IMPACT PERFORMANCE OF OUT OF DIE UV CURED PULTRUDED PROFILES FOR VESSEL STRUCTURES

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Abstract: *Out of die ultraviolet (UV) cured pultrusion is an automated process for manufacturing bent profiles that can replace the labour-intensive processes currently employed for manufacturing stiffeners for vessels structures. As the applied pulling forces are lower than in conventional pultrusion, profiles with low longitudinal fibre content can be manufactured, improving the transverse mechanical properties of the pultruded composites. Since impact response is significantly relevant for naval applications, in this paper, the low-velocity impact performance of a multiaxially reinforced UV pultruded profile has been compared to that of a typical pultruded composite. The impact resistance achieved for the multiaxial reinforcement configuration showed an 85% higher perforation energy threshold and a 100% higher maximum peak force than in the reference one. The damage tolerance of the multiaxial configuration was also higher, as when suffering a 30 J impact retained 60% of the stiffness, whereas the conventional pultruded composite only did 45%.*

Keywords: Impact behaviour; Pultrusion; Reinforcement configuration; UV curing; Damage tolerance

1. Introduction

The manufacturing processes currently employed in composite vessels are eminently manual, representing a high production cost for the shipyards. Moreover, the applied manufacturing technologies require highly skilled labour, present low production rates, and do not ensure repeatable mechanical properties, negatively affecting the robustness of the process. The consequences of these issues become even more noticeable in the specific case of the vessel hull or superstructure. These structures consist of a stiffened skin where each stiffener must have a different geometry adapted to the required shape. The stiffening profiles are manufactured by manually laminating over expanded polyurethane preforms, which are previously machined to the specified geometry and bonded to the skin [1]. The lack of robustness of this process leads to the oversizing of the vessel structures, not to mention that preforms do not have any function in service. Therefore, introducing automated and flexible technologies for manufacturing composite vessel structures would provide a competitive advantage to the European shipyards.

Pultrusion is one of the most automated and productive processes for manufacturing composite profiled shapes [2]. However, their use is limited because just straight or constant radius stiffeners can be manufactured by thermally cured pultrusion [3–7]. A feasible option for manufacturing profiles with a variable curvature is curing the pultruded composite out of the die by employing UV radiation. This approach is implemented in the out of die UV cured pultrusion technology [8,9]. Additionally, the pulling forces applied in this process are lower than in conventional pultrusion since the profile is cured out of the die. Thus, the amount of fibre reinforcement that must be oriented towards the longitudinal direction to bear with the applied pulling force can be reduced. Therefore, pultruded profiles manufactured by out of die UV cured pultrusion can offer enhanced transverse mechanical properties as more fibre reinforcement can be placed with that orientation. This feature is especially beneficial for naval applications, where stiffeners have to be able to withstand complex loading conditions, as well as being exposed to unintended impacts.

Hence, the present paper analyses how the impact response of stiffeners could be improved when taking advantage of the greater freedom for defining the profiles reinforcement configuration provided by out of die UV cured pultrusion. For doing so, a multiaxially reinforced pultruded composite made of quadriaxial non-crimp fabrics and unidirectional roving has been subjected to drop weight low-velocity impact tests. The impact behaviour reported for this reinforcement configuration has been compared to that of a typical pultruded composite. The peak load evolution, the damage, penetration and perforation thresholds, and the after impact residual stiffness of both reinforcement configurations have been experimentally determined to perform such a comparative study.

2. Methodology

2.1 Materials

The pultruded composites analysed in the present study were made of a photocurable vinyl ester acrylate resin provided by Irurena Group (IRUCRIL GFR-30 LED) and had a 3 mm thick and 75 mm wide flat plate geometry. The two different reinforcement configurations, illustrated in Figure 1, were tested. A reinforcement configuration consisting of a thick roving (4800 TEX) central layer surrounded by stitched continuous strand mat (CSM) tapes (300 g/m^2) typically employed in conventional pultrusion [10–12] was set as a reference; while the multiaxial reinforcement configuration had a thinner roving (4800 TEX) core with two quadriaxial non-crimp fabric tapes (600 g/m^2) placed on each side. The mat tapes in the reference configuration are 25 % of its reinforcement, while the multiaxial configuration has a 40 % of the fibre reinforcement placed in non-longitudinal orientations.

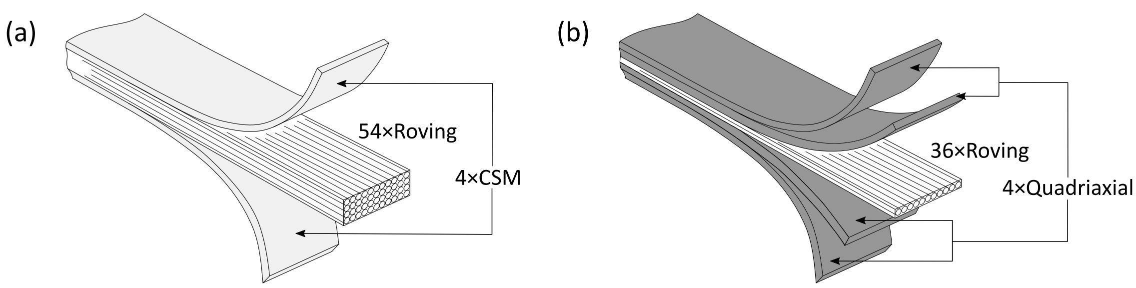

Figure 1. Reinforcement of the studied pultruded laminates: (a) reference and (b) multiaxial configuration.

2.2 Manufacturing process

The out of die UV cured pultrusion (Robtrusion®) line developed by the Polymer and Composites Technology Research Group from Mondragon University and Irurena Group was used for manufacturing the tested composites. This machine uses a resin open bath to impregnate the fibre reinforcement, which is then shaped and compacted in a die with a 100 mm length. Two FireJet FJ240 UV LED sources (Phoseon) placed at the top and bottom of the profile right at the exit of the die are used to cure the composite. A KR 510 R3080 (Kuka) robot arm is employed to pull the profile following a straight path with a velocity of 1.2 m/min.

To ensure that all the tested specimens had the same curing degree, they were subjected to a post-curing of 3 hours at a temperature of 100 ºC. Additionally, the ASTM D3171 standard was followed to experimentally determine the fibre, resin, and void volumetric content in order to assure that the quality of both analysed reinforcement configurations was alike.

2.3 Low-velocity impact tests

A drop weight Fractovis-Plus (CEAST) machine was used to perform the low-velocity impact tests. Initial drop heights ranging from 50 mm to 1000 mm and striker masses from 2 kg to 20 kg were set to define the applied incident impact energies ranging from 1 J to 200 J. A clamping ring with 40 mm inner and 60 mm outer diameters held the square specimens cut from the manufactured profiles during the impact events. These specimens were impacted with a 20 mm diameter hemispherical instrumented striker equipped with a 20 kN load cell, and an anti-rebound system ensured that they were impacted just once. The progress of the contact force generated between the striker and the specimen during the impact event was reported. The absorbed energy was computed by integrating the force versus time curves [13] following the next equations,

$$a(t) = \frac{F(t)}{m} \cdot \mathrm{g} \quad (1)$$

$$v_0 = \sqrt{2\mathrm{g}h} \quad (2)$$

$$v(t) = v_0 + \mathrm{g}t - \int_0^t \frac{F(t)}{m} dt \quad (3)$$

$$\delta(t) = v_0 t + \frac{\mathrm{g}t^2}{2} - \int_0^t \frac{F(t)}{m} d^2t \quad (4)$$

$$E(t) = \int_0^{\delta(t)} F(\delta) d\delta \quad (5)$$

where $F(t)$ is the contact force curve, $a(t)$ is the acceleration experienced by the impactor, m is the mass of the impactor, g is the gravitational acceleration, t is the time, v_0 is the initial impactor velocity, h is the initial height of the impactor, $v(t)$ is the impactor velocity curve, $\delta(t)$ is the specimen deflection and $E(t)$ is the absorbed energy curve.

A multi-parameter analysis has to be addressed to assess the impact behaviour of composites [14]. Usually, the peak force and dissipated energy as a function of the incident impact energies are reported. But additionally, the three-impact test method proposed by Feraboli *et al.* [14] was applied in this work. This method is based on the fact that the contact time experienced for a subcritical impact is a property of the striker and specimen stiffness and allows to experimentally determine the residual transverse stiffness of the composite specimens in the same way as the Compression After Impact standard test (ASTM D7136) does. It consists of a first subcritical impact performed to measure the impact contact time when no damage is generated, followed by a second supercritical impact which induces damage in the specimen, and finally, a third subcritical impact equal to the first one. Considering that the impact conditions are the same, the enlargement in the contact time measured for this third subcritical impact with respect to the one experienced in the first impact can only be a consequence of a decrease in the specimen's stiffness. Therefore, the residual stiffness of the composite can be quantified from the ratio between the contact times registered in the subcritical impacts performed when the specimen was undamaged and when it had already been damaged.

As the tested specimens are not opaque, the extent of the generated delamination damage could be analysed with the backlighting technique [15]. Computer vision was applied to avoid any subjectivity when determining the delaminated areas.

3. Results and discussion

3.1 Fibre and void content

The high fibre content and low porosity obtained in the pultruded composites manufactured by out of die UV cured pultrusion evidence the process quality. As collected in Table 1, a similar fibre content was achieved for the reference and the multiaxial configurations, making them suitable to study the effect of the reinforcement configuration on their impact response.

Table 1: Fibre and void volume content for each pultruded composite.

Pultruded composite	Fibre volume content [%]	Void volume content [%]
Reference	62.8 ± 0.3	0.3 ± 0.1
Multiaxial	62.1 ± 0.7	1.3 ± 0.2

3.2 Impact resistance

The trends followed by the impact response of both reinforcement configurations can be studied from the peak force and dissipated energy plots. As usual in thin composite plates [14], the peak force evolution from Figure 2 shows how it increases with the impact energy as long as only delamination damage is experienced and reaches a plateau when fibre breakage starts. A 13400 N maximum peak force is obtained for the multiaxial reinforcement configuration, while the reference configuration gets to a 6800 N maximum.

Three regimes can be differentiated according to the permanent deformations generated in the specimens in the dissipated energy plot from Figure 3. In the first regime, the low incident impact energies are not enough to dent the specimen surface and the striker rebounds. Therefore, the dissipated energy is below the 1:1 dashed line representing the available impact energy. The dissipated energy quadratically increases throughout the first regime until a point where the striker no longer rebounds, beginning with the second regime. From this point on, specimens are penetrated by the striker, and all the incident impact energy is dissipated. Finally, in the third regime, the incident impact energy is enough to perforate the specimens, and the dissipated energy reaches an asymptote.

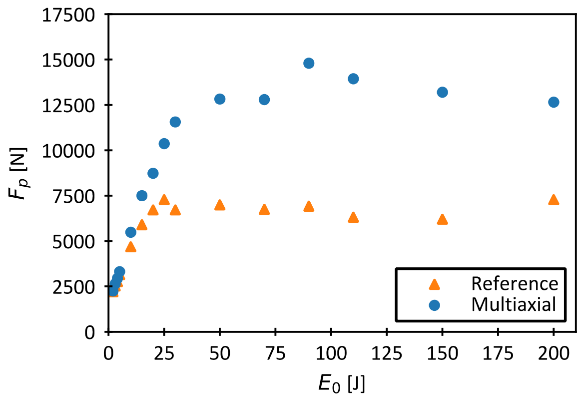

Figure 2. Peak force plot for the reference and multiaxial configurations.

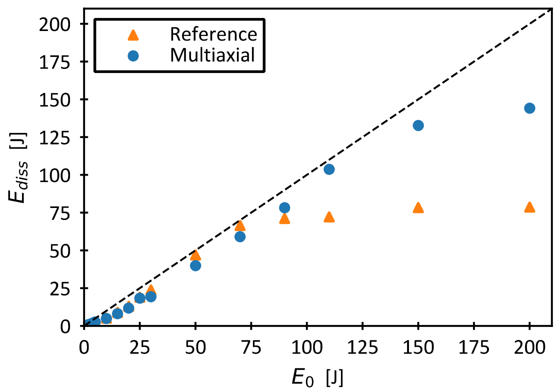

Figure 3. Dissipated energy plot for the reference and multiaxial configurations.

The critical impact energy above which the specimens experience damage is almost the same for both reinforcement configurations, as it is determined mainly by the resin fracture toughness. However, the improvement in the impact resistance provided by the multiaxial reinforcement configuration is evidenced by the considerably higher penetration and perforation impact energy thresholds achieved in comparison to the reference configuration. These characteristic impact energies are collected in Table 2.

Table 2: Delamination, penetration and perforation energy thresholds for the reference and the multiaxial configurations.

Pultruded composite	Critical energy [J]	Penetration threshold [J]	Perforation threshold [J]
Reference	1.2	50	75
Multiaxial	1.3	115	140

As the testing conditions are the same for both reinforcement configurations, the energy dissipated in the rebound region is related to the extent of the delamination generated in the specimens [14]. Hence, the delamination observed in Figure 4 for a 25 J impact are alike for both reinforcement configurations because the energy dissipated is similar in the two cases. A considerable delamination growth is noticed either in the multiaxial and the reference configurations along the pultrusion direction due to the bending stiffness difference between the tape and roving layers for that direction. However, in the multiaxial configuration, the delamination does not grow as much as in the reference one in the transverse direction.

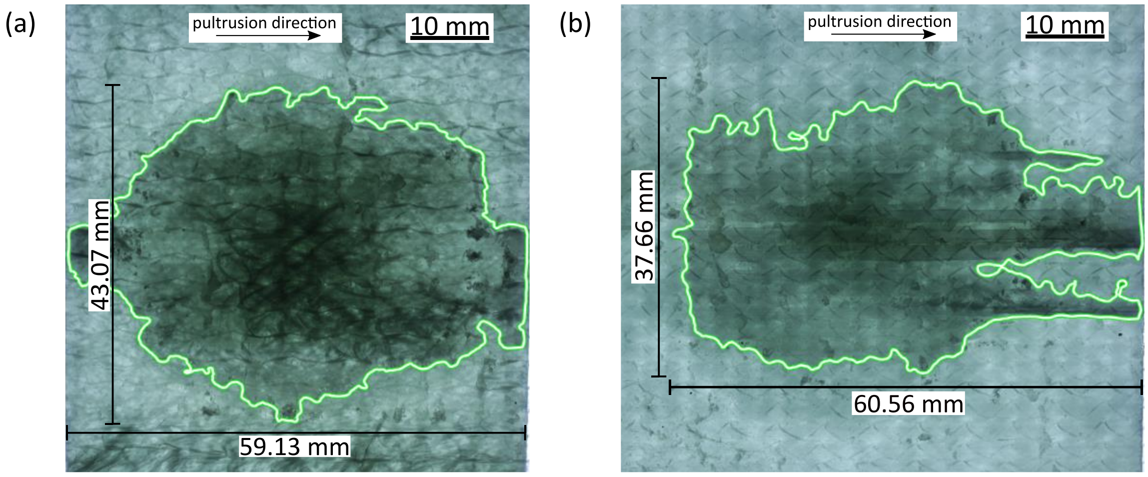

Figure 4. Delamination contours for the 25 J impact energy on the (a) reference and (b) multiaxial reinforcement configurations.

3.3 Damage tolerance

The mechanical performance loss caused by the impact events has to be assessed to completely address the impact response improvement provided by the multiaxial reinforcement configuration. Thus, the damage tolerance of both studied reinforcement configurations has been analysed, experimentally determining their post-impact residual stiffness when just delamination damage is experienced. As plotted in Figure 5, for low energy impacts close to the delamination threshold, that is to say, up to 10 J impacts, a similar decrease is observed in the residual stiffness of both configurations. From that impact energy on, the residual stiffness retained by the multiaxial configuration remains constant with a value of 60 % of the original one, while the reference configuration steadily losses stiffness, up to a point where for a 30 J incident impact energy, just 45 % is left.

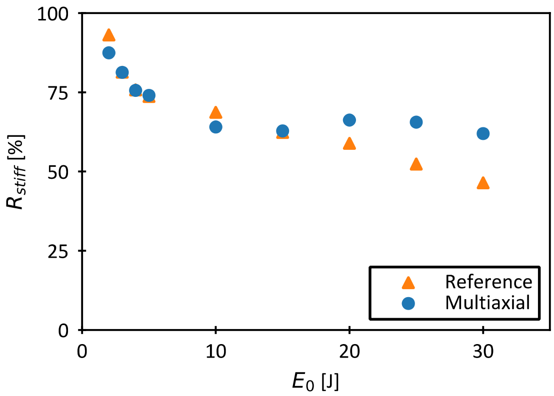

Figure 5. Residual stiffness plot for the reference and multiaxial reinforcement configurations.

4. Conclusions

The high quality of the pultruded composites manufactured by out of die UV cured pultrusion was contrasted. Two high fibre content profile configurations were satisfactorily manufactured, presenting a restrained void content, which gives an example of the reinforcement configurations that can be implemented in the profiles produced with this technology.

The drop weight low-velocity impact tests performed in specimens from both reinforcement configurations showed how, at incident energies close to the delamination threshold, the effect of the reinforcement configuration is not appreciated. However, as higher impact energies are applied, the improvement in the impact resistance and damage tolerance procured by the multiaxial reinforcement configuration arises. A 100 % higher maximum peak force, a 125 % higher penetration threshold, and an 85 % higher perforation threshold were obtained in comparison to the reference configuration. Additionally, the capacity of retaining stiffness after suffering an impact event is better in the multiaxial configuration, which even when presenting delamination of a considerable extent, still maintained 60 % of its original stiffness.

So, the present work evidence that apart from the productive benefits that an automated process like out of die UV cured pultrusion would provide to the manufacturing of stiffeners for vessels structures, other benefits related to the enhancement of their impact response could be attained.

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5. References

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