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# Effects of interply hybridization on the damage resistance and tolerance of composite laminates

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ABSTRACT

This paper presents an experimental study of the drop-weight impact response of interply hybrid laminates manufactured using polymer-matrix composite materials. Three different reinforcements, woven carbon fabric, woven glass fabric and unidirectional carbon tape, are combined with an epoxy resin using the Resin Transfer Molding (RTM) process. In-plane quasi-isotropic laminates are analyzed by combining pairs of materials and by changing their location in the through-the-thickness direction of the laminate. In addition, different impact configurations defined in terms of impact energy are performed to increase the number of case studies. The analysis is completed by non-destructive inspections based on ultrasonic technique and Compression After Impact (CAI) tests for the assessment of the residual strength. The results obtained highlight the effects of interply carbon and glass hybridization under low-velocity impact and CAI loading.



## 1. Introduction

The automotive industry is increasingly using Fiber Reinforced Polymers (FRPs) in the new generation of vehicle structures where lightweight is a critical design driver [1,2]. Until recently, FRPs were considered only for production of luxury and racing cars, but today their application is widening to mass-produced vehicles with the goal of reducing the whole structure mass and, in turn, the reduction of the fuel burnt and vehicle gas emissions [3].

Structures manufactured by stacking oriented composite plies have many design possibilities, a fact that is very attractive for the industry. However, the appropriate selection of these design parameters to deal with a suitable structure performance is an arduous task. The design variables of the plies (i.e. thickness, fiber orientation and preform architecture, materials, and location along the laminate), and other issues such as the own size of the structure [4,5], are parameters that can yield to structures apparently identical but with different structural performance. Therefore, besides the several properties that should be obtained experimentally to characterize the material, additional tests are needed to understand the response of a selected structure.

A large number of experimental work related with the out-of-plane low-velocity impact loading on laminated composite materials can be found in the bibliography [6]. Such particular load case requires special attention since it represents an important threat due to the low out-of-plane strength of the composite structure and, consequently, to the significant reduction of the load-carrying capability of composite structures. One of the main goals of the industry is to enhance the performance of a structure under impact, or simply to check how new structure concepts, that are good for particular purposes, behave under impact.

In the work of González et al. [7], the effect of the ply thickness in conventional fiber oriented plates was studied. It was detected that the increase in ply thickness implies a reduction of the damage resistance since it leads to larger projected delamination areas. Moreover, the increase in ply thickness results in a reduction of the residual compression strength for specimens impacted at energies that generated delamination areas smaller than the non-clamped area of the test specimen. Other works also proved that the residual strength is improved for thin ply laminates, but regarding the projected delamination areas alone there is not a clear trend [8–10]. Sebaey et al. [11] analyzed two cases of ply clustering in optimized and dispersed ply orientation laminates: one with a cluster located in the through-the-thickness mid-plane, and another with two clusters located on the top and on the back laminate faces. It was observed that the use of clusters implies a reduction in the impact peak load and wide delaminations near the clustered plies when compared with conventional laminates. Regarding the post-impact compressive response, it was observed that clustering

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improved the strength, a fact that was justified by the location and size of the impact delaminations.

In Sebaey et al. [12], the effect of the mismatch angle of adjacent plies without clustering was studied by means of two optimized stacking sequences: a laminate with small mismatch angles (10°–30°) and another with large mismatch angles (55°–80°). The results showed that the laminate with small mismatch angles had a better response since smaller indentation and dissipated energy were obtained, and also higher residual compressive strength. However, the projected delamination areas after impact were contradictorily higher, justified by the detection of fewer but wider delaminations at some interfaces.

Regarding the effects of fiber preform architectures under low-velocity impact loading, additional studies can be found. Some examples are: a comparison of warp-knit, plain woven and non-woven (chopped strands) laminates made with E-glass fabrics with polyester matrix [13]; a comparative study of unidirectional, 2D woven and 3D orthogonal weave fabrics, all formed with fiber and matrix of ultrahigh molecular weight and low density polyethylene, respectively [14]; effects of stitching in plain woven S2-glass/epoxy fabrics [15], or in unidirectional carbon/epoxy plies [16].

Another design possibility is the use of hybrid laminates [17]. Numerous experimental work focused on impact analysis on flat and monolithic hybrid laminates can be found in the literature, mainly those that use the same matrix but alternate different fiber materials along the stacking sequence (i.e. interply hybrid), or inside of the plies (i.e. intraply hybrid), and even combining metal foils and polymer-based plies (i.e. super hybrid or Fibre Metal Laminate (FML)). Some examples of mixing fiber materials are summarized in Table 1, where the range of fiber (chemical, inorganic or natural) and matrix materials tested is quite diverse. In addition, other studies combine ply materials with different out-of-plane reinforcements [16,18–20]. Regarding the effects of mixing fiber preform architectures, fewer studies are available. An example is the work of Aktaş et al. [21], where the effect of mixing woven and knit type fabric layers of glass/epoxy composite was analyzed. Finally, research on FML hybrids has also been performed: glass–aluminum (GLARE) [22,23], aramid–aluminum (ARALL) and carbon–aluminum [22], and also carbon–titanium and glass–titanium [24].

Regarding the available work on hybrid laminates with the fiber materials used in the present paper (carbon and glass, see Section 2.1), Naik et al. [33] compared the impact and post-impact compressive response of plain weave E-glass and twill weave of T-300 carbon interply hybrid laminates with laminates manufactured with a single composite material. It was shown that hybrid laminates presented less visual damage on top and bottom faces, smaller projected delamination areas and better residual compressive strength relative to the strength of non-impacted compressed specimens. Locating the plies of carbon outside and glass plies inside, yielded better results since smaller impact damage areas and lower sensitivity of the compressive strength to the impact damage were observed. Similar impact results obtained Sevkat et al. [35], using quite similar set of lay-ups made with plain weave S2-glass and IM7 carbon fiber composites. In addition, Sayer et al. [38] proved that placing glass plies on the impact face of the laminate, less energy is absorbed when compared with a laminate with the same thickness with glass plies located on the back-face.

Enfedaque et al. [36] performed X-ray-computed micro-tomography inspections to analyze the deformation and the fracture micro-mechanisms on impacted hybrid laminates of plain woven S2-glass and G0926 carbon fabrics. Two laminates of only carbon plies and four hybrid laminates with different stacking sequences and glass fiber content were considered. The results showed that the hybridization with glass implies higher impact peak loads and absorbed energies. For all cases, it was concluded that fracture of the bottom ply was the mechanism controlling the peak load upon impact. The X-ray images demonstrated that glass plies located near the top and bottom surfaces of the laminate were able to sustain the deformations imposed by the impactor without fracture due to their higher strain-to-fracture in comparison with the woven carbon plies. Therefore, glass plies prevented the propagation of interply cracks from the bottom ply toward the center of the laminate, thus increasing the maximum load-bearing capability of the composite. In addition, delamination did not develop between carbon and glass plies, but rather between carbon plies, resulting from the intraply cracks in such plies.

The present paper deals with an experimental study of the drop-weight impact response of interply hybrid laminates manufactured with polymer-based composite materials. Three different fibers are used: woven carbon fabric, woven glass fabric and unidirectional carbon tape. Combining by pairs of materials, three sets of laminates are manufactured by epoxy Resin Transfer Molding (RTM). To allow a suitable comparative analysis for each set, the corresponding laminates are selected with in-plane quasi-isotropy and the number of plies for each material is kept constant. The analysis include low-velocity impact tests at three impact energies, inspection of the projected delamination area by ultrasonic technique, and Compression After Impact (CAI) tests for the assessment of the residual strength. The discussion of the results obtained provides additional information regarding the mechanical response of carbon and glass interply hybrid laminates under low-velocity impact and CAI loading.

## 2. Materials, laminates and test configurations

### 2.1. Material types

The composite materials used are supplied by Hexcel®, and are qualified for aerospace programs. The fabrics, all named HexForce™ reinforcements, are suitable for the RTM manufacturing process.

**Table 1**
Low-velocity impact analysis of hybrid laminates alternating fiber materials through the stacking sequence.

| In-plane fibers | Hybrid type | Fabric | Matrix | References |
|---|---|---|---|---|
| Polyamide–Basalt | Interply | Woven | Epoxy | [25] |
| | Intraply | | | [26,27] |
| | Interply or Intraply | | | [19] |
| Polyamide–Glass | Interply | Woven | Vinylester | [28–30] |
| | | Unidirectional | Epoxy | [31] |
| | Intraply | Woven | | [32] |
| Polyamide–Carbon | Interply | Unidirectional | Epoxy | [31] |
| | Intraply | Woven | | [32] |
| Carbon–Glass | Interply | Woven | Epoxy | [32–37] |
| | | Unidirectional | | [38,39] |
| Carbon–Polyethylene | Interply | Woven | Epoxy | [40,41] |
| Glass–Polyvinyl | Interply or Intraply | Woven | Polyester | [42] |