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Composite Laminates Under Dynamic Extreme Conditions

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Abstract

Glass fibre laminates were subjected to experimental low velocity impact tests at three different temperatures, room, T = -25°C, T = -50°C, and the results were compared to investigate the impact behaviour in extreme conditions of composites applied in naval field. The experiments were carried out, first, at complete penetration of the specimens and then, at different energy values to investigate on the damage initiation and propagation. The indentation depths and the delaminated areas were measured and analyzed to validate existing semiempirical models for the prediction of the response of these materials in dynamic shock conditions, at the aim to help the navigation in the Artic Ocean in safety conditions.

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Keywords: low temperature, low velocity impact; composite materials; indentation, delamination.

1. Introduction

Composites Glass fiber reinforcements in a plastic resin as the matrix, is a very common composite material characterized by good physical, chemical, thermal, and mechanical properties. Its dynamic properties are deeply under attention due to the structure of the composite and the particular mechanism of damage formation. A lot of naval and aerospace construction parts are subjected to mechanical shock at low temperatures. In these conditions, the toughness of the material changes respect to the standard conditions causing different damage mechanisms.

In the above cited fields, it is very important the understanding of the dynamic behaviour of these structures in extreme temperature conditions which represent the base of the research presented in this paper.

The changes of the material properties with changing temperature was studied in [1] by Howard and Hollaway whereas in [2] Shindo et al. studied the thermal mechanical response of non-metallic woven composites with temperature-dependant properties. A finite element method was used to study the influence of crack formation, residual thermal stresses and weave curvature on the mechanical performance of glass–epoxy laminates at low temperatures.

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The tensile properties of a glass/epoxy composite which had been cycled with thermo-mechanical cyclic loads at low temperatures (up to 10 cycles) was applied to laminates from room temperature (r. t.) to –50 °C, to –100 °C, and to –150 °C (c. t.) using an environmental test chamber were researched in [3]. Myung–Gon Kim et al. showed that the tensile stiffness significantly increased with decreasing temperature, while thermo-mechanical cycling had little influence on it. The tensile strength, however, decreased as the temperature was decreased.

In [4], Sefrani et al. presented an experimental analysis of the effect of the temperature on both the stiffness and the damping of glass fibre laminates. They showed that the mechanical properties were appreciably maintained up to the glass transition temperature, where the damping increased sharply in a small temperature interval.

Experimental tests on aramid/epoxy composite samples reinforced with glass fibers were performed in [5] by the Sharpy impact method. up to –40°C with 10°C steps.

The effects of the volume fraction of fiber and the temperature on the impact toughness of the composite samples were tested. The impact damage was observed using a microscope at a magnification of 100.

The results showed a slight increase of the impact toughness of the composite samples with increasing temperature in the interval –40 °C to –10 °C. This was followed by a larger increase of the value of the impact toughness with increasing temperature in interval –10°C to room temperature. It was shown that the aramid/epoxy has a higher impact toughness than glass/epoxy at all the tested temperatures. Fiber failure was found in the composite sample and the appearance of damage as a coma in the sample itself. Increasing the volume fibre fraction decreased the impact toughness of the glass and aramid/epoxy.

In [6], the specimens were suddenly exposed to a temperature of –80°C for 2 h and then either immediately tested at that temperature or after allowing the samples to thaw to ambient temperature for 1 h.

In general, many scientists analyzed the properties of polymer composite materials at different temperatures but only a few of them tested their properties on impact loading and studied the change of their impact properties with changing temperature. That was one of the main reasons for the experiments reported in this paper.

2. Materials and experimental set up

Glass layers of dry fibre under fabric form were overlapped following the stacking sequence $[(0, 90)]_n$, n=6-16, and impregnated by epoxy resin to obtain laminates resulting in a nominal thickness in the range 1.8 - 4.5 mm. The fibre volume fraction was $V_f = 48\%$.

The experimental low velocity impact tests have been performed by a Ceast Fractovis drop weight machine, allowing to vary the impact energy by changing the impactor mass and the drop height. The instrumented impactor was cylindrical with hemispherical nose, 19.8 mm in diameter. Impact tests were carried out up to the complete penetration of the coupons supported by cylindrical supports having internal hole 80 mm in diameter. The square specimens, 100 mm in side, were cut from the laminates by a diamond saw and dynamically loaded in the centre with an impact velocity of 4 m/sec.

The updating of the machine by a thermal chamber allowed the tests at low temperature.

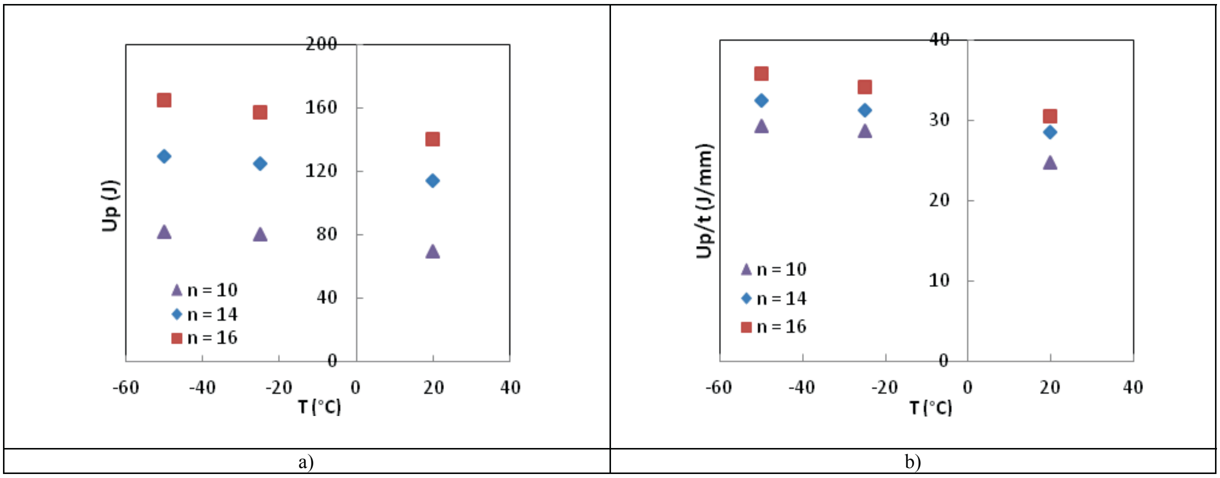
The complete load curves were recorded during each test by the CEAST DAS16000 acquisition equipment and successively studied to measure the penetration energy and the variable energy values obtained in correspondence of characteristic points on the force - displacement curve clearly evidencing a change in material behaviour like a damage, to perform the indentation tests. From the latter tests the study of the damage initiation and propagation was possible.

After each test, each specimen was inspected: the indentation depth was measured by a confocal microscope LEICA DCM3D that give the possibility to extract and record the three-dimensional shape of the surface from what it is possible to extract the section in correspondence of which derive the information about the profile and the measurement of the indentation depth left by the indenter. Since the transparency of the glass fibre laminates, the delaminated areas were obtained by visual inspections: each sample was photographed on the side opposite to the impacted surface with a light source placed on the opposite side (surface with the impact indentation), each photo was imported in a cad software where the delaminated area was bordered and measured.

3. Results

3.1. Penetration energy

Higher energies were necessary to penetrate the same laminates at the decreasing of the temperature and, as expected, the energy increases at the increasing of the number of layers. The result could be explained considering the more brittle behaviour of the laminates under dynamic loading at low temperatures [7] that result in an additional brittle damage like a bigger number of matrix cracks whereas a part of energy is absorbed for elastic deformation at room temperature. The brittle behaviour will be confirmed hereafter by the lower indentation depths measured.



a) b)

Fig. 1. Penetration energy (a), U_p, and specific penetration energy (b), U_p/t, as a function of the temperature, T, for the different thicknesses.

Interestingly, plotting the penetration energy, U_p, against the product txV_fxD_p, (Fig. 2) where t is the thickness, V_f the fibre volume fraction and D_p the penetrator diameter, the power law found in literature [8] was confirmed with a very good agreement of the exponent:

$$U_p = \alpha \cdot t^{\beta} \tag{1}$$

with $\alpha = 0{,}82$ J/mm$^{\beta}$ and $\beta = 1.4$.

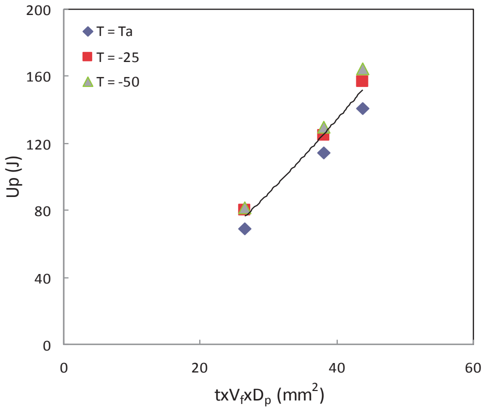
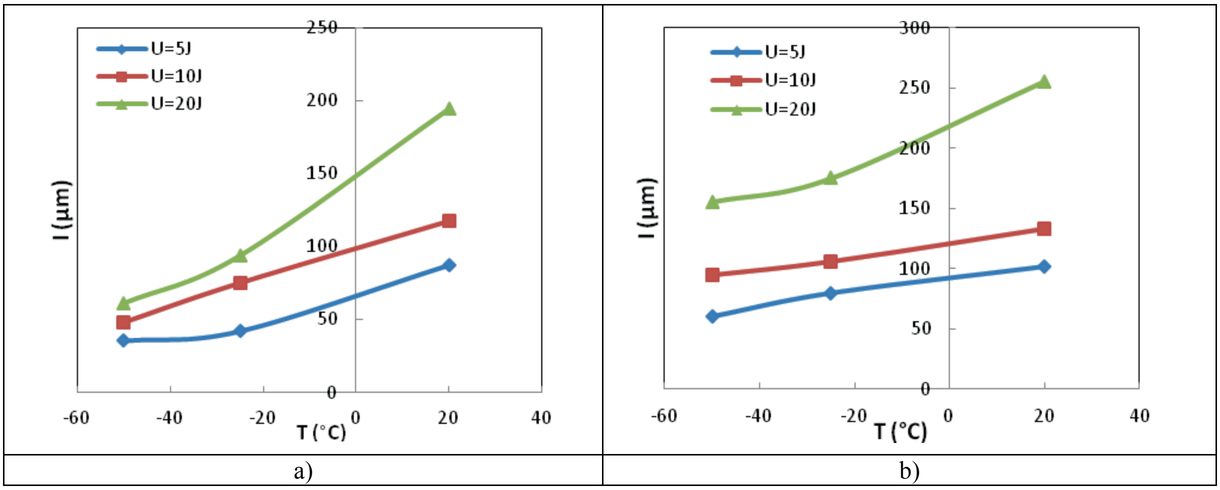


Fig. 2. Penetration energy, U_p, against the product txV_fxD_p, for the different temperatures tested.

3.2. Indentation depth and delaminated area

As the following figures confirm, the behaviour was confirmed to be more brittle at low temperatures. The indentation depth, in fact, the plastic deformation left on the surface of the laminates by the indentor-material contact, increases at the increasing of temperature and the increasing is more marked as the impact energy and the thickness increase.



a) b)

Fig. 3. Effect of the temperature on the indentation depth; n = 10 (a); n = 16 (b).

Plotting, then, the same values of indentation against the impact energy (Fig. 4-5 for example) it was noted a linear increase for the thicker laminates whereas a general logarithmic trend with an horizontal asymptote was evidenced for the thinnest laminates at low temperatures meaning that for these thicknesses the indentation increases up to a certain value of the impact energy after that it becomes constant. In the range of the investigated impact energies, the thickest laminates showed an higher volume for a big number of brittle damages.

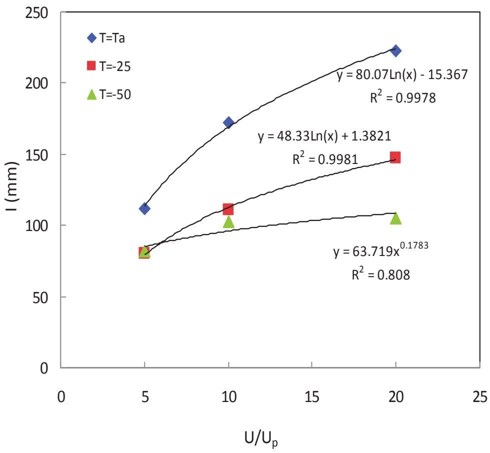


Fig. 4. Indentation depth, I, against impact energy, U. n = 14.

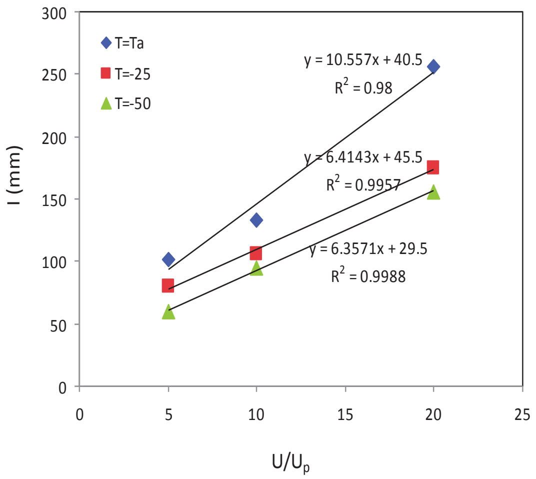


Fig. 5. Indentation depth, I, against impact energy, U. n = 16.

In the following two pictures, the delaminated area, A, measured as explained above, was plotted against the impact energy, U, for the 14 and 16 layers respectively. In general, at the decreasing of the temperature, an increasing of the damage extension was observed and the increasing is more evident at the increasing of the impact energy. However, while the 10 and 16 layers laminates exhibited very similar delaminations for all the temperature conditions tested when impacted at 5 J, different values and a smaller delamination at T = -50°C were measured on 14 layers impacted at the same energy.

Moreover, the delamination area was noted to increase at the increasing of the impact energy, as expected, but the trend seems to become more linear at the decreasing of the temperature. It could mean that, while at room temperature the damage tends to become constant at a certain impact energy value, it continues to increase at lower temperatures denoting more critical behaviours.

The extension of the delamination is larger at the increasing of the thickness also at lower temperatures confirming the difference between the relative importance of the bending effect predominant for the thinner laminates and the shear one, more evident in thick laminates.

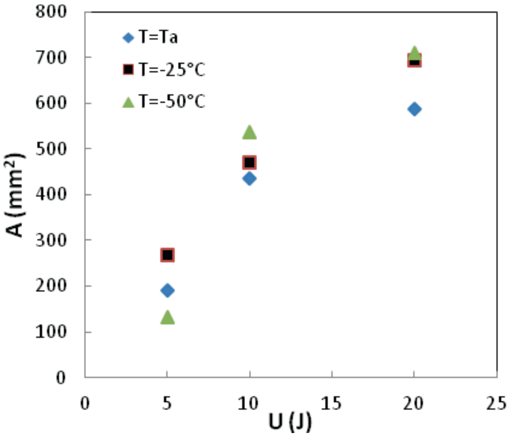


Fig. 6. Delaminated area, A, vs impact energy, U. 14 layers.

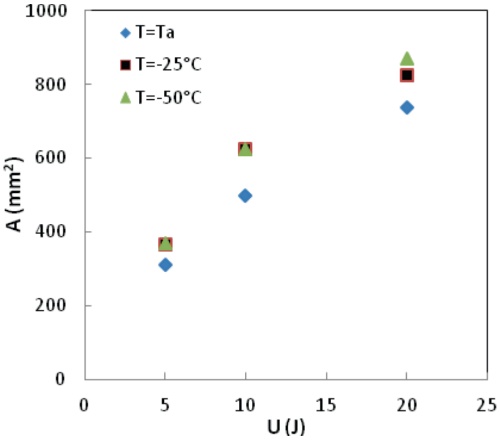


Fig. 7. Delaminated area, A, vs impact energy, U. 16 layers.

Since the open debate [9, 10] about the relative importance of the impact energy or the maximum force in governing the delamination extension, the delaminated area was plotted against the maximum load. Very interestingly, all the experimental data recorded for all the thicknesses, followed a single linear trend, irrespective of the temperature. In Fig. 8 the trend obtained for the 16 layers laminate was shown for example.

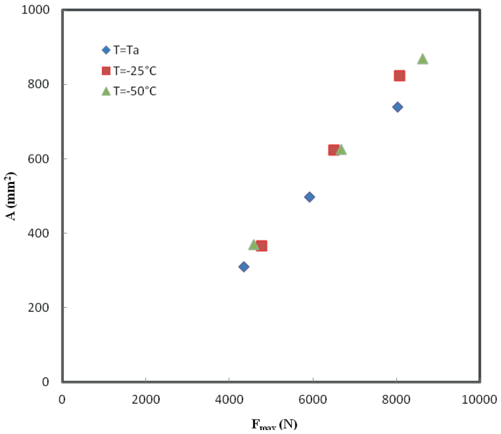


Fig.8. Delaminated area, A, vs maximum force, F_{max}. 16 layers.

4. Conclusions

Low velocity impact tests were performed on glass fibre laminates at room and two lower temperatures, T=-25°C and T=-50°C. The aim was to investigate the impact behaviour of composite materials for marine applications at low temperatures. The results showed a general brittle behaviour respect to the room conditions. In particular:

- higher energies were necessary to penetrate the same laminates at the decreasing of the temperature probably due to an additional brittle damage like a bigger number of matrix cracks;

- the power law equation found in literature for the prediction of the penetration energy as a function of the fibre volume fraction and the impactor diameter was confirmed also in extreme conditions;

- the brittle behaviour at low temperature was confirmed by the lower indentation depths respect the room conditions. The indentation depth, in fact, represents the plastic deformation left on the surface of the laminates by the indentor-material contact during the load, and it was found to increase at the increasing of temperature and the increasing is more marked as the impact energy and the thickness increase;

- about delamination, in general, at the decreasing of the temperature, an increasing of the damage extension was observed and, as expected, the increasing is more evident at the increasing of the impact energy. However, very interestingly, after plotting the delaminated area against the maximum load, all the experimental data recorded for all the thicknesses, was found to follow a single linear trend, irrespective of the temperature.

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