Interaction of Water with Carbon Fiber Reinforced Polymer Laminates under Dynamic Loading Conditions

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With the aim of simulating the real conditions during the navigation, in this framework, impact tests were performed by loading CFRP laminates immersed in the water from the front side. The specimens, made by vinyl ester matrix because of the lower moisture absorption compared to the other epoxy systems, are in the presence of the water to accurately simulate the incidental impact on the hull of the vessel, immersed or partially immersed, during the navigation. It can be caused by the ice in the Arctic Ocean, by a projectile due to a terroristic attack or by debris from an explosion. The results are compared with the ones obtained by loading the laminates in pure traditional impact tests in the air. The influence of the clamping device has been tested too. The exciting results obtained on carbon fiber laminates in the air (pure traditional impact tests), water-backed (with water on the back side) and waterfront (water only on the front side) conditions at room temperature are here reported and compared. They highlighted the critical role played by the complex fluid–structure interaction.

1. Introduction

In recent years, composite materials experienced an increased usage in different industries ranging from aerospace, wind energy, naval, and defense structures. In particular, the carbon resin composite materials (CFRP) are widely used to replace traditional ones in several fields, also in the naval one, thanks to their functional and structural properties. The potential use of these materials, combining different phases like matrix, reinforcements and interfaces, is influenced by many factors including manufacturing and environmental conditions, poor compatibility between base constituents, stacking sequence. Due to their inhomogeneity and anisotropy, composite laminates suffer severe damages under dynamic loading conditions: Low impact energies can cause large delamination that sensibly reduces the residual compression strength of the structure (Ref 1-5). Moreover, the damages can interact with each other in different and complex mechanisms, and they are often not visible damages (Ref 1).

Composite laminates made of carbon fiber reinforcements in vinyl ester resin are prevalent composite materials for marine use. However, naval construction parts are very often subjected to mechanical shocks in water at room and low temperatures: In these contests, the toughness of the material changes concerning the standard conditions, causing different damage mechanisms. The mechanisms of damage evolution also depend on the fluid that interacts with the structure. If the water supports the panel instead of the air, or the fluid overlies the same, the mechanisms of damage onset and propagation are governed by a different loading distribution (Ref 2). Moreover, the clamping device plays an essential role in the response of the laminates in dynamic conditions by influencing the load distribution. The problems here discussed are extremely important in the Arctic Ocean navigation where in addition to the presence of the water, the temperature plays an important role.

Impact damage does not represent a significant concern in metallic structures because their ability to dissipate the incident kinetic energy is entirely different to that of composites. First of all impact damage in metals can be easily detected as it starts at the impacted surface, while in composites, it often begins on the non-impacted surface or in the form of internal delaminations that can go easily unnoticed but can severely degrade the structural integrity of the component. This form of damage is referred to as barely visible impact damage (BVID). So, the damage could be present between the internal plies, but still not visible (Ref 1). A large number of works are about the mechanisms of damage initiation and growth (Ref 6-12). However, as mentioned, few studies (Ref 13-16) were found in the literature about the behavior of composite laminates subjected to impacts at low temperature, and few of them (Ref 17-22) face the problem of the fluid–material interaction. In (Ref 21, 22), the tested conditions are similar to the ones studied in the present research even if the panel dimensions in Kwon et al. are more extensive and the test apparatus is different. The main focus was to know the threshold force value for the beginning of the delamination and to compare the maximum load in the presence of the water with traditional dry impact. Even if the conclusions are different from what are observed here because of a different specimen dimension and different impact apparatus, as explained and recalled hereafter, they supply valid data for a complete comprehension of the phenomenon taking into account the additional mass represented

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by the water. The latter is responsible for the different response of the composite panel, the main focus of the present research.

Accordingly, to what asserted, it is critical in marine field to understand the dynamic response of composite structures in extreme temperature and water-backed or waterfront conditions, as well as to study the effect of the constraints. The study of the panel partially immersed or supported by the water represents the basis of the research performed in the present work. The same tests carried out here at room temperature are planned to be carried out in the next future at $T < 0$ to study the effect of the temperature on the dynamic response of the composite panels working in the Arctic Ocean.

However, due to the big number of associated parameters, the problem is not simple to understand. A large number of data are necessary to understand all the aspects of the phenomenon. It is needed to start by investigating simple conditions and adding parameters to study on, step by step, up to the simulation of the real condition.

A large number of experimental tests were performed at the University of Naples in the presence of the water with the final aim to have a better understanding of the impact phenomenon, to develop methodologies for the design, to achieve more efficient structures and more easily maintainable. These methodologies should suggest solutions through fast simulations from simple and few experimental tests with the help of theoretical, numerical and semiempirical models, avoiding a large number of experiments, saving time and costs.

In this frame, with the aim of simulating the real conditions during the navigation, impact tests were first performed by loading CFRP laminates immersed in the water from the front side. The air pillow directly supported the specimens to correctly simulate the incidental impact on the hull of a vessel immersed, during the navigation. It can be caused by the ice in the Arctic Ocean, by projectiles due to a terroristic attack or an accidental explosion. The results were compared with the ones obtained by loading the laminates in real traditional impact tests.

Additional tests were carried out to verify the influence of the water and the effect of the water–structure interaction as well as of the boundary conditions and the load distribution, by impacting the specimens supported simply by a thick water layer or clamped on it. In the latter condition, the water is only on the back side of the laminate, and the impactor is on the other one, in the air.

The nondestructive analysis was done to investigate the damage by using an ultrasound nondestructive technique (NDT).

The interesting results obtained on carbon fiber laminates in all the above-explained conditions at room temperature are here reported and compared. All the data from the whole performed experimental campaign are useful for the understanding of the non-simple interaction phenomenon between structure and fluid during the navigation.

From the results, it was highlighted that the fluid–structure interaction significantly influences the dynamic response of a composite panel, completely changing the load distribution and the energy absorption mechanisms.

2. Materials and Experimental Setup

Carbon fiber laminates obtained by overlapping 10 and 13, T700 carbon fabric plies (0°/90°) 300/sqm, resulting in 3 mm and 4 mm nominal thicknesses, were dynamically loaded.

Square panels, 600 × 600 mm, were fabricated at the University of Naples by vacuum infusion process using DION® FR 9300 vinyl ester resin. The latter is a non-accelerated, brominated fire-retardant epoxy-based resin for marine applications with high physical and chemical properties. The final volumetric fiber percentage, V_f, was about 50%. From the panels, rectangular specimens 100 × 150 mm, suggested by ASTM D7136 Standard, were cut by a diamond saw. Impact tests were carried out by a falling weight machine, Ceast/Instron. An instrumented cylindrical impactor centrally loaded the rectangular specimens with a hemispherical nose 19.8 mm in diameter. The total minimum mass of 3.6 kg of the impactor combined with the drop heights allowed to obtain the selected impact energies. The impact velocity was 4 m/s.

Impacts on specimens immersed in the water from the front side were performed. The tank full of water used for the experimental tests, 300 mm in diameter, is shown in Fig. 1(a): It was made in plexiglass to allow to observe the phenomenon visually.

Figure 1(b) shows the support in Plexiglas machined to accurately reproduce the one suggested by the ASTMD 7136 standards shown hereafter, having an internal rectangular window 75 × 150 mm² on which the specimens are placed . It was wholly immersed in the water and fixed on the bottom of the plexiglass tank full of liquid. Avoiding the water on the back side of the specimen, we sealed a thin polymeric layer on the rectangular plexiglass window before fixing in the tank.

The above-discussed equipment was arranged at University of Naples "Federico II", and any Standard did not suggest it nor existed before. To perform these innovative tests, it was necessary to modify the impactor supplied by Ceast/Instron:
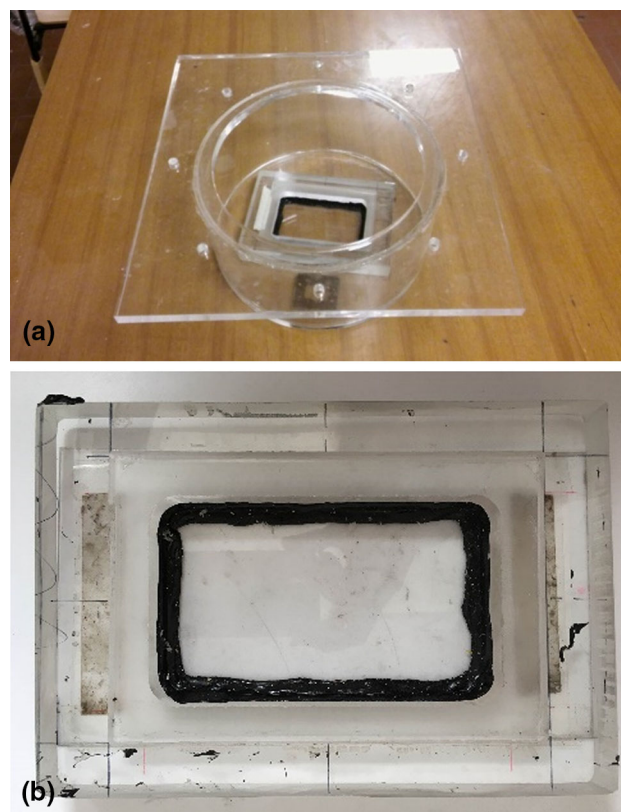

Fig. 1 Experimental setup: plexiglass tank containing water (a); detail of the support (b)

With the aim of impacting the specimens positioned on the plexiglass support on the bottom of the tank, it was necessary to use a longer blunt with the same cylindrical shape and the same hemispherical nose (Fig. 2a and b). It was glued and fixed by fixing screws on the first original body resulting in an imperfect rigid connection. The longer arms plus the effect of the glue plus screws caused, as shown hereafter, noise in the signals.

Traditional impact tests in the air (named air-backed, labeled as "Air" in the text) were carried out too by using the clamping device suggested by the above-mentioned Standard (Fig. 3a). Then, water-backed (WB) loading tests were carried out on the same typology of specimens supported on a thick water layer. The fluid is contained in a steel tank, 300 mm in diameter, covered by a thin silicon layer to avoid the water coming out (Fig. 3b), and clamped by four rubbers to reproduce the clamping device in Fig. 3(a). Additionally, the equipment shown in Fig. 4 was used to investigate the effect of the clamping device: The same steel tank full of water was used. The difference with the support shown in Fig. 3(b) is that it merely supports the specimens on the thick water layer, covered by the same thin silicon layer, without any clamping device. The cutout window is of the same size as the specimen so that it is freely floating on the water. The latter condition will be labeled in the text as free water-backed (FWB).

During the impact tests, force–time and force–displacement curves, as well as energy and velocity trends, were recorded by DAS16000 acquisition program. All the load curves recorded during the tests in each different condition are compared.

The delaminated areas were inspected by using a US Multi2000 Pocket 16×64 system by M2M: A Linear phased array Probe, 5 MHz, was used to perform the analysis.

The phased array systems could be used for all inspection types, traditionally made using conventional ultrasonic flaw detectors. The choice of a low-frequency probe ($f = 5$ MHz) is justified by a significant decrease in the signal attenuation and a more efficient measurement (Ref 6). The apparatus operates in the form of reflection in the sense that the probe is used to emit and to receive the ultrasonic waves. Pulse-echo technique was adopted for the acquisition. The depth of a reflective structure is inferred from the delay between pulse transmission and echo reception (Ref 20). In this way, the correct thickness plate is obtained on an undamaged sample, and the acquisition system is calibrated. The propagation velocity, 2400 mm/s, is registered according to Scarponi et al. (Ref 6).

C-scan inspections provided a plane view of specimens subjected to ultrasonic analysis. By appropriately setting the Gate, a relatively clear picture of the area characterized by delamination was obtained and, then, also correct sizing of the defect. Echo Max (abs) was the used Detection Mode: Once the
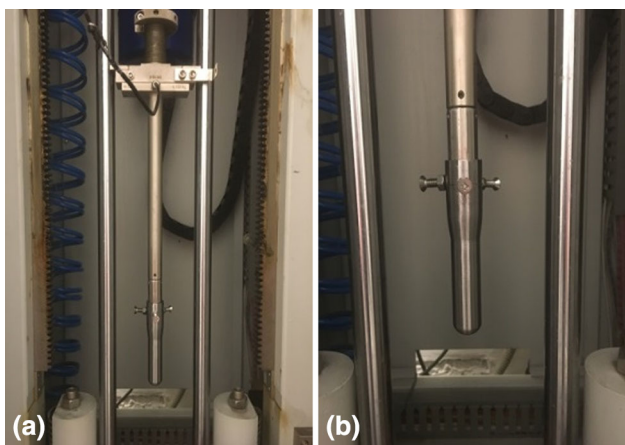

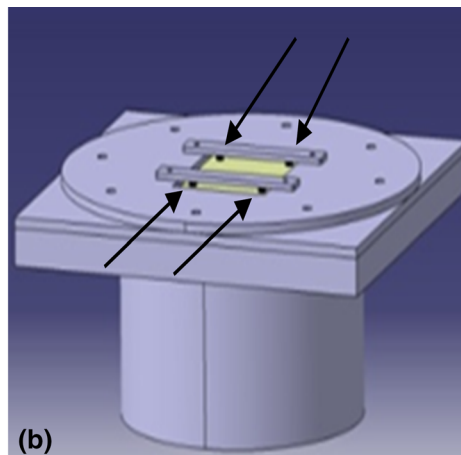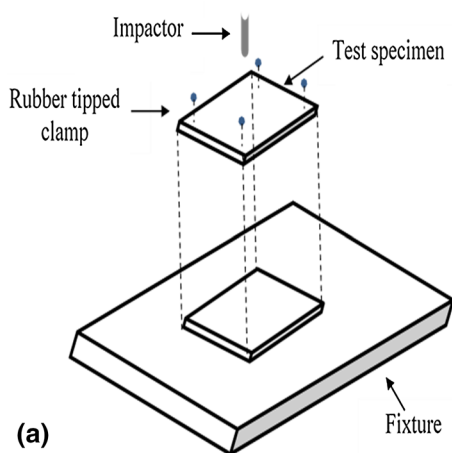Fig. 2 Longer impactor modified for the tests immersed in the water (a); magnification (b)

Fig. 4 Experimental setup: steel tank for free water-backed (FWB) impact tests

Fig. 3 Clamping device: (a) ASTMD7137; (b) clamped WB tests. Rubbers to clamp the specimen shown by narrows

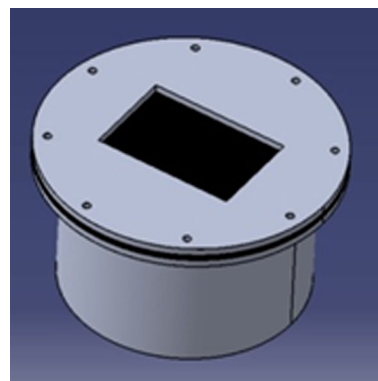Gate is set, on the implementation of the scan, only the peak that overcomes it will be recorded. The C-scan shows different colors as a function of the amplitude of the signal. Each delaminated area was, then, imported in a CAD software where it was bordered and measured.

At least three specimens were tested in each condition.

3. Results

3.1 Effect of the Thickness and the Load

Figure 4(a) shows the comparison among the load curves at penetration in the air for the vinyl ester carbon laminates with different thickness (3 and 4 mm): Higher values of the maximum force, F_{max}, initial rigidity and penetration energy, U_p, the latter obtained by the area under the load curve, on the 4 mm thickness laminate, were measured.

It was not possible to perform the same penetration tests in the presence of the water because of the thin silicon layer on the tank to avoid the water used.

In Fig. 4(b), the load–deflection curves obtained by impact energy of 20 J on the same laminates 3 mm and 4 mm in thickness, in the same pure impact test conditions in air, are reported. The graph clearly shows that closed-type curves are obtained: The samples are not penetrated/perforated by the impactor that rebounds, and the area enclosed in the loop of the loading and unloading trend of the curve represents the energy absorbed by the laminate, U_a, which is partially used to create damage. The latter results are higher for the thicker sample as well as the maximum load and the first rigidity. As a consequence of the increased stiffness, the deflection decreases at the increase in thickness. The same was observed on the laminates impacted by 10 J of energy not reported here for sh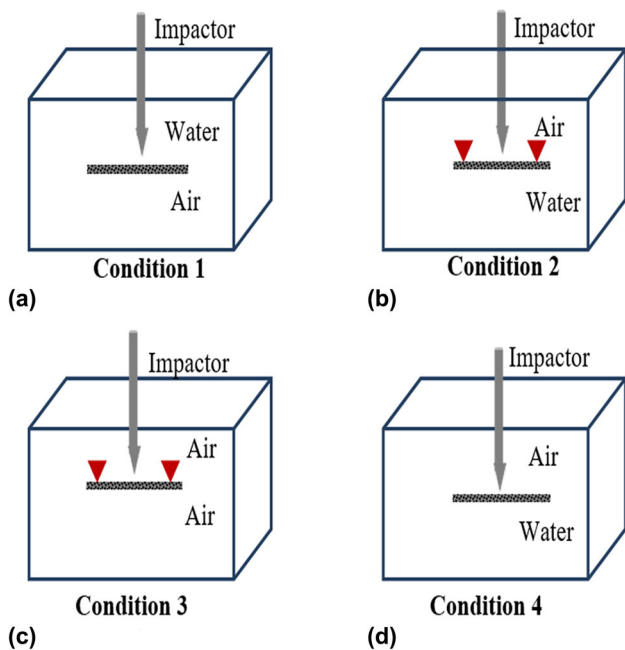ortness. Figure 15 and 16 shows the same behavior by comparing the load curves on the same laminates tested in WB and immersed conditions by the same impact energies of 10 J (a) and 20 J (b).

3.2 Fluid–Structure Interaction

By comparing the results obtained on specimens immersed in the water from the front side (condition 1 in Fig. 5), with the ones where the water is on the back side (WB) (condition 2 in the same figure) and the third one from the traditional pure impact tests (Air) (condition 3), a difference was found about
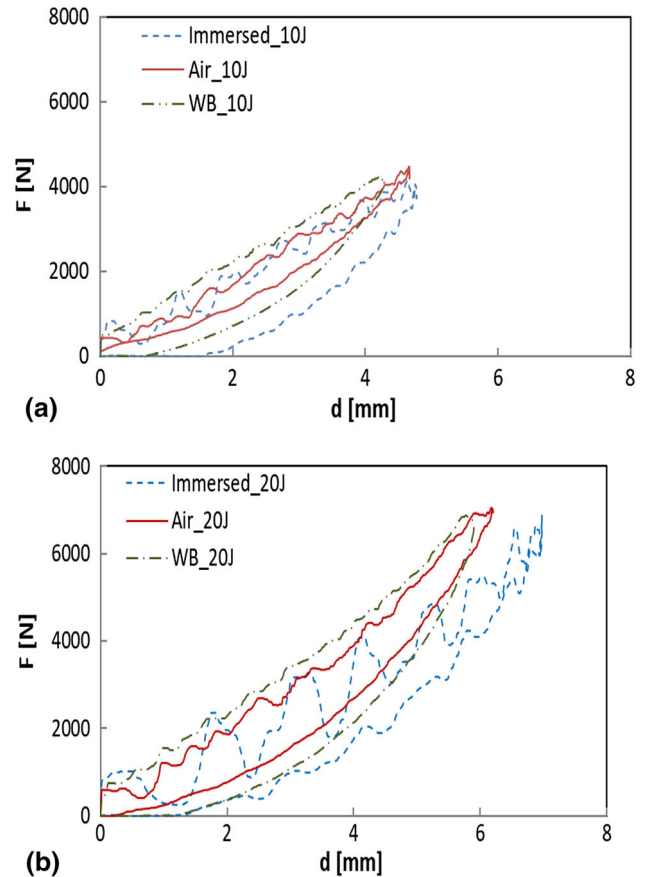

(a)

(b)

Fig. 6 Air-backed (Air), water-backed (WB) and immersed specimens (immersed) load curves; $t = 3$ mm; (a) $U = 10$ J and (b) $U = 20$ J (Color figure online)
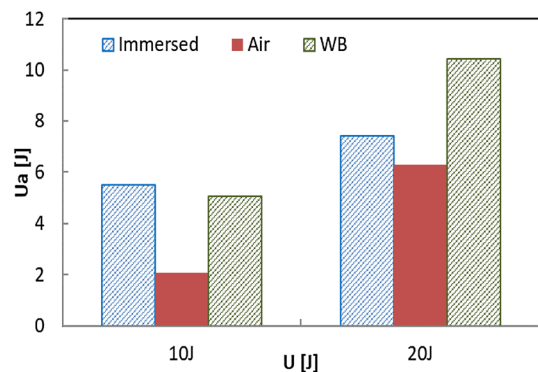

Fig. 5 Scheme of the tested conditions: Immersed (a), clamped water-backed, WB (b), pure impact test, air (c), free water-backed, FWB (d)

Fig. 7 Air-backed, water-backed and immersed specimen's absorbed energies, U_a; $t = 3$ mm

the absorbed energy and displacement. Figure 6 reports the load–displacement comparison on specimens 3 mm in thickness: All the load curves have similar shapes irrespective of the impact energy, showing the same initial rigidity and maximum loads very close to each other, whereas different amounts of absorbed energy and maximum deflection (Fig. 7 and 8) were measured. Also, the specimens 4 mm in thickness show the same behavior even if it is not reported for shortness. The results confirm the different mechanisms of damage evolution, represented by the different absorbed energy, in the presence of the water (Ref 2) and the various interactions between water and structures, the latter depending on where the thick layer of the fluid is positioned. However, the result about the maximum load is different from what is observed by Kwon (Ref 21, 22) who found higher values in air conditions even if, as already anticipated in the introduction, it is worth to consider that the panel dimension and the impact apparatus are not the same. The latter results represent an important point to investigate on since the influence of the impact energy, of the panel in-plane dimension and the open debate about the scale factor.

As anticipated, there is a clear noisy load curve when the panel is immersed in the water from the front side (blue curve in Fig. 6). Of course, since the noise is due to the above-explained imperfect rigid connection of the longer impactor, the curve is noisier at higher impact energy (blue curve in Fig. 6b).

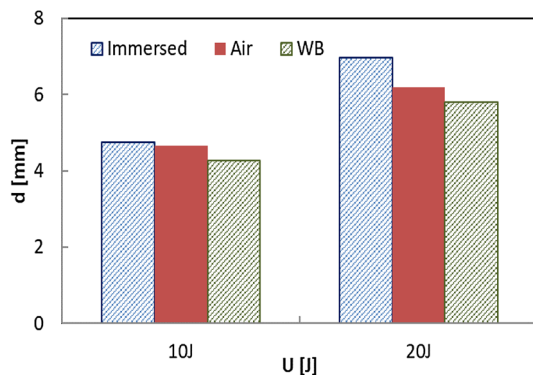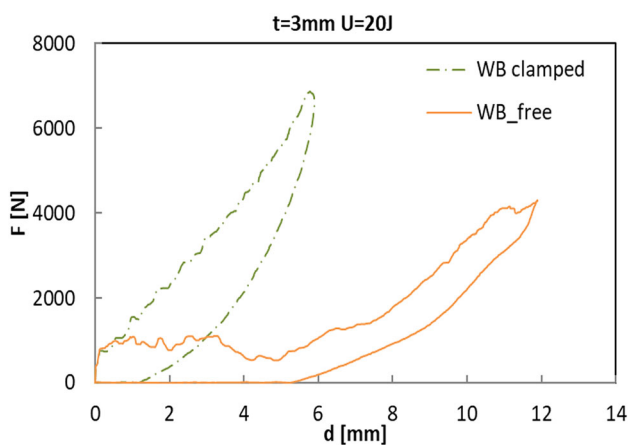An exciting consideration was suggested in the two impact energies used by looking at Fig. 7: The lower energy of $U = 10$ J results in higher absorbed energy when the panel is immersed in the water, even if the values of the WB and immersed conditions are very close to each other. The air-backed panel shows the lower values. At 20 J, the air-backed boards showed the lower energy absorption capability again, whereas in the water-backed conditions, WB, the sensible highest absorbed energy was measured.

Since the energy absorption is strictly related to the mechanisms of damage formation, what is above asserted denotes a strong influence of the entity of the load in determining the fluid–structure interaction and so the response of the panel. In the presence of water, when the impact energy is low (10 J), the distribution of the load is on the entire plane area of the specimens, precisely because of the presence of the

Fig. 8 Maximum displacement; $t = 3$ mm

Fig. 9 Clamped water-backed and water-backed free load curves. $t = 3$ mm; $U = 20$ J
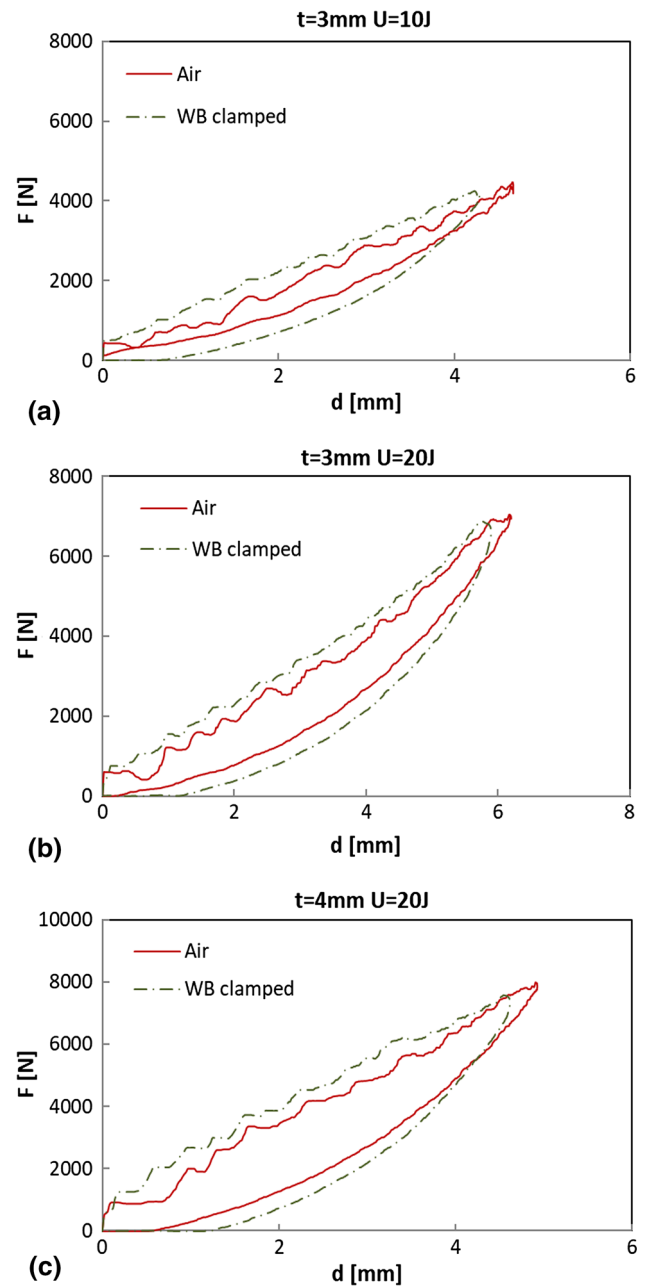

Fig. 10 Load curves in air-backed and water-backed tests; (a) $t = 3$ mm, $U = 10$ J; (b) $t = 3$ mm; $U = 20$ J; (c) $t = 4$ mm, $U = 20$ J

water. It happens irrespective of the fact that the fluid is on the back or the front side and the amount of the absorbed energies is similar (Fig. 7). The increasing load was usually found in a higher maximum deflection ($U = 20$ J in Fig. 8): When the water is on the front side (immersed panels), it is not opposed to this deflection (Fig. 8) since there is air on the back side, and a lower amount of energy is spent on bending (Fig. 7). At the same impact energy, the water on the back side, on the contrary, has a stronger influence in the load distribution, lowering the bending. The latter results in a higher amount of energy absorbed (Fig. 7).

In both cases, the laminates absorb the lower amount of energy in traditional pure impact tests in the air (Air). It is worth to mention that, as found mainly in the literature (Ref 23), at a fixed loading boundary condition, an increasing absorbed energy corresponds to more significant damage. The phenomenon is different if, as in the present case, different boundary conditions are compared. As hereafter shown, the damage caused by the same impact energy is more extensive when the panel is impacted in the air even if it absorbs the lower amount of energy (Fig. 7). The latter phenomenon could be explained by the fact that in real impact conditions (Air), the whole absorbed energy is directly spent to create damage as a consequence of a local Hertzian contact between the impactor and the specimen (Ref 24) and no load distribution phenomena, which need additional energy absorption, are present.
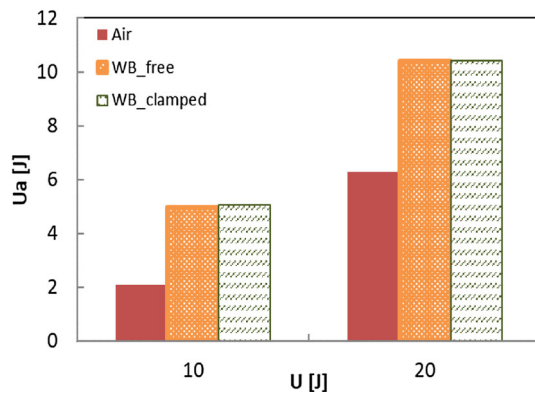
3.3 Effect of the Clamping Device and Fluid–Material Interaction

In Fig. 9, load curves obtained in free water-backed (FWB) and clamped water-backed (WB) impact tests, on the carbon fiber laminates, are reported with the aim of comparing the influence of the boundary conditions. As it is observable, there is an essential different initial rigidity between the two conditions as well as a different maximum displacement.

The maximum load in the clamped WB condition is clearly higher than the one on free water-backed one, as well as the initial rigidity represented by the slope of the increasing part of the curve: It means that the mechanism of the interaction between impactor and material, and of the load distribution inside the specimen, is different. Also, the shape of the curves is different when the water supports the samples. After an increase up to the maximum load, the unloading part of the curve decreases even if the displacement of the sample continues to increase; the decreasing curve reaches, then, a minimum value and increases again up to a second maximum load, higher than the first one. Different explanations of the particular behavior were given in (Ref 2) where no negligible role of the vibrations of the system was highlighted.

However, the energies absorbed in the two different conditions are similar (Fig. 11), as well as the internal damage when the impact energy is 10 J (Fig. 12). When the impact energy is higher (20 J in Fig. 12), the delamination is sensible and lower in WB free conditions and the value is higher a little with respect to the same at $U = 10$ J. The latter denotes once

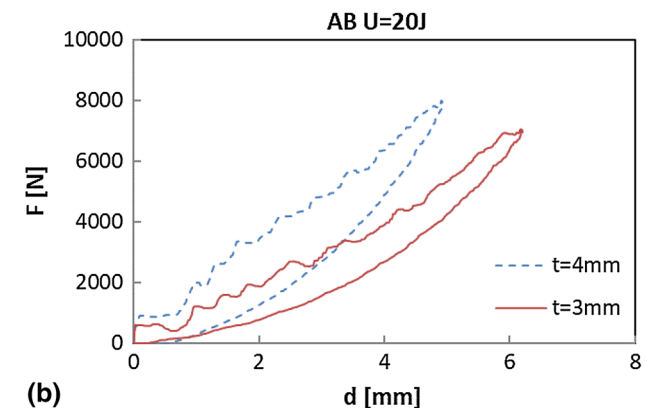**Fig. 11** Absorbed energy, U_a, vs. impact energy, U. Composite laminates ($t = 3$ mm)

Fig. 12 Delaminated area: effect of the boundary conditions; $t = 3$ mm
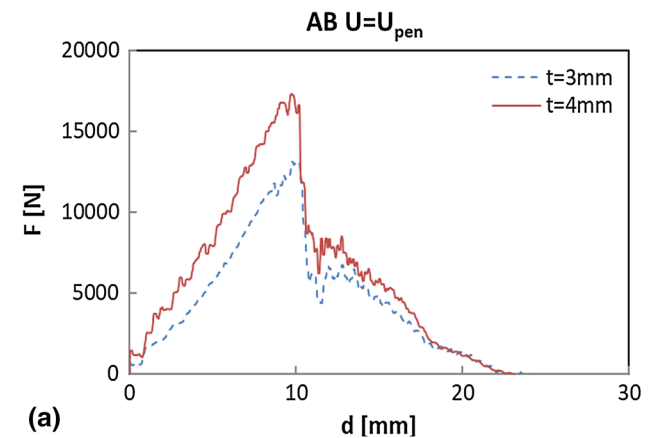
Fig. 13 Load–displacement curves at penetration (a) and 20 J (b) in AB condition

Fig. 14 Load–displacement curves at 10 J (a) and 20 J (b) in WB condition. Effect of the thickness
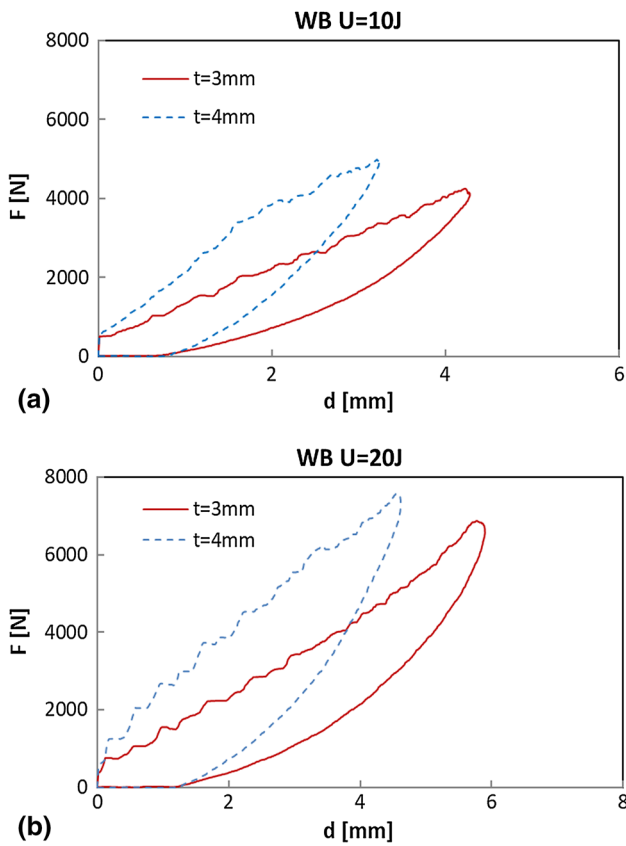

Fig. 15 Load–displacement curves at 10 J (a) and 20 J (b) in immersed condition. Effect of the thickness

again a strong influence of the boundary condition connected to the entity of the load and complicates the phenomenon under study and highlights the needs of impact tests at higher energy values. The mechanisms of damage formation and their interactions are, then, completely different if the only water supports the specimen. Because the interaction phenomena are very complicated to understand by only the experimental observations, it represents a good point to investigate on, through analytical, theoretical models, as already started to do in collaboration with the NY University within the SMP supported by ONR (Ref 25).

Even if the clamping device is the same in air and on the water (air and WB test conditions), a sensibly different absorbed energy, U_a, by comparing the area between the loading and the unloading part of the curve can be seen in Fig. 10. The absorbed energy, U_a, is measured and reported in Fig. 11. The latter shows what is explained above about the similar absorbed energy measured on free supported and clamped water-backed impacted specimens at both impact energies and also the lower Ua obtained in traditional impact tests in the air. Even if the absorbed energy is lower when the panel is in contact with water (Fig. 11), Fig. 12 and 13 shows that the damage measured by the US is lower than the one measured after the impacts in the air. Because of the larger contact area in both the water conditions and the less extension
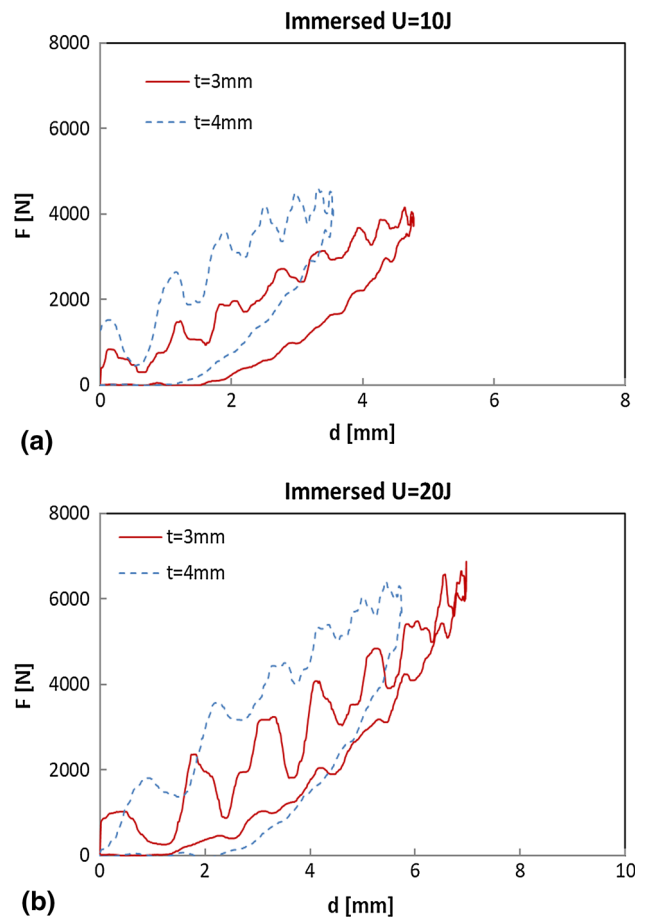
of the delamination (Fig. 12), it means a different and larger load distribution when the water interacts with the specimens (Ref 2), even at fixed boundary conditions. Since the only difference in the tested conditions is the presence of the water, the part of the energy in excess, not used to create damage, can be used only to distribute the load on the entire surface because of the presence of the water (Fig. 14, 15 and 16).

4. Conclusions

In the research discussed in the present paper, novel low-velocity impact test conditions were studied with the aim of understanding the critical issues during the navigation of a ship made of composite panels. The main aspects to consider during the design of a composite structure for marine applications are as follow:

- fluid–structure interaction significantly influences the dynamic response of a composite panel;
- the absorbed energy was found to be higher in the immersed and WB conditions even if the lower damage
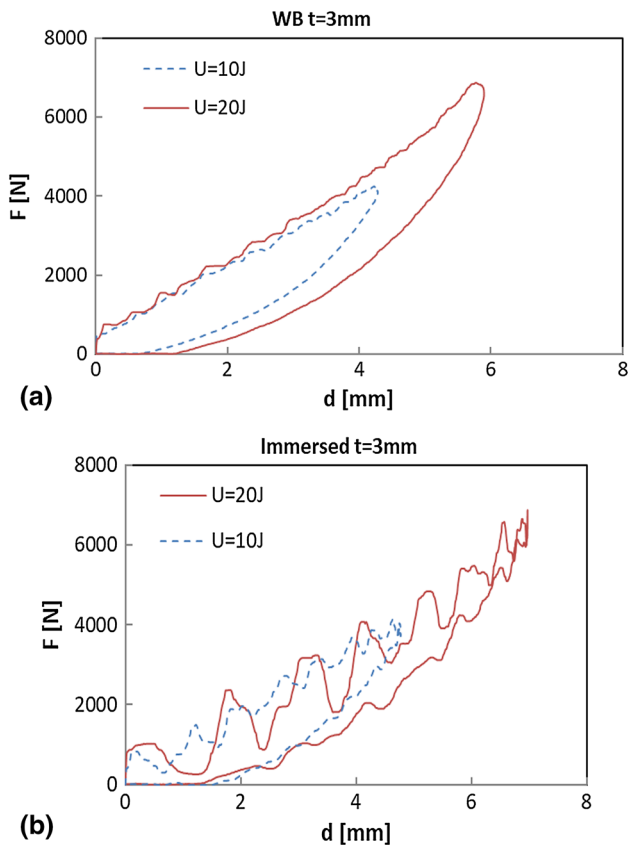
WB t=3mm

Immersed t=3mm

Fig. 16 Effect of the impact energy in WB (a) and immersed condition (b)

extension was measured;

- the clamping device strongly influences the dynamic behavior of the laminate;
- at a fixed clamping device, the only difference between WB and pure Air impact tests is in the amount of absorbed energy denoting a different loading distribution and so the importance of the presence of the water.

Acknowledgments

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