EFFECT OF PLY THICKNESS ON THE IMPACT RESPONSE OF INTERLEAVED NON-CRIMP FABRIC LAMINATES

S.M. García-Rodríguez[1], V. Singery[2], Ph. Sanial[2], J. Costa[1]

[1]AMADE, Polytechnic School, University of Girona, Campus Montilivi s/n, 17071, Girona, Spain
Email: sgarciarodriguez91@gmail.com
[2]Chomarat, 39 Avenue de Chabannes, 07160, Le Cheylard, France

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Abstract

Interest in thin-plies is growing rapidly in composites industry, not only because of the design versatility they offer, but also because of their performance in delaying transverse matrix cracking during impact. On the other hand, interlaminar toughness influences the delamination onset and propagation during low-velocity impact or other damaging load modes. For this reason, interleaving has recently emerged as a promising toughening approach to improve the inter-ply resistance. This paper presents an experimental investigation into the effect of ply-thickness and interleaving by non-woven thermoplastic veils on the delamination resistance of thin-ply non-crimp-fabric (NCF) laminates. We evidenced that the introduction of fibrous polyamide veils contributes to delay delamination initiation and, in some cases, to arrest their propagation.

1. Introduction

Carbon fibre reinforced composites are used extensively in the aircraft industry as they exhibit higher specific properties and design possibilities than their metallic counterparts. Additionally, they reduce the maintenance costs that corrosion or fatigue exposed components would otherwise require. However, their Achilles' heel continues to be the out-of-plane response, especially for components manufactured by resin infusion (RI) methods. The advantages that RI provides in terms of time and cost are limited to the use of low-viscosity resins, which are inherently brittle [1]. In service, this results in impact damage susceptibility. Accidental strikes may reduce the structure´s load-carrying capacity, induced by matrix cracking, fibre-matrix debonding and delaminations [2,3].

Two design parameters are used to assess the impact performance of composites: the damage resistance and the damage tolerance. The former is the ability of a structure to resist damage initiation and growth. The latter deals with the effect of existing damage on the residual properties [4]. Extensive research has been conducted to design for and characterize damage resistance and tolerance (i.e. by means of non-destructive inspection [5] and compression after impact (CAI)/open hole tests [6,7], respectively). In general, material properties such as the mode I and II interlaminar fracture toughness (G_{Ic} and G_{IIc}), the interlaminar fracture toughness (ILSS), the matrix fracture toughness (K_{Ic}) and the laminates' flexural and compressive properties govern the damage progression during impact [1]. However, clear conclusions have not yet been reached.

The development of new manufacturing techniques such as the *tow spreading method* permits the fabrication of plies with thickness below 125 µm, namely thin-plies [8]. Because of the positive size-effects, thinner plies have the capability to delay/suppress matrix cracking and delamination growth during impact and other loading events. Consequently, besides entailing a large design space, they allow for structures with higher strain allowable [8]. Yokozeki T. *et al.* [9] examined the low-velocity

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impact response of thin- and thick-ply quasi-isotropic $[45/0/-45/90]_{ns}$ laminates. Although they had similar post-impact projected delamination areas (quantified by ultrasonic C-scan imaging), delaminations adopted an elongated shape along the longitudinal axis of thin-plies. This shape-effect resulted in narrower damage widths and increased the CAI strength. Similarly, Saito H. *et al* [10] reported a 23% increase of the CAI strength of thin-ply based quasi-isotropic laminates. Yokozeki T. *et al.* [11] enlarged their previous study [9] to investigate the effect of ply thickness on their laminates' damage sequence. They performed Quasi-Static Indentation (QSI) tests, Finite Element Method analyses and X-Ray characterization and concluded that thinner plies supressed delaminations in the face opposite to the indenter, and thus, fibres failed suddenly by stress concentration.

When composites are stressed, delaminations' initiation and propagation deteriorates their mechanical properties potentially until catastrophic failure. Accordingly, the interlaminar fracture toughness (in mode I and II, G_{Ic} and G_{IIc}) contributes to control damage during fracture events. There exist two approaches to modify the laminate´s ILFT [12]. *Intrinsic* toughening methods delay damage by creating inelastic deformation ahead of the crack tip. Conversely, other approaches reinforce not the tip but the wake of the crack (*extrinsic* toughening), whereby fibre-matrix debonding mechanisms result in crack tip shielding. In whole, such toughening concepts result in dramatic improvements in composite´s G_{Ic} and/or G_{IIc} [1]. Nevertheless, if toughening is to be implemented efficiently, a critical consideration has to be taken in account: the toughening method cost, time and suitability for RI.

Kuwata and Hogg [13,14] researched the effect of interleaving by non-woven veils on the ILFT of thick-ply CFRP laminates. They considered different types of fibre architectures and resin systems. Prior to infusion, they introduced a fibrous veil of polyamide (PA), polyester (PE), carbon (C), or a PE/C combination at the mid-plane of the laminate´s stack. For Mode I testing, G_I values increased with the introduction of thermoplastic interleafs. This was attributed to the fibres´ capability to bridge the crack wake and/or to plastically deform. Particularly, the PE veil outperforms in almost every case and a two-fold improvement of G_{Ic} is observed for PA interleaved weave fabric/epoxy specimens. On the other hand, toughening with thermoplastic veils improved the G_{IIc} value without exception. This was attributed not to fibre bridging but to the ability of the fibre-resin system to yield and debond during crack propagation.

In this study, we investigated the impact behaviour of quasi-isotropic Non-Crimp-Fabric (NCF) laminates manufactured with thin and thick plies (namely THIN and THICK, respectively). Furthermore, we reinforce two additional thin-ply laminates with non-woven veils of two different types of co-polyamide (PAVEIL1 and PAVEIL2, respectively). This toughening method was selected by virtue of its low cost, suitability to RI methods and its ability to toughen extrinsically [1]. The objective was to highlight differences in terms of damage resistance and tolerance. To this purpose, a low-velocity impact and QSI campaign was developed. All the previous experiments were accompanied with C-scan and, when considered, with X-Ray MicroComputed Tomography (µCT) inspections.

2. Materials and methods

C-ply™ bi-angle [+45/0] and [-45/0] NCF layers were stacked to form $[45/0/-45/90]_{ns}$ quasi-isotropic laminates. The fabrics were made of T700 carbon fibre and impregnated with RTM6 epoxy resin by Resin Transfer Moulding. Four panels with the same nominal thickness (2mm) but different number of plies were considered (thick- and thin-plies). Additionally, two types of co-polyamide non-woven veils were positioned at every interface of two thin-ply laminates, Table 1. Both interleaves have a similar areal weight, but different fibre´s diameter distribution and packing. Further details are not given because of confidentiality.

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Table 1 Quasi-isotropic laminates considered in this study

Name	Lay-up	Areal weight/ply (gsm)	Interleaving
THIN	$[45/0/-45/90]_{4s}$	67	-
THICK	$[45/0/-45/90]_{2s}$	134	-
PAVEIL1	$[45/0/-45/90]_{4s}$	67	PA veil type 1
PAVEIL2	$[45/0/-45/90]_{4s}$	67	PA veil type 2

Two specimens of each laminate type were impacted at 10 J and three were indented quasi-statically at 5.24, 4 and 3 mm indenter displacement, respectively. The specimens were 100x150 mm. Impact testing was performed in a CEAS Fractovis Plus 7536 falling weight machine and according to the ASTMD7136/D7136M–15 standard. The QSI experimental set-up developed by Wagih *et al.* [15] was adapted for rectangular specimens. A velocity of 0.5mm/min was selected to avoid dynamic effects. Finally, damaged specimens were inspected in the front and back-faces (impacted and non-impacted) by means of ultrasonic C-scan imaging. The projected delamination area was computed as the average value of both measurements.

To investigate the damaged microstructure, two impacted specimens from the THIN and THICK batches were scanned by µCT. A region at the vicinity of the impact site determined from a previous C-scan was observed. The scan settings were: 70 kV, 75 µA and 2500 ms. The voxel size was 11 µm. The X-Ray system consisted of a 100 µA X-ray source and a 2400x2400 pixels detector manufactured by HAMAMATSU.

3 Results and Discussion

Subjected to QSI or impact loads, delamination extended differently depending on the laminate, as evidenced by C-scan (Figure 1). We observed different back-face failure mechanisms and delamination spatial distributions (Figure 2).

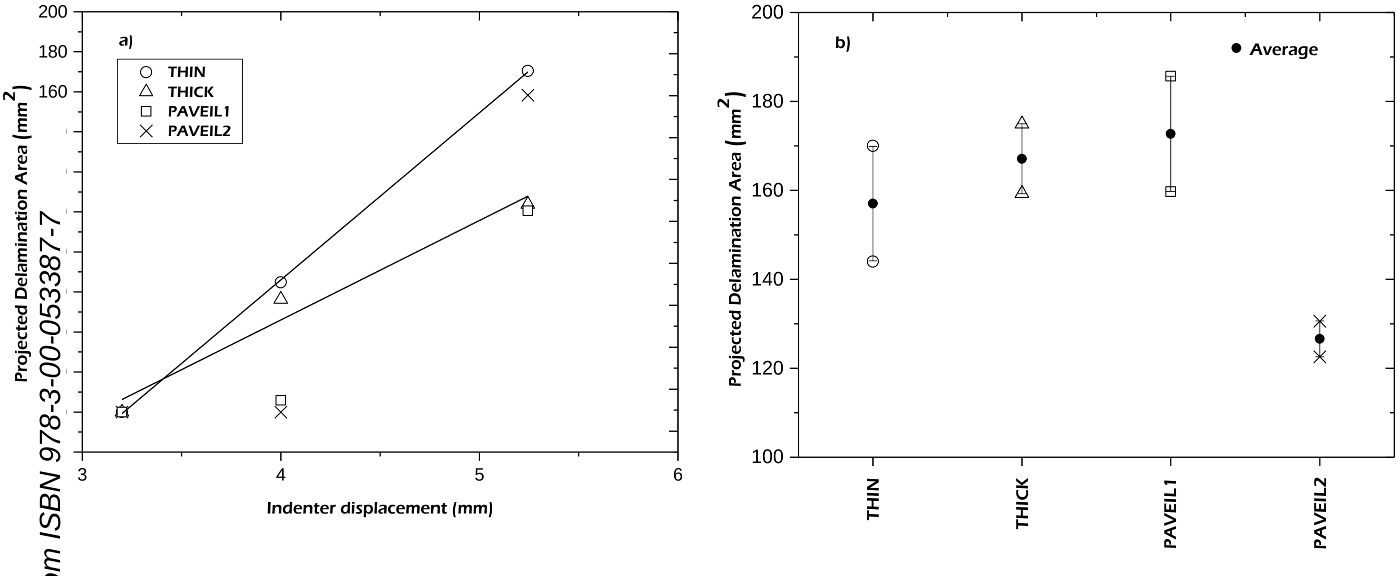

Figure 1 C-scan projected delamination areas of a) indented and b) impacted specimens. The vertical bars highlight the dispersion between measurements

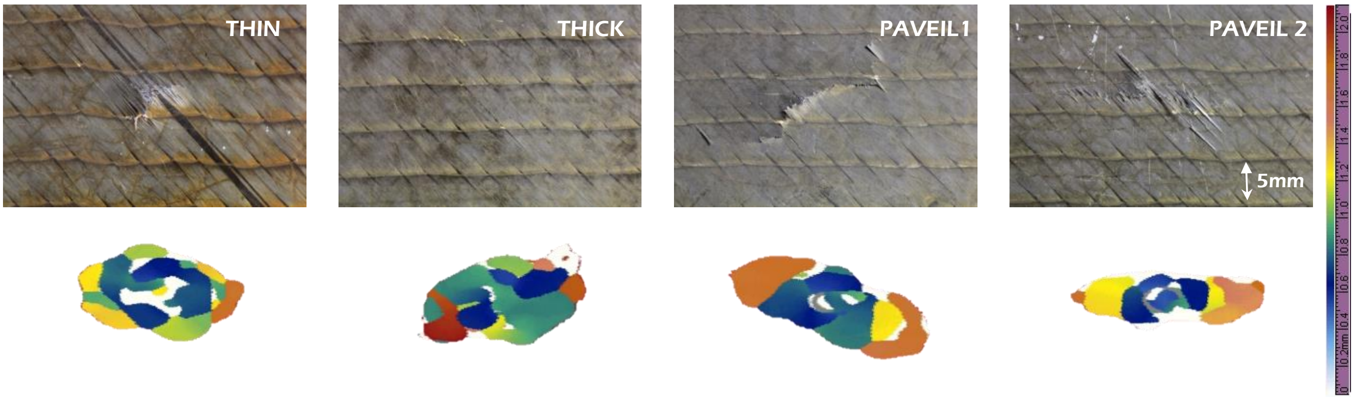

Figure 2 Representative 10 J impacted specimens' back-face. Front face C-scan inspections are also plotted, where the colour scale represents different delamination depths (in mm). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper

Similarly to Wagih A. *et al.* [15], the thin and thick-ply specimens' delamination area varied linearly with the indenter displacement in QSI test, Figure 1 a). At 5.4 mm, the THIN´s projected delamination area was 34% higher than that of the THICK. This magnitude is in agreement with Saito H. *et al* [10]. In fact, they reported damage tolerant thin-ply composites with greater delaminations than its thicker counterparts. On the other hand, interleaved specimens behaved non-linearly: damage developed only at the maximum indenter displacement. The PAVEIL1 and PAVEIL 2 delamination area decreased 36% and 7% with respect to the THIN. Finally, with regards to impact (Figure 1 b)), the PAVEIL2 specimens displayed the smallest averaged delamination area, 19% lower than the THIN case.

Samples from the same batch displayed similar back-face failure mechanisms for impact and QSI tests. Therefore, only a representative specimen is reported (top part of the Figure 2). Subjected to the same damage-level, fibres started to break along the 45° direction of THIN specimens whilst no damage developed in their THICK counterparts. Additionally, we distinguished delaminations oriented at 0°, ±45° and 90° directions in both cases (bottom part of the Figure 2). On the contrary, interleaved specimens highlighted a different damage response: the veils contributed to elongate delaminations along the longitudinal axis, particularly for the PAVEIL 2. This effect resulted in lower delamination width, which may increase the CAI strength [9].

With this reduced experimental study, we conclude that interleaving thin-ply NCF by different types of PA non-woven veils delays damage in the form of delaminations, Figure 1 a). Additionally, it may contribute to arrest their propagation, resulting in lower projected delamination areas, Figure 1 a) and b). However, the dispersion presented in some measurements and the lack of understanding at a microstructural scale calls for the use of μCT inspection (Figure 3).

Subjected to 10 J impact, THIN and THICK specimens presented different failure scenarios: thicker plies delaminated extensively, brought about by shear/bending dominated matrix cracks [1]. Its fibres did not break. On the other hand, thinner plies reduced inter- and intra-ply cracking and concentrated damage to a region near to the impact point, but fibres failed in almost the entire bottom half-part of the laminate.

We have presented an investigation into the effect of ply-thickness and/or interleaving on the damage resistance of thin-ply NCF laminates. However, this study is still limited and further work should be devoted to:

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- Study the damage tolerance: CAI testing
- Elucidate the sequence of failure modes underlying structural damage: µCT inspections
- Understand the influence of veils on the interlaminar fracture toughness: mode I and II fracture toughness tests, between others

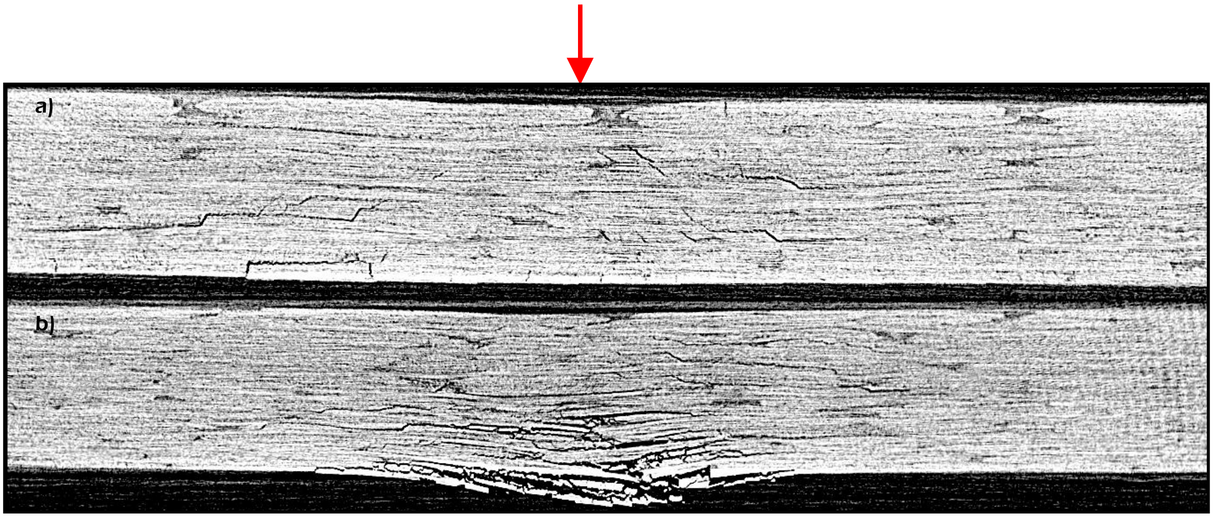

Figure 3 µCT cross-sections of a) THICK and b) THIN specimens impacted at 10 J. The arrow indicates the impacted point

3. Conclusions

The effect of ply-thickness and interleaving by non-woven thermoplastic veils on the delamination initiation and propagation of thin-ply NCF laminates was studied. Specimens from all batches were subjected to impact and QSI tests, and damage was evaluated by means of non-destructive inspection methods (visual, C-scan and µCT inspections). The experimental results provide evidence that fibrous veils delay delamination initiation and may arrest, in some cases, their propagation. Therefore, we consider this type of reinforcement a potential candidate to manufacture large aerospace components in a cost- and time-effective way. Regarding non-reinforced materials, thin-plies reduced delamination extent and presented extensive fibre breakage at the bottom part of the laminate.

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