# Reduction of Slamming Damage on GFRP Panels in Dry/Wet Conditions in Hulls of High-Speed Boats

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**Abstract.** In this work we investigated slamming impact damages on symmetric GFRP for high-speed boats' hulls, and two ways to reduce it, the first one consisting in inserting a Kevlar's layer, while the second one consists in putting a 3D-printed sacrificial viscoelastic panel on top of the composite. Both the solution showed good reduction in impact damage and in energy absorption, but 3D-printed layers showed a consistent reduction in energy absorption even at higher energy levels.

**Keywords:** Slamming impact · GFRP · Aramidic fiber · 3D-printed layer

## 1 Introduction

Slamming is a significant event during navigation that occurs as a sudden force that strikes the vessel vertically on the bow and generates energy by the impact of a boat's hull on the free surface of the water. This force results in pulses of short duration (typically on the order of a few milliseconds) that act on a small surface and give rise to high-pressure peaks. The severity of such impacts and the resulting damage to the vessel are so unpredictable that operators proceed cautiously and slowly to avoid additional damage during voyages, a situation that is aggravated in the case of high-speed crafts [1].

In the case of GFRP vessels, slamming is unique in that the impact of the sea is converted into energy that is dissipated in a composite material, producing different levels of damage, which makes studying it very complex. This phenomenon has become one of the most important in ship design directly affecting the cost, capacity, and comfort [2].

In this work, we investigated two ways to reduce the slamming damage, the first one consisting in inserting a Kevlar's layer in the middle of the composite, while the second one consists in putting a 3D-printed sacrificial viscoelastic panel on top of the composite.

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## 2 Experimental Methods

For the slamming tests, 100 × 100 mm GFRP panels were prepared from 0–90 woven fabric and +45/−45 biaxial fabric, and polyester resin, using RTM technology. The panels have been left in vacuum bags for 24 h at ambient temperature, and then put in hoven at 60ºC for 2 h. The lamination configuration was $[0/90, +45/-45, 0/90]_s$.

We also prepared 250 × 250 mm panels to be put in a salt spray chamber to analyse the effect of aging. The spray was made by 3,5% in weight of salt, and unmodified and kevlar-modified panels were left in the chamber for a period of 200, 400, 600, 800 and 1000 h and then tested under slamming impact. To choose the impact energy, some preliminary impact tests were made on 250 × 250 mm dry panels, and then we took the impact energy in which the response was the most elastic, identified at 45,5 J for unmodified panels, and 40,3 J for the kevlar-modified panels. The panels with the viscoelastic layer were not put into the salt spray chamber because that kind of structure is very less sensitive to this kind of aging.

For the manufacture of the viscoelastic layers, a 3D Ultimaker-3 printer with two independent extruders was used to avoid contamination between the two polymers used, and the film was printed on a 200 mm x 300 mm hot bed by sequentially printing layers of molten material. The mechanism for energy dissipation is based on the incompressibility of a material with a Poisson coefficient close to 0.5, as most elastomers have. In this case, the elastomer (Thermoplastic Polyurethan TPU) is surrounded by cell walls of a stiffer material (Nylon). After receiving the impact, the elastomer is forced to deform but it is in confined by the rigid walls that impede the deformation. Forced in a state of volume invariance, the elastomer responds increasing its apparent stiffness modulus.

The viscoelastic layer is made of a periodic repetition of TPU hexagonal structures on the $z$ plane, surrounded by Nylon. The section on the $z$ axis of the TPU structure is also hexagonal. This structure has a nylon core, also hexagonal, as shown in Fig. 1. The largest corner of the TPU hexagon measure 5.60 mm.

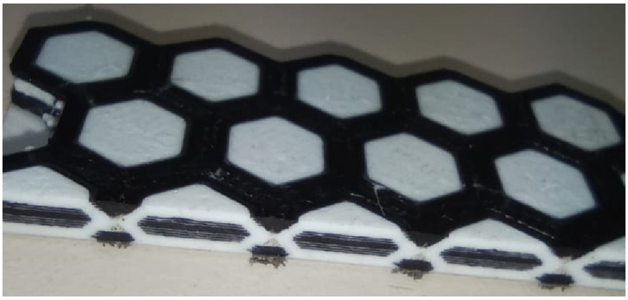

**Fig. 1.** Section of a viscoelastic layer. Is possible to identify hexagonal structures of TPU (in white) and of nylon (in black)

The Kevlar-modified specimens were prepared with the same lamination configuration of the unmodified panels, but right in the middle a hybrid fabric layer, made of aramidic woven and glass fibers mat, was inserted. So, the final configuration was $\left[0/90, \pm 45, 0/90, \mathit{Kevlarlayer}, 0/90, \pm 45, 0/90\right]$.

To simulate the slamming impact, i.e. an impulsive force on the specimens, a low velocity drop weight test was conducted. The impactor head is launched by gravity, guided on two rails. The specimen is installed and clamped on the base. The anti-rebound system is designed to be activated with a laser reader, avoiding repeated impacts. Changing the height and weight of the impactor, we changed the energy of the test. Additionally, an acceleration sensor or single-axis accelerometer was installed. The accelerometer sends the information to a data acquisition system to record acceleration versus the time of impact. From these accelerations we evaluated the energy that the panels received during the impact, and the value of the energy absorbed in delamination, cracking and in general damage processes, as suggested in a previous work [3].

An ultrasonic inspection of each of the specimens was conducted to evaluate damage after LVI. For this purpose, an immersion tank manufactured by Tecnitest was used with a motorized head to sweep the entire surface with an accuracy of 0.1–0.2 mm at a maximum inspection speed of 100 mm/s, and the apparatus was connected to a Masterscan 335 data acquisition and management system, showing the results in a C-scan representation with a color scale indicating the differences in ultrasonic attenuation in each zone of the panel.

## 3 Results

Impact tests gave different kind of response. At low impact energies, the response was totally elastic. At higher energies the panels start absorbing some energy. Finally, at rupture, all the energy is absorbed. This is shown in picture 2. We evaluated the absorbed energies for all the samples, as shown in the Table 1. We plotted the absorbed energy against the impact energy, obtaining the results shown in Fig. 3 (Fig. 2).

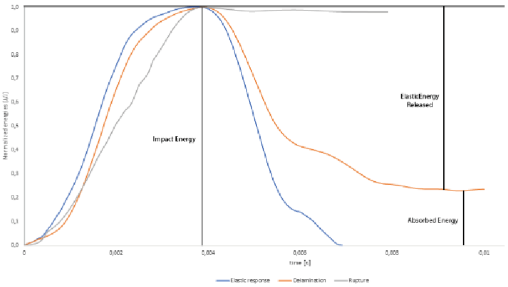

**Fig. 2.** Examples of normalized energies for GFRP panels with different response: totally elastic response (blue), partially elastic response with a certain amount of energy absorbed in delaminations and crackings (orange), and complete penetration into the specimen, where all the energy is absorbed (grey)

**Table 1.** Impact energy and absorbed energy for every specimen.

| Unmodified | | | Kevlar | | | Viscoelastic Layer | | |
|---|---|---|---|---|---|---|---|---|
| **Spec.** | **E_imp** | **E_abs** | **Spec.** | **E_imp** | **E_abs** | **Spec.** | **E_imp** | **E_abs** |
| 1u | 20,34 | 2,35 | 1k | 21,38 | 0,00 | 1_vl | 39,37 | 14,53 |
| 2u | 20,95 | 8,02 | 2k | 27,09 | 0,00 | 2_vl | 49,69 | 19,70 |
| 3u | 26,59 | 20,10 | 3k | 31,27 | 2,99 | 3_vl | 65,65 | 22,25 |
| 4u | 27,12 | 14,82 | 4k | 35,22 | 5,34 | 4_vl | 71,09 | 38,74 |
| 5u | 32,23 | 23,27 | 5k | 37,00 | 8,48 | 5_vl | 87,16 | 68,66 |
| 6u | 33,59 | 26,87 | 6k | 40,69 | 8,95 | 6_vl | 116,09 | 71,28 |
| 7u | 34,71 | 30,72 | 7k | 44,31 | 10,52 | | | |
| 8u | 36,68 | 27,66 | 8k | 49,73 | 19,16 | | | |
| 9u | 42,90 | 32,66 | 9k | 64,73 | 25,74 | | | |
| 10u | 47,75 | 45,79 | 10k | 69,03 | 44,72 | | | |
| 11u | 47,85 | 47,11 | 11k | 70,20 | 43,90 | | | |
| 12u | 66,40 | 66,40 | 12k | 75,43 | 51,49 | | | |
| | | | 13k | 75,76 | 60,16 | | | |
| | | | 14k | 84,73 | 58,81 | | | |
| | | | 15k | 85,15 | 48,58 | | | |
| | | | 16k | 115,39 | 113,90 | | | |

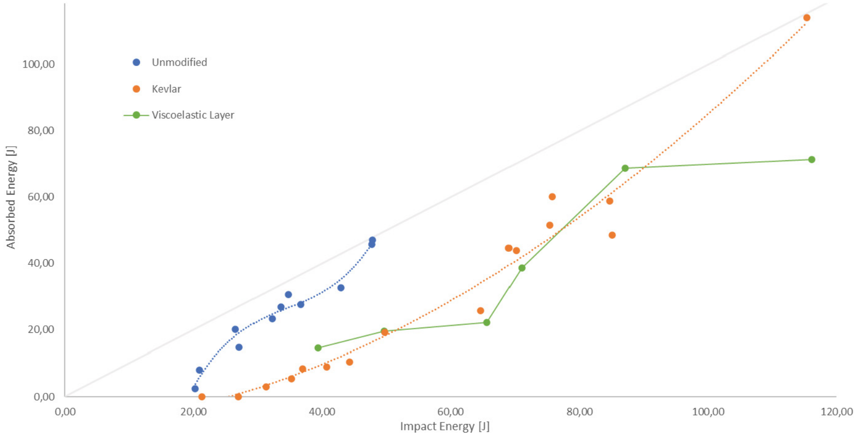

**Fig. 3.** Absorbed energies in LVI by different kind of specimens: unmodified (blue), with kevlar (orange) and with a viscoelastic layer (green)

As we can see, both unmodified and Kevlar-modified panels present a complete elastic behaviour at low energy, while the specimens with the viscoelastic layer present, even at low energies, a certain amount of absorbed energy, due to resin debonding near the viscoelastic layer. At higher energies, unmodified panels reach quite fast the rupture point, identified at almost 50 J, while all the other specimens present just delamination (more or less severe) but without complete rupture. At high energies, i.e. around 70 J, Kevlar-modified specimens start presenting severe delamination and fiber rupture, while those modified with the viscoelastic layer show less severe delamination and small fiber rupture. Finally, at 120 J, Kevlar-modified panels reach rupture absorbing all the energy, while the viscoelastic layer still preserve the panel, even if there is a severe delamination and some fiber rupture. Normalizing this plot respect to areal density (weight [kg] / surface [$m^2$]), we obtain the same results, as shown in Fig. 4.

Ultrasounds analysis show even better results, as shown in Fig. 5. Unmodified specimens and Kevlar-modified specimens present the same behaviour, even if at different energy levels: the damaged surface grows with the impact energy because of delamination processes, until the point in which fiber rupture start, at which delamination processes stop leaving places to fiber rupture processes. Specimens modified with viscoelastic layer show a similar behaviour, but at energies way higher. Only the last specimen, at 116 J, present fiber rupture. In general, visual inspection confirm this hypothesis.

The specimens put in the salt spray chamber showed an interesting response to the effect of aging, according to Zong's and Joshi's previous work [4]: the more the panels remain in the chamber, the most elastic the response to the slamming impact. This can be attributed to the absorption of humidity, that made the polyester resin more plastic and flexible [4]. Unmodified specimens showed this effect in a more gradual way than kevlar-modified specimens, as showed in Figs. 6a and 6b.

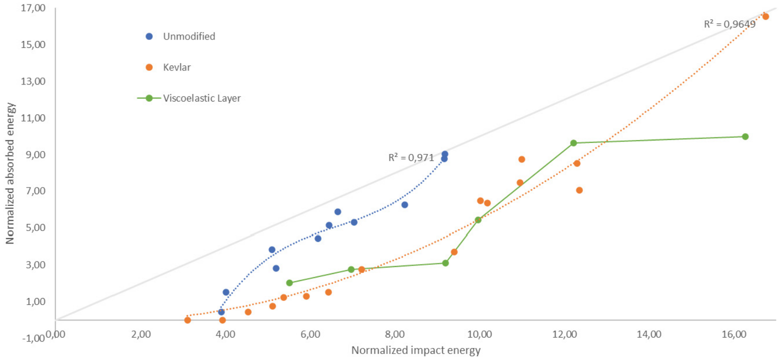

**Fig. 4.** Energies absorbed by different kind of specimens normalized with areal density: unmodified (blue), with kevlar (orange) and with a viscoelastic layer (green)

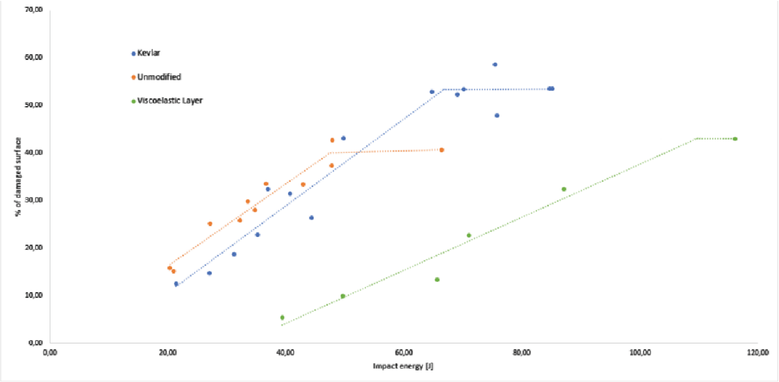

**Fig. 5.** Percentage of damaged surface for different kinds of specimens, measured with ultrasounds analysis.

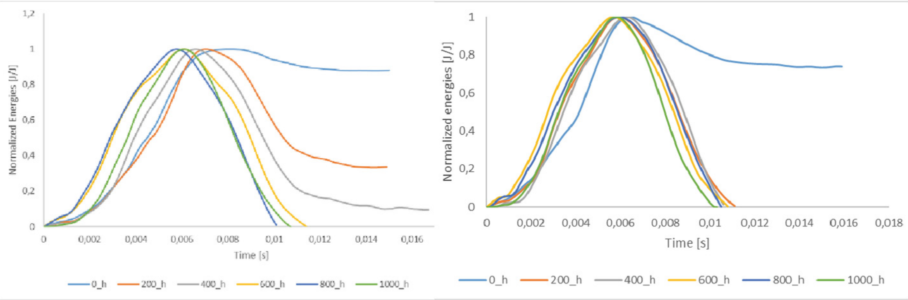

**Fig. 6.** Absorbed energies in LVI for aged specimens. In 6a are shown unmodified specimens, put in the chamber for 0, 200, 400, 600, 800 and 1000 h, while in 6b are shown the kevlar-modified specimens, aged in the same way.

## 4 Conclusions

Investigation of impact damage showed how both solutions (i.e., with a Kevlar layer and with a viscoelastic layer) resist better to slamming impacts, with a range of energy absorption without rupture way wider than the unmodified specimens. For the range of 50 J–75 J, specimens modified with the viscoelastic layer show a more elastic behaviour than Kevlar-modified specimens and present a very smaller delaminated surface. At high energies Kevlar-modified specimens reach rupture (i.e., with impactor penetration) while the specimens with the viscoelastic layer are still resisting well to the impact, just with a little bit of fiber rupture. The salt spray chamber showed how, in the beginning of the aging process, the humidity absorption made the composite panels more compliant.

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