Peer-reviewed version available at J. Mar. Sci. Eng. 2019, 7, 6; doi:10.3390/jmse7010006

Article

Engineering Design Driven by Models and Measures: the Case of a Rigid Inflatable Boat

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Abstract: Rigid-hulled inflatable boats are extremely practical and popular nowadays. They offer a effective conciliation among usability and costs. Their stable and seaworthy behaviour is guaranteed by performing hydroplaning hulls coupled with unsinkable inflated tubes. At the same time, their design is often based on tradition and preconceptions. Rarely, the design assumptions are validated by the reality or, even, by deeper investigations. In this article, both numerical methods and experimental mechanics techniques are proposed as an essential way for supporting the designers in their decisive tasks. Three different situations are detailed where a numerical or an experimental approach shows its benefit inside the engineering design process: firstly permitting to investigate the behaviour of materials driving the fiberglass selection; then measuring the levels of stress and strain in the hull during sailing; finally, using all available information as a base for developing numerical models of the hull slamming in waves. Even if the discussion is focused on a rigid inflatable boat, large part of its considerations is relevant beyond this special case.

Keywords: boat design; experimental mechanics; stress-strain analysis; numerical modelling; rigid inflatable boat; fiber-reinforced composite.

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1. Introduction

A rigid-hulled inflatable boat or, in a simpler way, a rigid inflatable boat (RIB) [1], represents a very popular family of light crafts, offering high performances and additional practical advantages.

These crafts demonstrate stability in navigation thanks to specific design solutions pairing a solid and resistant hull with flexible tubes at the gunwale [2]. In addition, the inflatable collar permits to keep buoyancy even in the case of a huge quantity of water is shipped aboard in relation to bad sea conditions [3].

RIBs are generally between 4 and 9 meters as length, although, sometimes, they can raise up to 18 meters. These boats are often moved by one or more outboard motors with, typically, a power between 4 to 200 kW. RIBs represents a valid sailing solution to an extremely wide range of utilization, able to include special applications as rescue craft, safety boats for sailing, tenders at the service of larger boats and ships [4]. Their shallow draught, high maneuverability, speed and relative resistance to damage in low-speed collisions are specific advantages offered by these vehicles thanks to specific design solutions and materials.

The hull is commonly realized in steel, wood or aluminum [5], even if in the recent decades Fiber-Reinforced Polymer (FRP) composites grow into the largest material solution. FRP composites permit, in fact, to create desired shapes and smooth surfaces thanks to manufacturing processes which competitiveness is difficult, if not impossible, to tie using other materials [6].

Between the large family of reinforced materials for boats building [7], the Glass-Reinforced Plastics (GRP) seem to represent the best compromise between the different needs, with special attention of performance against costs. At the same time, reinforces in carbon fibers [8] or in natural ones (as flax or basalt [9-10]) can be preferred whenever special conditions occurred as, for instance, highest structural requirements (e.g. stiffness, lightness) or eco-sustainability are respectively

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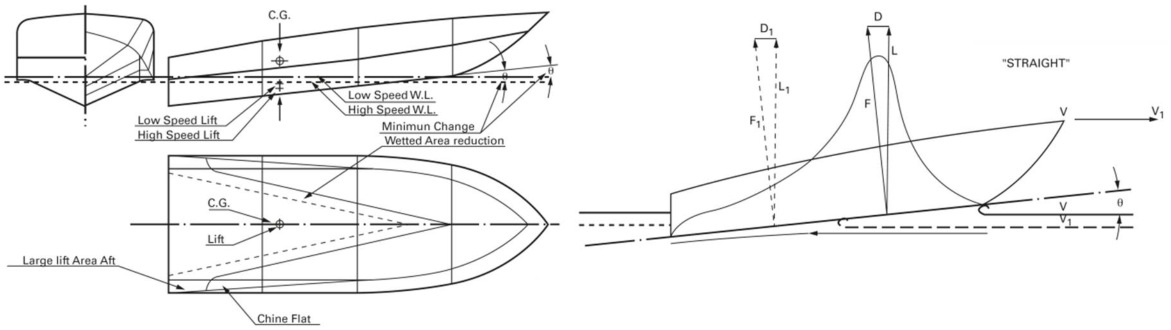
required. Some boat manufacturers also weave with other uncommon solutions of reinforcement (including Kevlar or nanofibers [11]) into the composite sheets for extra strength, moving the general technology toward hybrid materials [12, 13].

Beyond the material selected, the hull of a RIB has to be carefully designed and shaped with the scope to increase the boat performance in the water by optimizing its hydroplaning characteristics [14]. It means that benefits are offered not only in terms of speed, maneuverability, consumptions but also of safety, comfort, usability [15-16].

As one, the design is often based, in the case of RIBs, on tradition and preconceptions [17]. For instance, some designers are relatively unaware of the stress/strain levels characterizing a hull during the different conditions of sailing, since their attention is mainly concentrated on the observance of standards and technical prescriptions. Furthermore, not all naval design studies seem to be dealing daily with the concepts of numerical simulations, as an instrument to aid the optimization of boats [18]. Still today many designers continue to work in traditional terms of centers of mass, water lines, hull lines, 2D schemes, hydrostatic tables and so on, trying in this way to put a limit on the complexity of the real fluid-structure interactions (Figure 1).



(a) (b)

Figure 1. Example of diagrams traditionally used during the engineering design process for evaluating: a) hull behaviour as speed varies; b) trend of the forces on the hull while under way.

Besides, numerical modelling and simulations, permitting to describe in mathematical terms the multiple aspects of the real world and their evolution over time, could be an essential part in ship design process and optimization [18]. Today the role of modelling is widely consolidated in many sectors, thanks to the dramatic increase in computer speed that now allows the scientific calculation of complex systems, otherwise inaccessible to comprehension, completing more traditional tools.

Unfortunately, we are far from having mathematical models and calculation tools so handy and versatile to provide valid answers in all the various fields of ship design. As we go into detail to better address the problems, we discover the complexity of reality [19]. This concern is particularly manifest in the realization of a high-performance crafts. For their optimization, in fact, it is a question of solving the fluid dynamics equations around the boat, taking into account the variability of winds, waves and speed [20]. But the interaction between the fluids (air and water) and the structural components (hull, submerged appendages, sails and mast) must also be considered. And this is only to indicate what are the most important aspects to consider with the goal of minimizing water resistance and maximizing the thrust of the sails. To proceed in this way, it is still necessary to manage a complex modelling, taking into account aspects such as: the viscosity of the water, the transition between laminar flow and turbulent flow (with the vortices born), the turbulent trails generated by the interaction of the flow with the immersed parts, the shape of the wave that is generated on the hull and more [21, 22]. For example, one should solve equations that shape the coupling between the air and water motions and the resulting waveform, supplemented by additional equations constituting the models for the calculation of turbulent energy and its rate of dissipation [23]. It follows that the ability to make accurate calculations is not always within the reach of all designers and even partial solutions take their usefulness [24].

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2. Materials and Methods

The present study intends to show how experimental mechanics techniques and numerical methods can be conveniently use in supporting design choices without an excessive intensification in the workload or in the complexity of the design procedure. In particular, there are here presented:

1. In-lab experiments with the aim at investigating the behaviour of fiberglass, used in the boat manufacturing, by testing specimens in tensile, flexural and impact tests. Different mixtures of resins and glass reinforcements are also compared with the scope to select the best combinations of material properties.
2. In-field experiments, installing a network of sensors and instruments on the RIB for acquiring data during sailing: three outings on the sea, in normal and extreme conditions, with the scope to evaluate the stresses and strains in the hull gliding through waves.
3. Numerical simulations by the use of Smoothed-particle hydrodynamics (SPH), combined with FEM with the scope to investigate the effect of waves motion and impact on ship structures.

2.1. In-lab experiments

The current regulation in yachts design is UNI EN ISO 12215 regarding *hull construction and scantlings* for *small crafts* especially in that part (*Part 5*) concerning the *design pressures for monohulls, design stresses, scantlings determination*. It specifically suggests the use of tensile, flexural and interlaminar shear tests as material test methods providing the minimum mechanical properties that composite materials must have to be used to build the hull (Table 1).

Table 1. mechanical properties, reference standards for testing and minimum thresholds (ISO 12215)

Propriety	Standard	Threshold [MPa]
Flexural Strength	ISO 178	135
Flexural Modulus	ISO 178	5200
Interlaminar Shear Strength	ISO 14130	15

Then, a specific standard was used in each, able to provide information to carry out that test. These standards detail aspects as the geometry of test equipment, the testing speed, the dimensions and number of specimens. In particular, it states that, for each type of resin under investigation, a minimum of 5 specimens is required.

In this study, 7 resins were analyzed and compared: Epoxy, Orthophtalic, Iso-neopentilic, Vinylester and 3 different Polyesters. Tests were carried out using an *Italsigma* hydraulic testing machine with *100kN HBM Gmbh* load cells.

2.1.1. Tensile tests

The tensile tests were planned and carried out following the indications of ISO 527-1/4 standards. Since the sheet was made up of layers of coupled mat, the direction of tension made no significant difference. The samples had nominal dimensions of width 25 mm, length 250 or 150 mm and thickness 4 mm. Supports in aluminium 50 mm long and 3 mm thick were glued to the samples using LOCTITE 9466 AB glue. A minimum of five samples were tested for each resin system. The test speed was 0.02 mm/s (figure 2a).

2.1.2. Flexural tests

The flexural tests were planned and carried out to the ISO 178 standard. The samples were realized in rectangular shape, 10 mm length, 80 mm width 3.5 mm thickness, and distance between supports of 56 mm, or 4 manually laminated samples 15 mm length, 110 mm width, 5.5 mm thickness and distance 90 mm. For each resin system at least five samples were tested. The test speed was 0.02 mm/s (figure 2b).

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2.1.3. Interlaminar shear tests

The interlaminar shear tests were planned and carried out to the indications of the ISO 14130 standard. The samples were rectangular, length 10 mm, height 40 mm, width 5 mm, height 20 mm, with the distance between supports of 17.5 mm. The test speed was 0.02 mm/s (figure 2c).

The failure methods were investigated with particular attention.

(a) (b) (c)

Figure 2. Equipment and samples during the a) tensile, b) flexural and c) interlaminar shear tests.

2.2. In-field experiments

A prototype RIB, based on the Mariner 530 model, was used for stress tests. It was a 6-seater, 450kg boat, 4.95m long and 1.75m in the beam, with a 15kW/20hp engine (Figure 3).

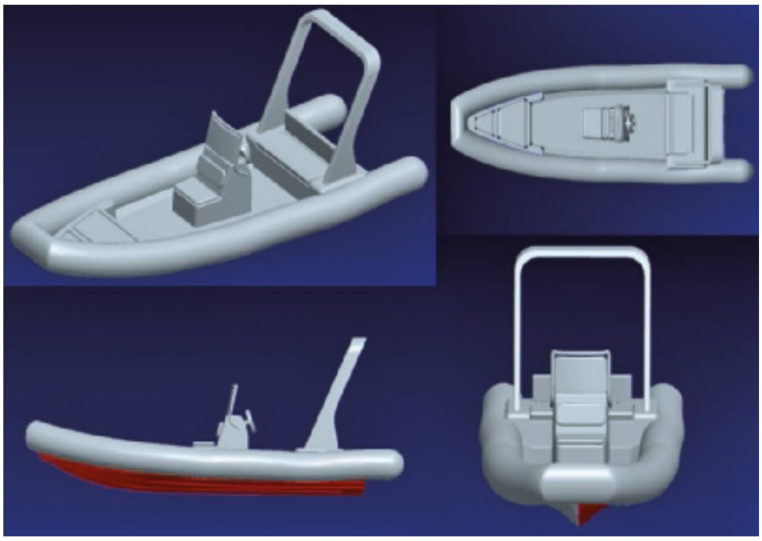

Figure 3. A prototype RIB used for sailing tests

Experiments monitored accelerations and strains installing strain gages and accelerometers on the boat (Figure 4). Accelerations were measured in the fore and aft and athwartships directions of the hull. The values of acceleration made it possible to correlate tests carried out in different sea conditions, but also to provide an interesting overall parameter for evaluating the comfort.

Strains were measured in 6 different locations on the hull, revealing longitudinal and transvers deformations. In total 15 measures were realized: 3 accelerations and 12 deformations. In particular, the strain gauges were positioned in the way to monitor the most remarkable parts in terms of water effect during the different conditions and speeds of sailing (figure 4a). The duplication of strain gages (and measures) in a symmetrical configuration was preferred for a better investigation of unexpected phenomena.

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Boat surfaces were carefully cleaned and treated before gluing the strain gauges (figure 4b). The glue was also used to protect these sensors (figure 4c). The weight effects of the fuel tank and driver were also monitored (figure 4d). A three-axis accelerometer was placed in the cockpit, together with data acquisition, signal conditioners/wireless amplifiers and other electronic devices. (Figure 4e).

The tests were carried out on three different days, two with calm sea, to verify the sensitivity of the measurement system even under very low stresses. Each test day saw several measurement sessions using trajectories, speeds and acceleration in an attempt to represent best various driving styles. Inside each test day, several test sessions were realized. Each session of measure lasted about 1 minute: this choice made it easier to analyse data and separate the effects.

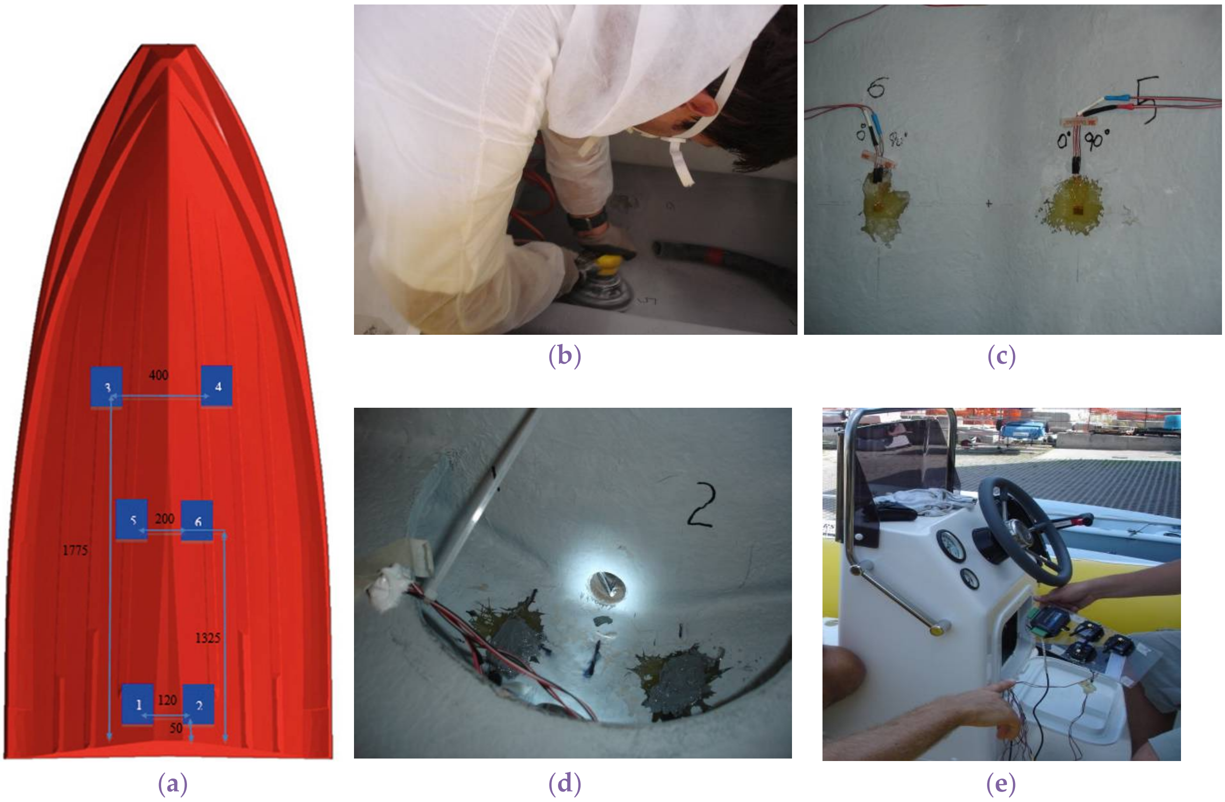

Figure 4. Placement of the strain gauges: a) map of placement; b) preparing the surfaces for gluing on the strain gauges; c) train gauges in the cockpit, affected by the weight of the fuel tank and driver; d) stern strain gauges to monitor the most stressed areas; e) data acquisition and other ICT devices.

2.3. Numerical simulations

The numerical study of the impact between a moving body and a free surface of water is a familiar problem both in the naval and aeronautical fields, and concerns the interaction phenomena between hulls, offshore structures, aircraft with the water surface, sometimes considered in its wave motion. The main purpose of this type of research is to trace the load transferred during the impact to the structure under examination to verify the conditions of resistance or proceed to a redesign. Usually, these studies start from experimental tests, interpreted through empirical laws and, only recently, studied through numerical simulations.

These investigations must be implemented by numerical codes that permit to properly model the fluid-structure interaction. These codes originate from the Lagrangian formulation programs developed for crash problems, but also allow the interface of continuous based on Eulerian spatial description. In this kind of calculations the fluid constitutive model, the fluid-structure interaction algorithms and the computational efficacy represent critical aspects. This study present an alternative approach based on mixing Finite Elements (FE) and Smoothed-particle hydrodynamics (SPH).

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Slamming simulations were performed with LS-Dyna commercial software. SPH elements were used for fluid modelling. SPH particles, equispaced and of identical size (radius of influence of 25 mm) were placed in a fluid region of dimensions 7 m x 3 m for a depth of 1.5 m. The properties of the fluid were modelled by means of a state equation according to the Gruneisen formulation (Eq. 1).

$$p=\frac{\rho_0 C^2 \mu\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu-\frac{a}{2}\mu^2\right]}{\left[1-(S_1-1)\mu-S_2\frac{\mu^2}{\mu+1}-S_3\frac{\mu^3}{(\mu+1)^2}\right]^2}+(\gamma_0+a\mu)E \tag{1}$$

where E represents the internal energy per unit of volume, and $\mu = \eta - 1$ where η is the ratio between final and initial density. The numerical values of the other constants are reported in Table 2.

The fluid is initially at rest, is subject only to gravity acceleration and is constrained in space by non-reflecting edges, so as to avoid the reflection of the pressure waves.

Table 2. Water constants according to the Gruneisen model.

C [m/s]	S_1	S_2	S_3	ρ_0 [Kg/m^3]	γ
1480	2.56	1.986	1.2268	1000	0.5

The hull was modelled using Finite Elements (FE) *shell* type, 4 nodes with 2 points of integration in the thickness, for a total of 26000 elements (as shown in Figure 5). The hull thickness was considered constant throughout the model, and equal to 12 mm. The material had the characteristics of a composite laminate with a matt of glass fiber and polyester matrix, with properties of E1 = E2 = 24 GPa, ν = 0.3, ρ = 2800 Kg / m^3, implemented as an elastic linear material without damage models.

The numerical simulation simulated the entry into the water (as drop test) with an entry speed of 8 m / s. The speed component was purely vertical and the hulls inclined with the bow to a greater portion of the stern (as shown in Figure 5).

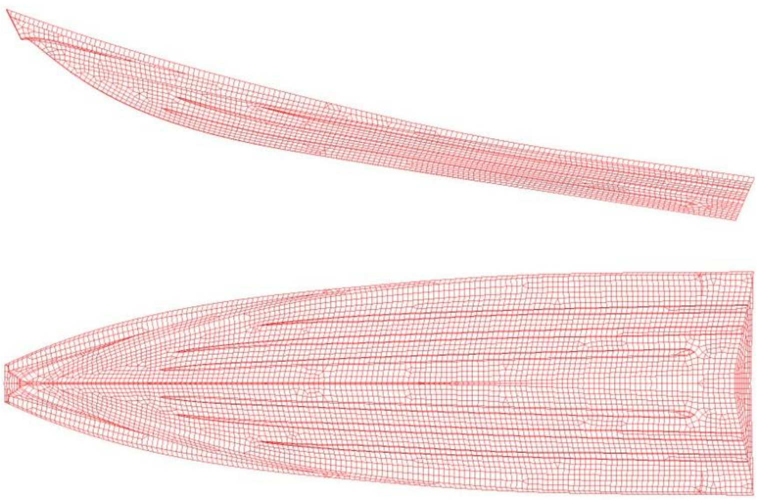

Figure 5. Discretization of the model through shell elements. The hull is discretized by 26000 shell elements with 4 nodes with 2 points of integration in the thickness.

3. Results

3.1. Material properties

3.1.1. Tensile properties

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Tensile tests provided a measure of the strength (σ) and stiffness (E) of the laminate as a whole, thus including both the contribution of these seven resin and fibres in their specific stratification.

In particular, Figure 6a shows the stress-strain diagrams noting that:

- the standard requires tensile strength of 80 MPa which is amply satisfied by all the resin systems. As a practical result, all the materials and sequence of stratification under investigation are adequate for creating the strength laid down by the standard;
- almost all the resins showed an ultimate tensile stress of between 220 and 250 MPa with better characteristics for isoneopentilic and orthophthalic resins at 0.5 bar, while hand laminated polyester resin and epoxy resin had the worst performance;
- for hand laminated polyester, this performance is due to the greater percentage of resin compared with fibre and to the presence of air porosity in the manual laminate compared with other techniques (VARTM);
- epoxy resin shows decidedly low values in relation to the problems illustrated in starting reticulation of the resin in the sample sheet.

3.1.2. Flexural properties

Similarly, Figure 6b shows the stress-strain diagrams for the flexural tests noting that:

- the standard demands flexural strength of 135 MPa and a flexural modulus of 5200 MPa which is amply satisfied by all the resin systems; all the resin systems are thus adequate for offering the strength specified by the standard.

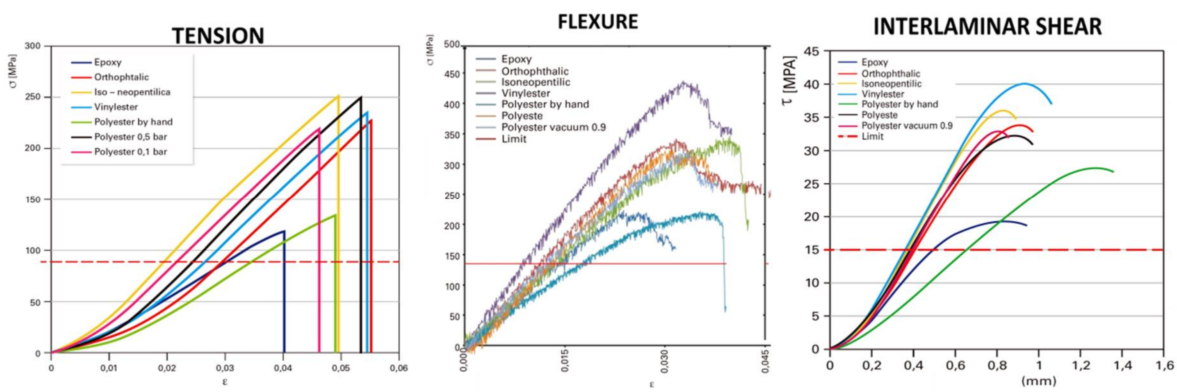
The resins can be grouped into three categories:

- best resin: Vinylester, which has properties decidedly superior to the others but is more expensive; it is recommended for special or high-performance applications;
- hand laminated polyester and epoxy: these have the worst characteristics, but it must be underlined that the poor result of epoxy resin is linked to the fact that it was made at environmental temperature, normally epoxy resins have much better performance;
- the others: they all show very similar behaviour and are equivalent.

3.1.3. Interlaminar shear properties

Finally, Figure 6c shows the main results obtained from the interlaminar shear tests. For each sample the shear methods were classified and the calculation of the maximum shear force is shown. In particular, it is shown the shear-displacement diagrams where it is possible to note that:

- the standard requires interlaminar shear resistance of 15 MPa which was largely satisfied by all the resin systems;
- the best system is once again vinylester with performance decidedly better than that of the others: in this case too epoxy resin shows unusually low values for the partial reticulation of the sample sheet;
- the remaining resins have similar behaviour with a slight preference for isonepentilic resin.



(a) (b) (c)

Figure 6. Diagram and standard limits for: a) tensile tests; b) flexural tests; c) interlaminar shear tests.

3.2. Loads and deformations

Each navigation tests started with the transport thought the port and launch in the basin (Figure 7). Figure 8 shows an example of a cruising followed during a measurement session, starting from calm water in the port followed by sudden accelerations. In particular, the GPS trace shows the presence of specific criteria in the measurements. In this case, for instance, the criterion was to reach the maximum speed (about 20 km/h), then turn in a fixed time through a set angle marked on the helm. In this way the RIB ran over its own wake, with waves of roughly the same height, to improve the repeatability of the measurements.

(a) (b)

Figure 7. Initial phase: a) transport through the port and b) launch in the basin of the rigid inflatable instrumented boat.

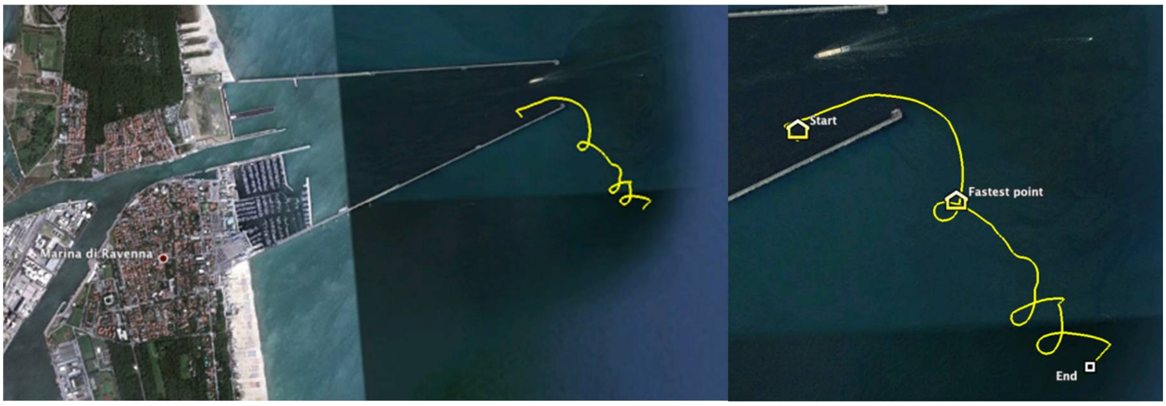


Figure 8. Example of route followed during one of the test sessions: strong acceleration and repeated rotations made it possible to investigate the effect of self-generated waves on the hull.

Figure 9 shows an example of a part of measures acquired during this specific test. The acceleration is expressed only with its vertical component (the most significant) while for stress all three components are evident. Although strains (and related stresses) were very far from the safety limits of fiberglass, these tests aimed above all to represent a method that makes possible to create an “instrumented prototype” for resistance tests and design evaluation.

This prototype was not only intended to investigate the behaviour of the craft during normal operation, but also in extreme conditions laid down by the specifications or future regulations such, for example, as the inflatable being dropped from heights from 3 to 6 m, which are being prepared, or sailing on moderate or rough water.

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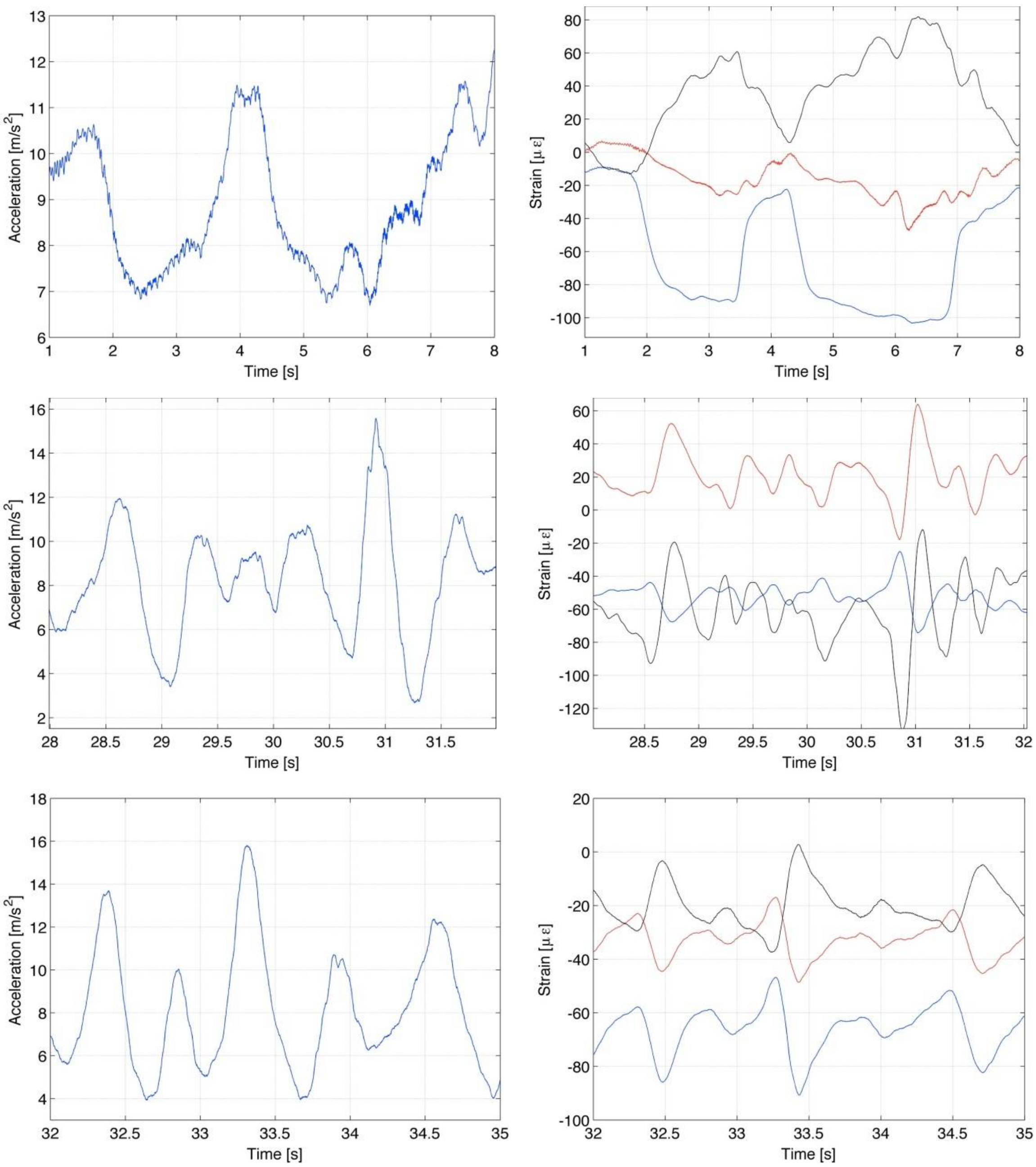

(a) (b)

Figure 9. Investigating the hull behaviour in different moments: a) accelerations and b) strains

3.3. Numerical predictions

This simulation permitted to investigate the situation of the hull impacting against the water surface in specific conditions (e.g. impact speed, impact direction and so on) in terms of time evolution of displacement, speed and acceleration (Figure 10).

In this case it is possible to note that the maximum acceleration is achieved shortly after the start of the impact, when the speed is high and only a small part of the hull is in contact with the water. This force counteracts the inertia of the craft. A moment is then generated which deforms the hull to the outside and tends to "push" the structure. As water enters the inlet, the wet surface of the hull increases and elastic strain energy accumulates. As the wetted surface increases, the moment caused by the hydrodynamic force increases and generates a bending moment that is opposite and stronger than that generated by inertia, bringing the deformation of the hull back to neutral position.

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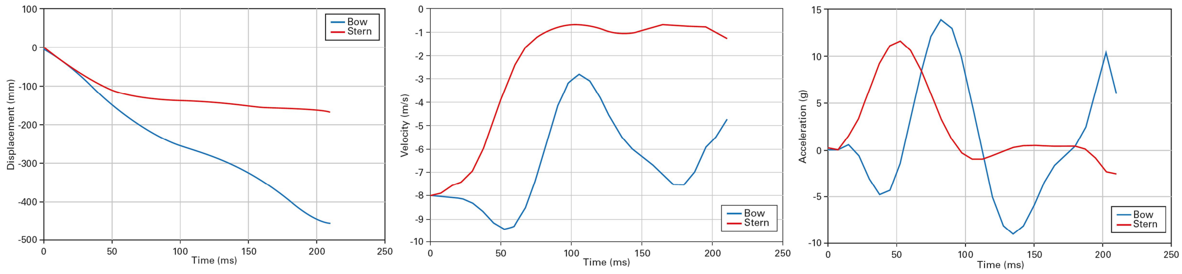

Figure 10. Displacement, Speed and Acceleration of the bow and stern during the impact.

Figure 11 shows a sequence of images of the water entering while Figure 12 shows the (Von Mises) stress level associated with the deformations of the hull. The colors in the figure represent the range from 0 MPa (blue) to 50 MPa (red). The most stressed regions are the keel, where the hydrodynamic pressure is maximum, and the terminal part of the side members, where a greater mass is concentrated and therefore the elastic deformation is maximum.

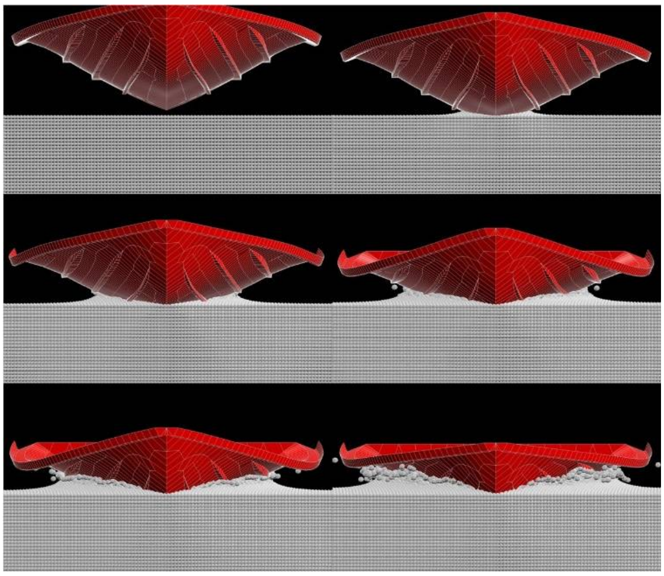

Figure 11. Sequence of the simulation of the entry into the water of the hull.

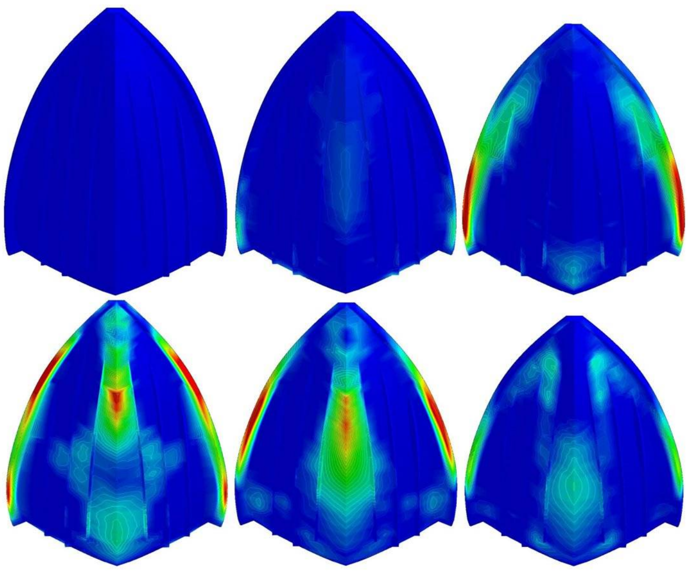

Figure 12. Longitudinal tensions in the hull generated during slamming.

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4. Discussion and Conclusion

This article, as said, aims at demonstrating how numerical models and experimental techniques, even in the case of simplified and quick procedures, can be conveniently used for supporting the designers in their decisive tasks.

Concerning those experiments that can be performed in lab, the article shows how they can be implemented in accordance with well-known standard arriving to a practical characterization of the resin systems, supporting a final selection. But experiments also provided additional evidences that can be useful for a more informed choice as, for instance:

- the epoxy system does not appear to be usable at typical temperatures for boat production;
- there are significant difference in mechanical performances obtainable with advanced techniques compared with the classic manual methods.

Concerning the experiments in sailing conditions, the article shows the advantages of the RIBs respect to other traditional boats, but also its limits when its specificities are not reflected in the design process. Extremely safe, thanks to the inflatable collar that makes it unsinkable and increase the lateral stability, but also thanks to its low weight and dimension, this craft present several functional benefits. Driven by very powerful engines in relation to their displacement, RIBs can plane on waves and do not simply slide along the water. This, which means much of the hull spends a great deal of its time in the air, considerably reduces drag, optimizing speed and efficiency.

At once, from experimental data it was possible to immediately observe the intense impulsive loads acting on its structures, together with a maximum at the intersection between the hull and the water line. This peak moves and changes in intensity as the hull planes, decreasing and moving astern the more of the hull is out of the water. At the same time the hull undergoes strong and continual impacts on the water surface that demand careful and robust design. Besides, clearly understanding what happens in the interaction between fluid and structure is not an easy task, especially in non-nominal conditions as in the case of a strangely shaped hull moving in rapid zigzags among the waves.

With the aim at moving a step toward this comprehension, numerical models and simulations can provide a help, as demonstrated. Through the coupled SPH and FEM methods it was possible to study the complex aspect of fluid-structural interaction and the mutual influence between the fluid motion and the hull deformation. For instance, observing the behaviour of stern and bow during their entry into the water, it was possible to recognize that the stern, the first to touch the water, is also the first to decelerate. This generates a moment on the hull that slightly increases the fall speed of the bow, which impacts on the water afterwards. The peaks of the maximum accelerations of the stern and the bow are therefore out of phase. And so on.

Funding: This research, named '*New concept boats*', was funded by the Emilia Romagna Region, Italy, as part of the Regional Operation Program that uses resources from European Regional Development Fund (ERDF) with the aim to strengthen economic and social cohesion in the European Union.

Acknowledgments: The research was supported by Mariner Srl, Stilplast Srl, Ravenna with technical support and donations in kind. In-lab experiments were carried out at the MaSTeR Lab, University of Bologna, under the supervision of Lorenzo Donati and Enrico Troiani. In field experiments were carried out in front of the port of Ravenna, Italy, Adriatic Sea, under the supervision of Giangiacomo Minak. Special thanks to Vanda Roversi, Riccardo Panciroli, Ana Pavlovic for their efforts.

Conflicts of Interest: The author declare no conflict of interest.

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