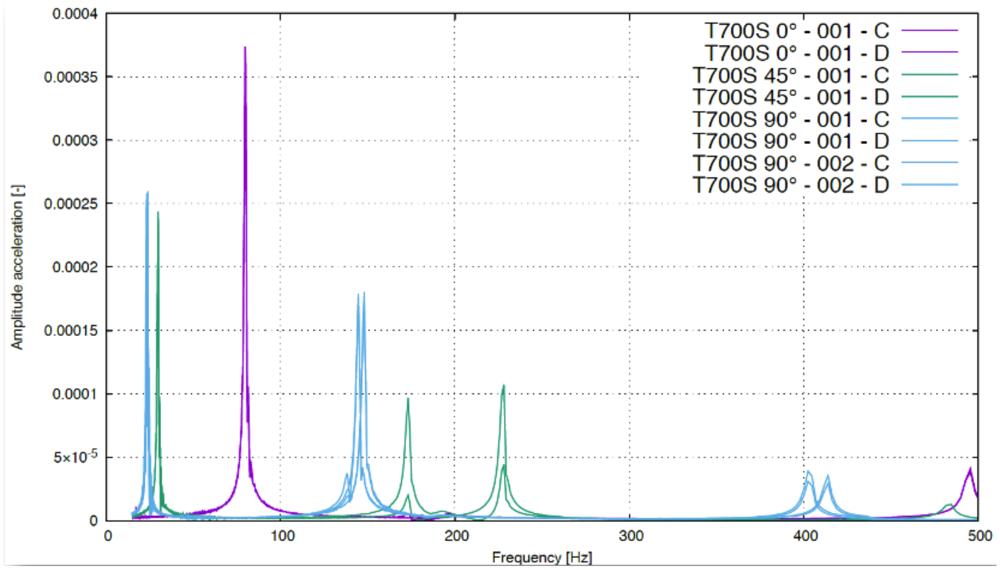

Figure 13: View of modal response of various composites with different angle for the plies. Three main configuration have been considered at 0°, 90°and ±45°.

5 CONCLUSION

In this study, it has been proposed to review the design of composites carbon mast for a dinghy boat. Conceptual parametric model built in **3D**EXPERIENCE offers the ability to automate the process between the parameters of design model and and their effect on the design criteria (stiffness, strength and stability). This automation was used to setup a design of experiments to identify the effect of the parameters and their interpolation. Then an optimisation was performed to identify composites mast in agreement with sailors requests. Manufactured masts were submitted to static and dynamic tests in the shed before the tests of sailors in training camp campaigns. Advanced monitoring provided in-situ data to calibrate fluid-structural simulation and get a better understanding of the real loading cases to be considered for the design suggested previously.

Sailors were observing impressive difference over the seven masts built. The change of composites plies stiffness and layup was the key parameter to explore for better behaviour of the structure. On this point, remaining work is under the way to improve the damping behaviour of those composites plies with experiments on coupons to qualify the damping parameters per ply and angle. Olympic Games are approaching and the tests continue on mast n°7 with a possible decision to use it further which should be taken in the coming weeks.

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