Viscoelastic Layer Insertion to Reduce the Propagation of Energy by Vertical Impacts on Glass Fiber Reinforced Plastic (GFRP) Laminates

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***Abstract*– The insertion of a viscoelastic layer is proposed to mitigate damage by vertical impact. For this purpose, unmodified GFRP panels and others modified with the viscoelastic sheet are made. With the use of an accelerometer, the force of the vertical impacts due to weight drop on the panels is measured, in order to quantify the critical points of damage. The absorbed energy is obtained through the mathematical formulation developed for this purpose. Damage is observed qualitatively by characterizing with penetrating inks to establish a comparison between viscoelastic-modified panels and non-modified panels. Impact force versus time curves are presented to assess damage mitigation in the GFRP. The benefits of the modification are evaluated, and its protection to the laminate is checked.**

Keywords: slamming, GFRP, viscoelastic, impact, acceleration

I. Introduction

The damage propagated within a GFRP laminate was demonstrated in the results of a previous investigation that with the use of viscoelastic sheets, protect the layers from fatigue damage with low energy. In this document, the response of the use of viscoelastic sheets to high energy vertical impacts is studied.

Varela [1] proposed to introduce a layer of pure viscoelastic within the laminate, to dampen the noise and reduce microcracks on structural surfaces. Maly [2] also proposed the design of a composite material with several layers in multiple directions to cushion the impacts on a GFRP laminate. They take advantage of the high rigidity of composite materials [3] but lower damping, combining high levels of energy dissipation with minimal structural rigidity. To analyze the energy that is dissipated and transformed into damage during the vertical impact tests, is an alternative to take advantage of the viscoelastic capacity.

But what is happening within the laminate? In GFRP the energy dissipated in the material after the impact is not evenly distributed. The orthotropy of the material, makes that the deformations observed behave with a variable tension profile inside the laminate, as suggested by López and Seresta [4]. These tensions and deformations on the laminate are not uniform and jump between layers in the transverse direction. Depending on the type of compound, damage is unpredictable. Abrate [5] indicates that "The state of stress in the vicinity of the impact is very complex and requires detailed analyses. Accurate criteria for predicting initial failure are generally not available and analyzes after initial failure are questionable." Vertical impact tests are carried out based on the principle of energy conservation. To study the energies that are produced and dissipated, in the case of GFRP materials it is very complex to evaluate as indicated by Belingardini [6]. This technique provides complete results on the observation of potential energy, which is transformed into kinetic energy. In the case of these materials, they dissipate the energy received through the laminate, and depending on the intensity of the impact, causes different types of damage.

According to the Catwell review [7], the energy absorbed is definitely an important variable to quantify and compare the results obtained in impact tests. The representation of the equal energies applied during the impact of a biaxial composite material, presented by Lopes and Cammanho [8], confirms that the measurement of the energy absorbed is a good comparison factor. It is found that below the equienergy curve, the specimen is not able to absorb all the energy, accumulating the excess in the impactor.

For the study of this dissipation of energy, it is necessary to consider that the use of pre-impregnated materials "out of autoclave" -OoA, cured in the furnace, requires special attention. The research presented in this document was carried out with this type of material.

For the study of the energetic behavior presented during the vertical impact, an accelerometer with computer data acquisition system was used. The use of this equipment is

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adequate, because allows to quantify the energy returned, as demonstrated by Baucoma [9] and Svenson [10]. Elavenil [11] and Grasso [12]. They used this system to develop the behaviors of the generated forces and displacements in GFRP materials.

According to the observations made by Choi [13-14], during the impact the panel begins to bend elastically generating internal stresses and deformations. These are the product of the response to different energies that are transferred from the impactor. After the elastic limit or material damage threshold has been exceeded, the laminate cannot return all the impact energy and the first intralaminar cracks begin to appear. These are observed in a cross section and are marks with normal direction to the impact surface, location changed between layers.

If the impactor continues acting on the panel introducing more energy into the laminate, it goes to the stage in which the interlayer delamination appears. These are oriented in the form of ladder joining the cracks in the matrix. Thereafter, the impactor will break the fibers.

In the case of the vertical impact of low energy, during the milliseconds that the deformation takes place, residual damage occurs in the laminate, and accumulates into the material at the micro structural level [15]. A complete report reviewing the damage resistance imposed by impact of a GFRP was published by Tomblin [16]. Zilong [17] and Sánchez [18] confirm that the evaluation of residual resistance is an important complement in the investigation of a sequence of impacts at different heights. This allows to obtain an exponential relation between the energies, to associate it with the tendency in the change of flexibility.

The proposal of insertion of viscoelastic layers, will definitely dampen the propagation of damage, caused by the energies that remain in the panel after the impact. These energies produce damage from the point of view of analytical micromechanics. House [19] concludes that there is no theoretical analysis on the viscoelastic nature of the matrix, and its damping depends on the orientation of the fibers.

The comparison presented between the unmodified GFRP, and the modified GFRP laminated panels opens an important door to the design of laminated structures. This analysis, from the point of view of the micromechanics, takes advantage of the property of the viscoelastic to have a tension of bending and transverse shear, in an intermediate level between the viscoelastic material and the matrix [20].

Other works prior to the investigation were developed by the author to investigate more about the future of viscoelastic sheets [21-23].

II. Materials and Methods

A vertical impact equipment was built by weight drop, which was configured to work in the conditions shown in Figure 1. The impactor car is launched by gravity on two rails coated with chrome, to reduce the effect of friction. The test piece to be impacted is installed in the base. The anti-rebound system is designed to be activated with a laser reader, controlling the number of impacts. Additionally, an acceleration sensor or single-axis accelerometer was installed.

The accelerometer sends the information to a data acquisition system to tabulate acceleration versus the time of impact.

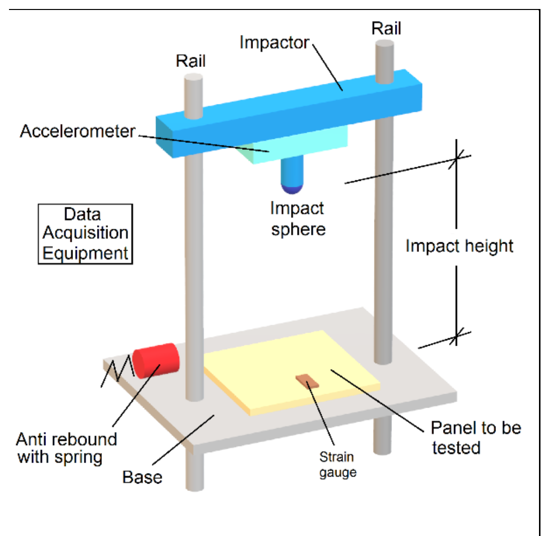

Figure 1 Detail of the performance of the weight drop equipment

The weidht drop equipment has a structure that holds the panel to the base, with all its edges embedded. The dimensions of the panels are 270 mm x 270 mm and can only be placed horizontally. The impactor car was manufactured with electromagnets for its fastening and launching. Guide bolts allow to add more weight to the tests. In the lower part of the impactor car has the impact tip, with a magnetized sphere. An electric motor regulates the height of the impactor, which is measured with a laser light. Figure 2 shows the detail of the equipment of impact.

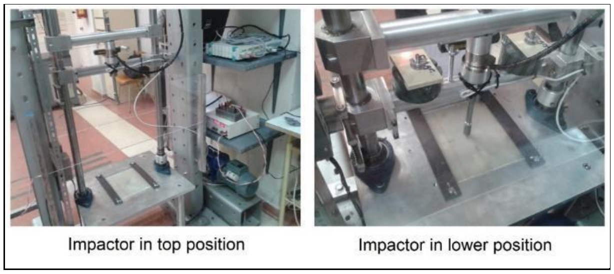

Figure 2 Gravity weight drop impact equipment

The acquisition of data of accelerations G that are recorded by the accelerometer, allows to obtain the profile of the deformation behavior of the panel during the impact. For the handling of data, the following equations were used, in order to obtain the energy curve returned by the specimen after the impact. This allows to assess the energy level delivered during the impact, and how much of this energy is converted into micromechanical damage. G: non-dimensional number of gravities.

t: Instant of time in seconds (s) per acceleration data.

M: Car impactor mass in kilograms (kg).

F: Magnitude of the force that is breaking the layers during the impact and its variation between sheets, calculated with Equation 1 and valued in Newtons (N).

V: Variation of the speed as the car impactor breaks the laminate. It corresponds to the speed steps in meters per second (m / s), during the time in which the impactor car is touching the specimen. It is calculated with Equation 2.

X: Total displacement from the start of the impact in meters (m). Corresponds to the deformation of the surface of the impact face of the laminate, during its bending and restitution. Its value is calculated with Equation 3.

E: Value of the total energy of the impact received by the impactor, calculated with Equation 4 in joules (J).

K: Total kinetic energy delivered by the impactor, calculated by Equation 5 in joules (J).

Eo: Initial energy of the impactor in joules (J) and depends on the launch height and the weight of the impactor.

Ea: Energy absorbed by the panel and that becomes damage. This is evaluated with Equation 6 in joules (J).

$$F(t) = 9.81 * M * G(t) \qquad (1)$$

$$V(t) = v_t + \int_0^t \big(9.81 * G(t)\big)dt \qquad (2)$$

$$X(t) = \int_0^t \big({}^3\!/_2 * 9.81 * G(t) * \Delta t^2\big)dt \qquad (3)$$

$$E(t) = \int_0^t \big(F(t) * x(t)\big)dt \qquad (4)$$

$$K(t) = \int_0^t {}^1\!/_2 * 9.8 * M * \big(V(t)\big)^2)dt \qquad (5)$$

$$E_a = E_0 - (|E(t)| - |K(t)|) \qquad (6)$$

For the tests, laminated GFRP panels were made based on OoA pre-impregnated material (Out-of-Autoclave curing). The material prior to its use, should be kept 24 hours in a sealed plastic bag, so that they reach room temperature. That is, because they were refrigerated at -18 ° C in the storage room. With this, the material does not acquire humidity. The material used was triaxial Gurit WE-91, which comes in fabrics of 1 mm thickness, sheets of 3 layers oriented in 3 directions (0 ° / -45 ° / 45 °) and cut to 270 mm x 270 mm corresponding to the dimension of the base, of the test equipment. Two kinds of panels were prepared, "unmodified" and "modified." Unmodified panels were laminated with a total of nine layers (0 ° / -45 ° / -45 ° / 90 ° / + 45 ° / -45 ° / 0 ° / -45 ° / 45 °) The first layer is on the impact side, and the last layer is the opposite to the impact, which is attached to the strain gauge for the measurement of its micro deformations.

Modified panels were manufactured with a viscoelastic sheet, laminated with a total of 10 layers (0 ° / -45 ° / 45 ° / viscoelastic / 90 ° / -45 ° / + 45 ° / 0 ° / + 45 ° / -45 °). The first layer is on the side of the impact, and the last layer is the opposite of the impact, which has attached the strain gauge to the measurement of its micro deformations.

For the manufacture of viscoelastic sheets, a Sirius 3D printer was used. It had two independent extruders so that there is no contamination between the materials. Prints on a warm bed of 20 cm x 30 cm, on which it makes the superposition of layers of material. The equipment used is of polymer injection type, with molten deposition modeling. It softens the material to produce the layers, which are very accurate, and their finish is almost perfect. The sheets have hexagonal cells or capsule, and the elastomer goes inside. For the manufacture of the outer capsule, acrylonitrile butadiene styrene (ABS) of 3 mm was used. And for the interior elastomer, a linear thermoplastic polyurethane (TPU) was used. Figure 3 shows the viscoelastic sheets manufactured.

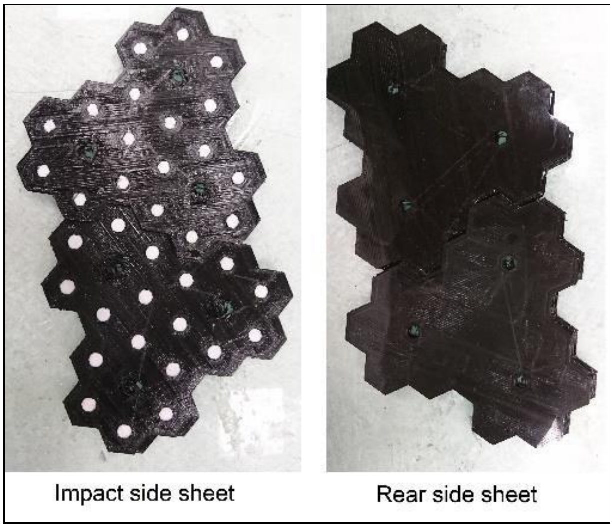

Figure 3 viscoelastic sheet
[https://doi.org/10.1016/j.oceaneng.2018.04.029]

The panels were laminated on a Teflon tool. The inner part was protected with the breathable fabric and the unmovable fabric, in the upper part. A polyethylene bag was used for the vacuum. During the curing of the panels in the oven, the system breathed through these fabrics, allowing the gases not to remain inside the pre impregnated. A vacuum pump was used whilst it was cured in the oven. The applied temperature ramp was 120º C for a time of 120 minutes. Simultaneously in the oven, an unmodified panel and a viscoelastic modified panel was cured. In Figure 4 there are two panels prepared for the curing process, placed in the oven with the vacuum system.

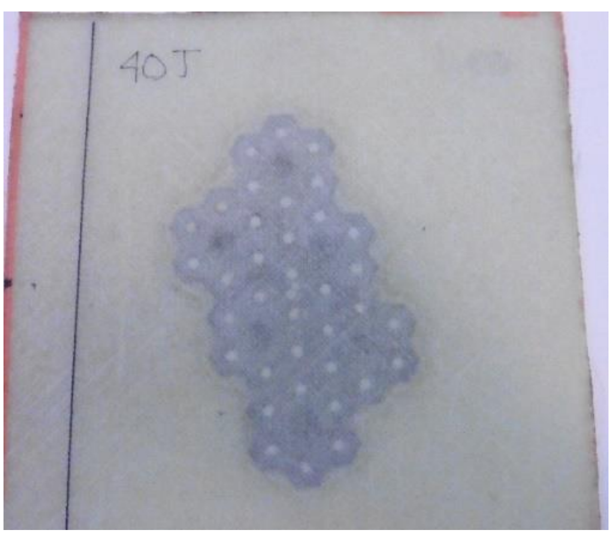

Figure 4 Panels before curing in the oven

In Figure 5, a cured panel with the viscoelastic sheet inside is observed. The surface shown is the impact face.

Figure 5 Viscoelastic sheet inside the cured panel

The impact tests were carried out with different energy ranges. This was achieved by varying the impactor weight and the impact height. The detail of the tests is shown in Table 1. The nominal value of energy considered is detailed, the height at which the impactor was launched, the total weight of the impactor car, the reading of the strain gauge on the surface contrary to the impact, the number of rebounds, and the number of impacts applied to the same panel.

Table 1
Conditions of impact tests

Nominal value of Energy (J)	Impact height (m)	Applied weight (kg)	Micro deforma -tions (μm / m)	Rebounds	Im-pacts
Unmodified panels					
10	0.18	5.549	502	1	1
20	0.37	5.549	749	1	1
30	0.55	5.549	1130	1	1
40	0.73	5.549	1401	1	1
50	0.36	13.829	1710	1	1
60	0.44	13.829	1828	1	1
130	0.97	13.829	3250	1	2
Modified panels with viscoelastic layer					
20	0.37	5.549	252	1	1
30	0.55	5.549	480	1	1
40	0.73	5.549	655	1	1
60	0.44	13.829	991	1	1
80	0.44	13.829	1040	1	1
120	0.85	13.829	1273	1	3
130	0.97	13.829	1338	1	3

Figure 6 shows the unmodified panels impacted from 10 J to 60J, on the opposite side to the impact face, where the strain gauge is located.

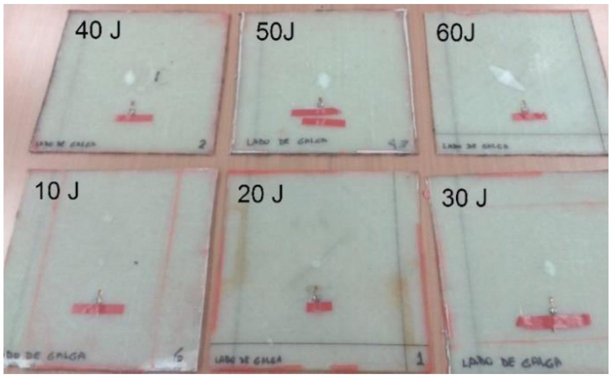

Figure 6 Impact tests from 10 to 60 J of energy to unmodified panels on the opposite side of the impact face

In the case of panels modified with the viscoelastic layer, some tests failed as seen in Figure 7.

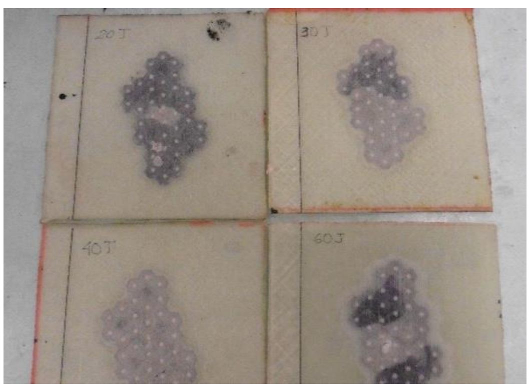
Figure 7 Detachment of the viscoelastic layer after impact

The viscoelastic layer was detached from the laminate. These tests were repeated by placing an additional resin, prior to curing in the oven, to increase the adhesion of the sheet to the panel.

To observe the evolution of the delamination inside the panel after the impacts, they were characterized with fluorescent penetrating inks to expose them to ultraviolet light. This allowed to compare intralaminar and interlaminar damage in both cases. In Figure 8 the characterization sequence performed is observed. Impacted panels were cut 60 mm x 60 mm. Then, they were drilled with a 0.5 mm drill bit. The perforated specimens were immersed in fluorescent penetrating liquid, so that the ink penetrates through the interlaminar and intralaminar delamination and can be observed under the fluorescent light.

The panels, once washed of the penetrating ink, were cut into very thin sections. A sequence of sections was assembled to compare the intralaminar and interlaminar delamination. Using the Rhinoceros software, delaminations were modeled in 3D.

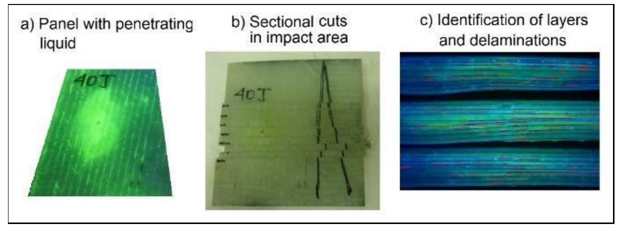

Figure 8 Procedure for evaluation with fluorescent penetrating ink test

Using the Rhinoceros software, the delaminations were modeled to show how the layers were separated. In Figure 9 modeling is exemplified for a modified panel impacted at 40 J and a perspective is observed from the impact surface.

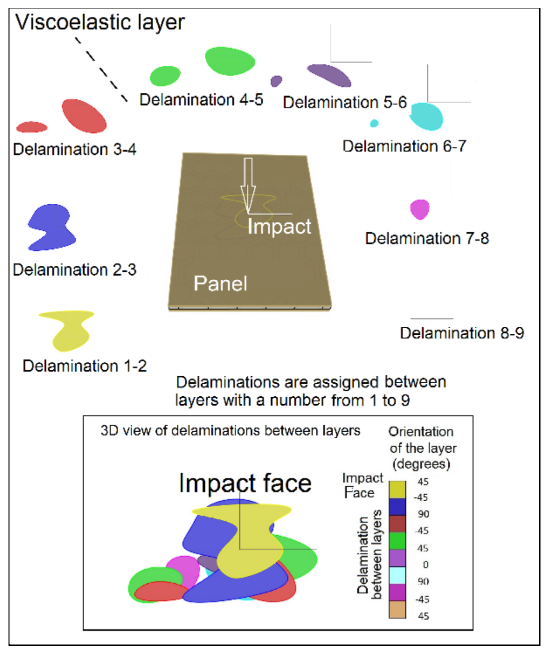

Figure 9 Delaminations represented in Rhinoceros 3D of an impact at 40 J.

II. Results

A. Results with unmodified panels

The impact tests presented consistent results. Figure 10 shows the deformations obtained by the strain gauge readings. The curves have a behavior and an increased value as expected.

The regularities in the curves change over 50 J, and this is observed in the impacted panels that have a diamond shape with severe damage.

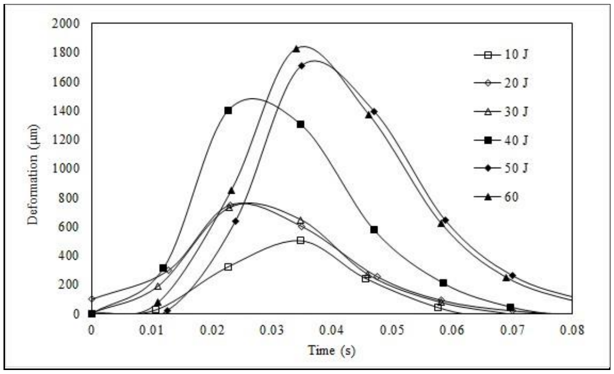

Figure 10 Deformation data of the strain gauge from 10 J to 60 J

From the characterization with penetrating inks to the panels tested with a single impact, was possible to observe under ultraviolet light, the delaminations and cracks that occurred inside the panel. In Figure 11 we can see the panel impacted at 40 J marked for the cut to the left, and on the right its respective damage sequence. There is a remarkable amount of staggered damage, which has joined the intralaminar cracks and the interlaminar cracks producing breaks. In the area of impact, the damage has completely delaminated the panel between layer 7 and 8. The impact energy has been absorbed by the laminate, affecting the entire thickness. There is also a significant number of micro cracks that occur at the level of all layers.

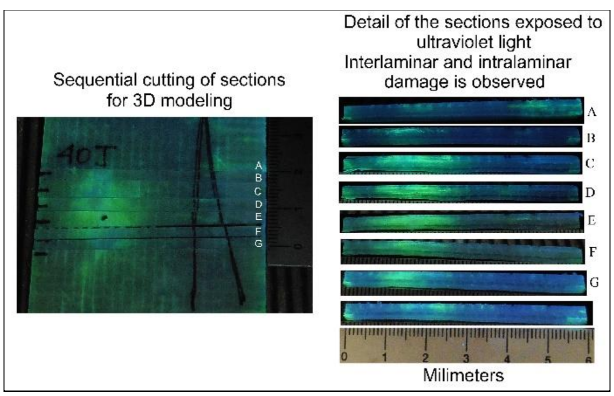

Figure 11 Unmodified panel impacted with 40 J exposed to ultraviolet light

However, in Figure 12, in which a panel impacted at 50 joules is presented, no steps are observed. The energy that became damage, produced intralaminar delamination that joined vertically damaging up to layer 7 and 8. The number of micro cracks is much higher, and is observed massively throughout the area of influence of the impact. There are also interlaminar delamination, which are observed over the entire section of cut.

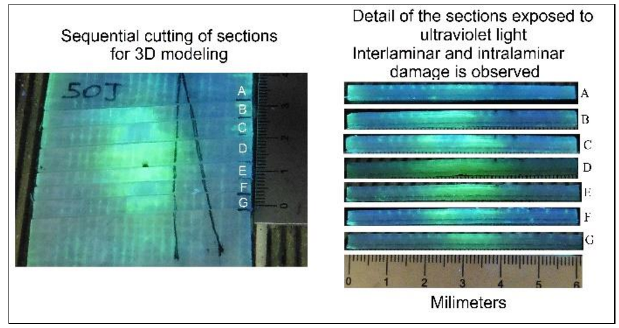

Figure 12 Unmodified panel impacted with 50 J exposed to ultraviolet light

In the two impact tests, at 130 J, impactor penetration was obtained. In Figure 13 it is observed that with the first impact, the panel has a severe damage on its back face. The panel was completely delaminated in all its layers. On the second impact, the impactor punctured the panel and was caught in it.

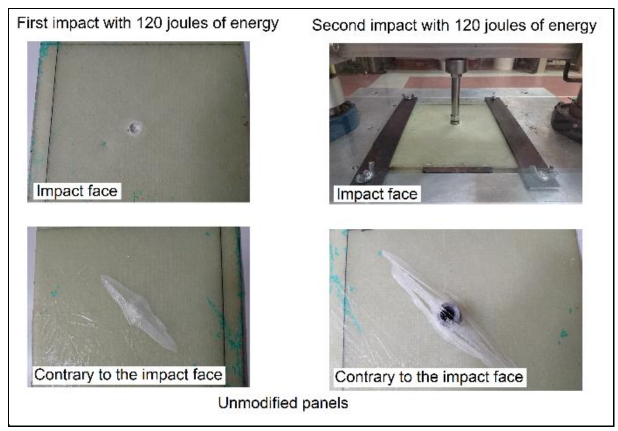

Figure 13 Unmodified impacted with two impacts to 130 J of energy each one

From the results of the models of delamination between layers done with the software Rhinoceros, related to the accelerations to observe the critical peaks, figure 14 shows the results of the peaks of acceleration and its corresponding delamination for the impact of 20 J. Between layer 3 and 4 there is a sudden change in acceleration, because it is observed that the delamination is larger than the precedent. The following delamination have regular variations, being very insignificant, those corresponding to the tensile stress face of the panel.

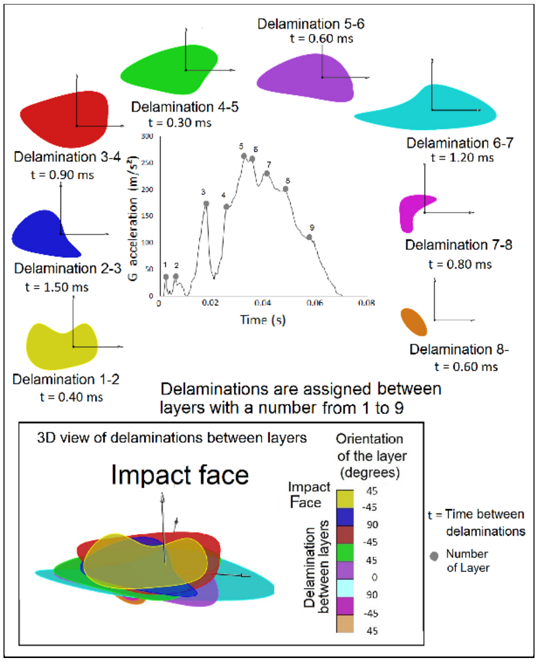

Figure 14 Acceleration curve and delamination of the impact to 20 Joules in unmodified panel

In Figure 15 to 30 J, the delamination follows the orientations between layers, and the peaks in which they break are clearly observed. Between layer 4 and 5, a significant jump in acceleration occurs. This is observed in the form of delamination, which takes a different orientation. Damages are greater and the panel has continuous layer separation.

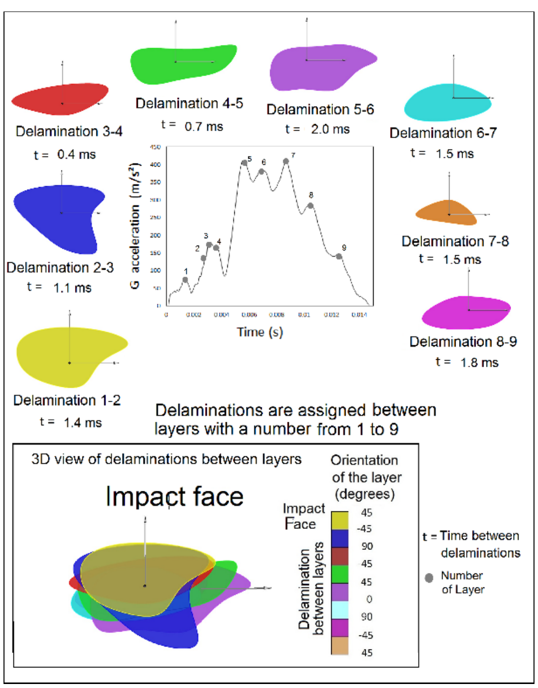

Figure 14 Acceleration curve and delamination of the impact to 30 Joules in unmodified panel

In Figure 16 to 40 J of impact, it is observed that the damage occurs in more closed times and the delamination is significant. The separations of the layers follow the directions of the fibers oriented by the preceding layer and the subsequent layer. The acceleration peaks are more irregular, and the panel is restored without producing delamination peaks.

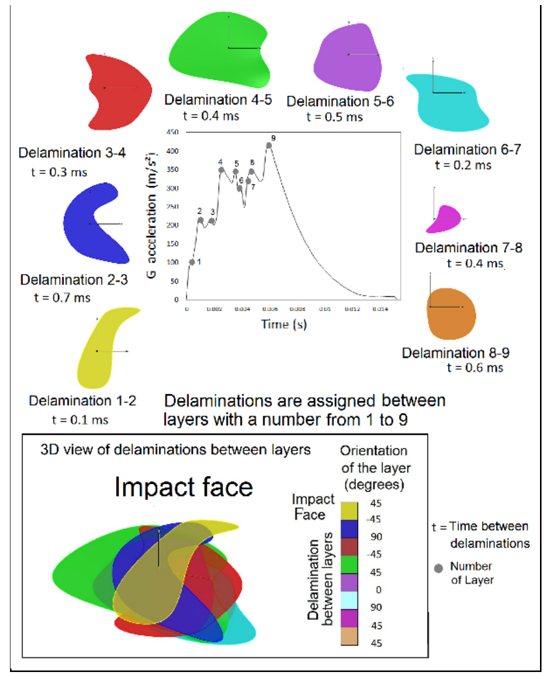

Figure 16 Acceleration curve and delamination of the impact to 40 Joules in unmodified panel

In Figure 17 according to the data handling with the indicated formulation, it is observed that after the impact of the 40 joules, the curve shows a sudden change in the panel's behavior. There is a loss in your ability to return energy. The accelerometer records a large amount of energy absorbed during the impact.

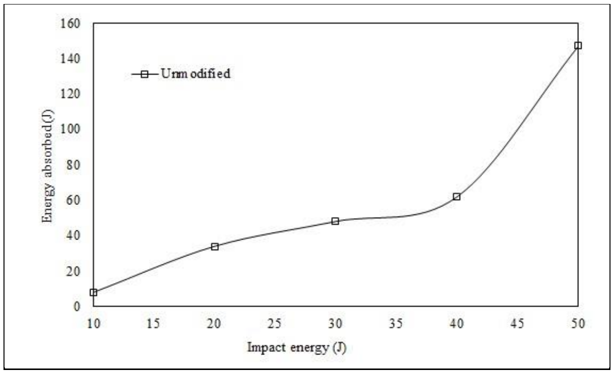

Figure 17 Absorbed energy vs impact energy

B. Results of Modified Panels With Viscoelastic Layer

The deformation data recorded with the strain gauge is shown in Figure 18 for the tests in which there was no detachment of the viscoelastic layer. On the 40 J it is observed that the panel deforms and restores maintaining the tendency of the curve as in the low energy tests.

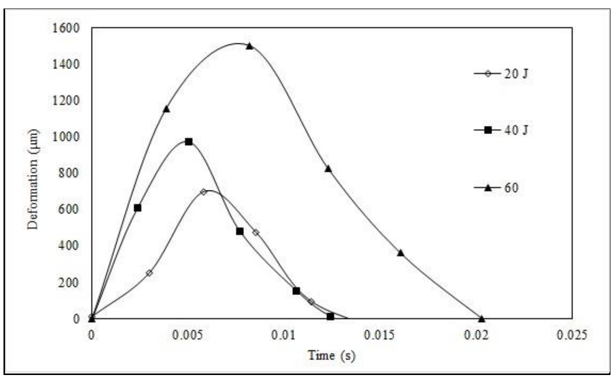

Figure 18 Deformation data of the strain gauge from 20 J to 60 J

The test of three repeated strokes with the same energy of 120 J, was performed without detachment of the viscoelastic layer, as shown in Figure 19. In the second impact, there was perforation without reaching parts of the viscoelastic layer, in the face of the impact. On the opposite side a delamination following the orientation of -45 ° was observed. In the third impact, breaks appeared in the face of the impact that were oriented in two directions close to the impact. On the opposite side of the impact, a new delamination of larger size appeared at + 45 °. There was no penetration at the end of this trial.

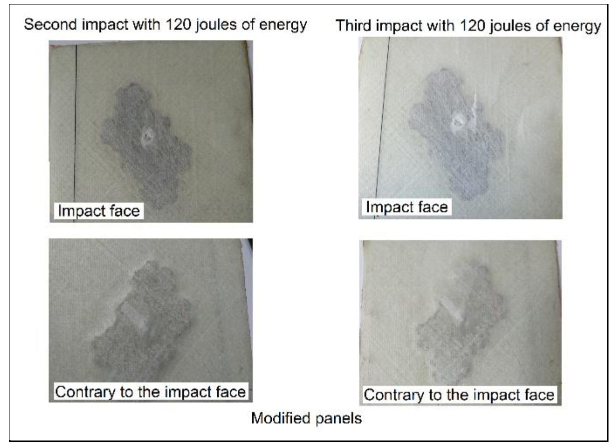

Figure 19 Modified panel impacted with three impacts to 120 J of energy each one

The impact test at 130 J, had very similar results and did not penetrate the impactor.

The acceleration curves clearly show the critical point when the impact reaches the viscoelastic layer as indicated in Figure 20. The acceleration peak dampens the subsequent peaks reducing the abrupt changes of acceleration between layers. The correlation with delamination represented in 3D, of the characterization with penetrating inks, shows that after the viscoelastic layer, these are minor.

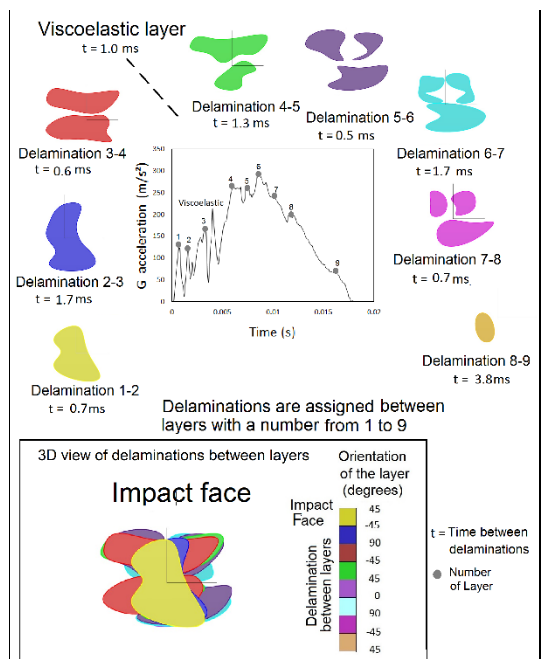

Figure 20 Acceleration curve and delamination of the impact to 40 Joules in modified panel

The acceleration profile shown in Figure 21, graphs more closed peaks after impact, which are dampened as the panel is blended. The layers are broken in different directions and in different areas as seen in the 3D planes of delamination. Times are shorter between critical peaks before the viscoelastic layer and are greater between delamination after the viscoelastic layer.

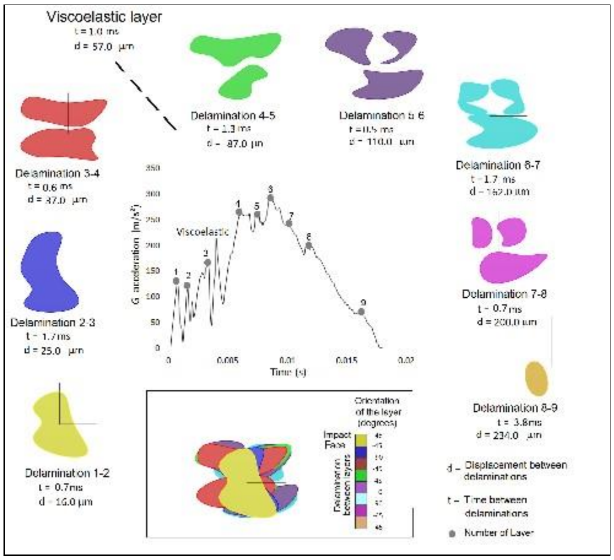

Figure 21 Acceleration curve and planes of delamination of the impact to 80 Joules in modified panel

Characterization with fluorescent penetrating inks, allows to observe that the damage in the layers under the viscoelastic sheet is minimal, as shown in Figure 22. The interlaminar delamination do not form connections with the intralaminar cracks. There is damage in different orientations, and there are sections that do not show damage. It is also observed that the viscoelastic sheet is adhered to the panel by the additional adhesion that was included during the curing process.

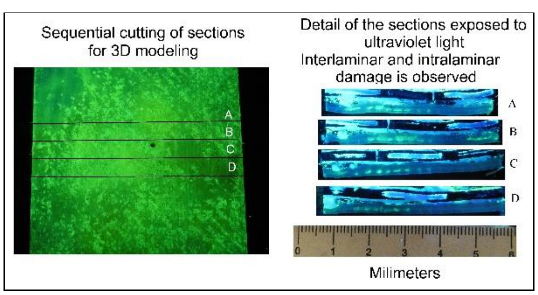

Figure 22 Modified panel impacted with 40 J exposed to ultraviolet light.

The energy absorbed, calculated with the proposed equations, has a tendency as shown in Figure 23, in which it is plotted versus the impacts applied to the panels. It shows that the increase in energy absorbed is gradual up to 110 J of impact. After this value, there is a significant change in the energy that is transformed into damage.

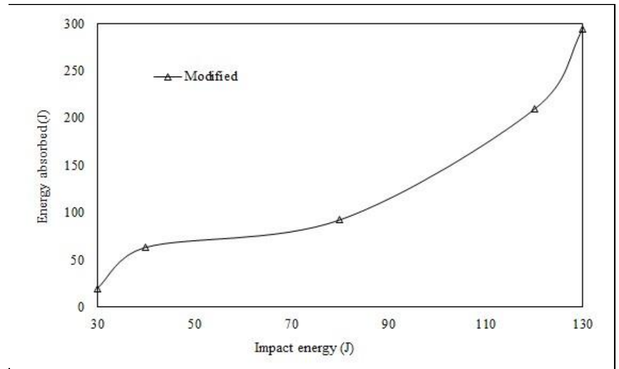

Figure 23 Percentage of energy returned in modified panels with viscoelastic layer

V. DISCUSSIONS

Figure 24 shows the deformation curve of the strain gauge for a vertical impact of 20 J to a modified and unmodified panel. It is observed that at that low energy, the response of the modified panel is in a lower time. The viscoelastic layer changes the rigidity of the panel and causes it less deformation. The modified panel takes the hit energy faster and returns it with a lower energy of damage inside.

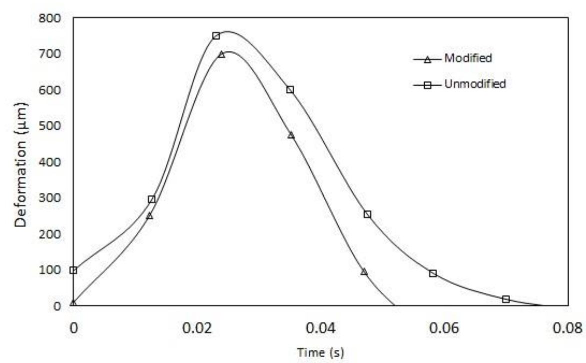

Figure 24 Comparison of the deformation to an impact of 20 J

In Figure 25, for a vertical impact of 40 J, the response to impact is still less for the modified panel. Its deformation is also smaller, which indicates that there is a significant difference in damage inside. The tensile stress that delaminates the panel will be less in the modified, meaning that less energy is transformed into damage.

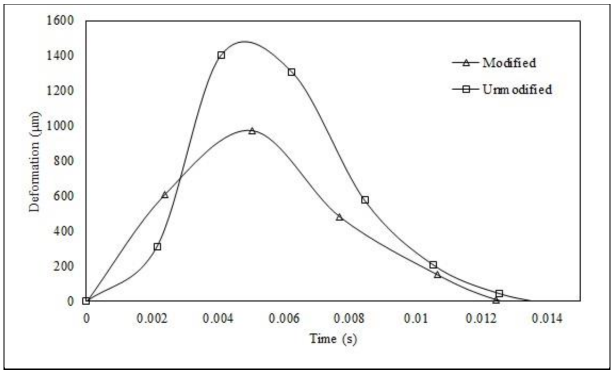

Figure 25 Comparison of the deformation to an impact of 40 J

If we compare two sections at a destructive energy level for the panels, as seen in Figure 26, in fluorescent light, it's observed that the impact of a modified panel of 80 J, has a much lower damage under the viscoelastic layer, than the panel impacted at 60 J without modification. The unmodified panel presents damage in all of its layers, complete delamination of the last layers and multiple breaks in the matrix. On the other hand, the modified panel has a low level of damage, which indicates that it has been protected by the viscoelastic sheet.

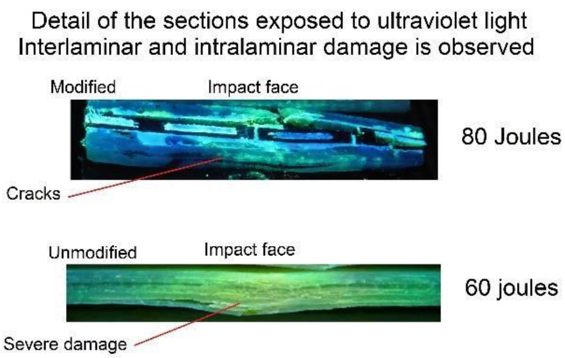

Figure 26 Comparison of sections of impacted panels exposed to ultraviolet light

To summarize the 3D models of delamination between layers for both panels, Figure 27 is shown, in which delaminated panels are compared for some vertical tests carried out. The impact of 50 J in an unmodified panel is similar to the impact of 80 J in a modified panel. The viscoelastic sheet allows level of damage gets displaced, transforming high energy impacts into low energy. On the opposite side to the impact face of the panel, it is observed that the difference in damage ratio is much lower in the modified.

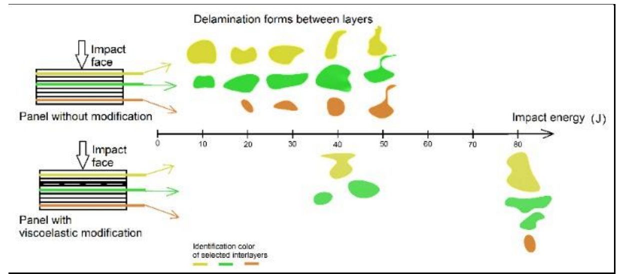

Figure 27 Comparison of 3D delaminations for vertical impacts

Comparison of the energy absorbed versus the applied impacts is observed in Figure 28. The unmodified panel loses its ability to give energy back, over 30 J, whilst the modified panel, over 120 J. This difference corresponds to the energy returned by the viscoelastic material of the sheet. This is compressed, preventing energy from accumulating in the laminate.

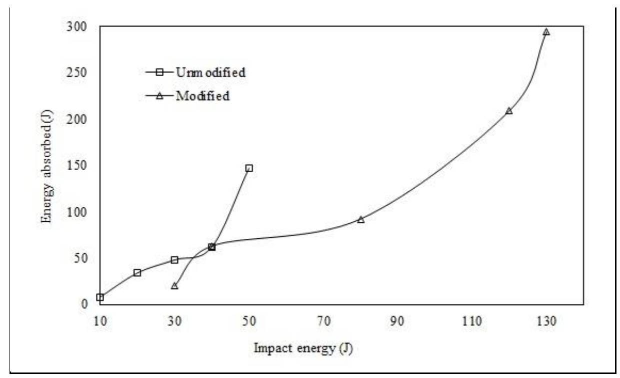

Figure 28 Comparison of absorbed energy versus applied impacts

V. CONCLUSIONS

It is demonstrated that definitely the inclusion of the viscoelastic sheet protects the GFRP from the destructive damage of impact loads. This is the future of laminate construction. The impact energy, which destroys the layers, is not absorbed after the viscoelastic layer inserted.

It is time to change the mindset of panel builders and other GFRP systems. The correct insertion of the viscoelastic sheet is the solution to lengthen the useful life of the structures. It is the solution to improve the performance and handle the residual resistance of the laminates.

This does not imply structural modifications, neither changes in the structural design, due to its only being included in the laminate and we take advantage of its benefits.

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