

IMPACT BEHAVIOR OF COMPOSITE FAN BLADE LEADING EDGE SUBCOMPONENT WITH THERMOPLASTIC POLYURETHANE INTERLEAVE

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ABSTRACT

Impact damage tolerance and damage resistance is a critical metric for application of polymer matrix composites where failure caused by impact damage could compromise structural performance and safety. As a result, several materials and/or design approaches to improve impact damage tolerance have been investigated over the past several decades. Many composite toughening methodologies impart a trade-off between increased fracture toughness and compromised in-plane strength and modulus. In large part, mechanical tests to evaluate composite damage tolerance include static methods such as Mode I, Mode II, and mixed mode failures. However, ballistic impact damage resistance does not always correlate with static properties. The intent of this paper is to evaluate the influence of a thermoplastic polyurethane veil interleave on the static and dynamic performance of composite test articles. Static coupon tests included tension, compression, double cantilever beam, and end notch flexure. Measurement of the resistance to ballistic impact damage were made to evaluate the composites response to high speed impact. The interlayer material showed a decrease of in-plane performance with only a moderate improvement to Mode I and Mode II fracture toughness. However, significant benefit to impact damage tolerance was observed through ballistic tests.

1 INTRODUCTION

Damage resistance and damage tolerance in composite structures are critical concerns; driving both structural design and safety requirements. Damage resistance defines the ability of a material to resist permanent change following impact; whereas damage tolerance defines the material's ability to function after a permanent physical change has occurred[1]. The terms are commonly used to describe the response of a composite material as the energy of an incident projectile (either low or high velocity) is dissipated[2]. A clear delineation between low and high velocity impact has not been made, however has been classified by various groups[3]. Cantwell and Morton[2] classified low velocity impact as up to 10 ms⁻¹, due to the test techniques which are typically used to characterize low

velocity impact damage (LVID). Shivakumar and co-workers[4] define low-velocity impact as an event which can be treated as quasi-static; meaning a wide velocity range would qualify as it is dependent on the material and physical properties of the target and impactor. As opposed to a quasi – static response following low velocity impact, a composite response to high velocity impact is dominated by stress-wave propagation through the material[5].

While low-velocity impact is important for aircraft structures, due to events such as tool drops, high velocity impacts represent in-service impact events such as hail damage and most commonly-bird strike. When a bird strikes an aircraft, the relative velocities between the two objects are so high that the impacted material could suffer instant damage and failure. This situation can be simulated by high velocity impact testing; which provides damage representative of in-service events that could lead to the immediate failure of the material[6]. Mustapha noted several composite parameters affecting the impact resistance of a composite, including hardness/strength, ductility, microstructure and thickness; and noted several potential failure modes. Furthermore, under impact loading, damage modes such as fiber breakage, matrix cracking, and delamination may appear together[7].

Mitigating delamination failure has been the subject of materials researchers and composite designers for decades. Most successful approaches include the addition of a secondary – often more compliant- phase to the composite. The toughening material is often, but not always, a thermoplastic polymer or a rubber. Two primary approaches to incorporating such materials into the composite have been widely investigated. The first includes blending a toughening material into the matrix and the other includes placing the toughener at the ply interfaces.

The blending approach, or matrix toughening, was first introduced in 1974 when researchers at the Ford Motor Company developed and incorporated preformed particulate core shell particles into an epoxy matrix- as well as other thermosetting polymer systems[8]. The blending approach is widely used in commercial prepreg materials; allowing mechanical properties, i.e. toughness/strength balance, to be dialed in based on the type of resin and toughening phase that are used to engineer a material system[9]. Over the past four decades, attention has been given to material design which leads to the toughening material primarily positioned at the ply interface; rather than homogeneously distributed throughout the matrix. In 1988 Hercules designed a material where, during cure, toughening particulates precipitated from the epoxy matrix into the interlaminar region. Comparable approaches include spraying or placing preformed particles on the prepreg during laminate fabrication[8]. For example, Toray has used this approach with Nylon particle interleave to improve compression after impact and this material is used on the Boeing 787[10].

The evolution from homogenous dispersion of a toughening material to particulate distribution at the interply region continued to evolve to include application of non-woven toughening veils for improved interlaminar toughening. There have been numerous papers documenting the benefits to Mode I and/or Mode II fracture toughness of such materials. Several researchers have evaluated low velocity impact tests and report a reduction in delamination following application of a thermoplastic veil[11].

The mechanism of failure through application of a veil interleaf differs from that of a homogeneously dispersed toughening material. The blended material system improves fracture toughness through increased fracture toughness of the matrix itself[12]. Therefore, the toughened matrix increases the energy required to initiate failure, but crack growth rate is unaffected. The trade-off of the blended system is an accompanying reduction in tension and compression strength[9]. Application of a secondary phase at the interface (whether it is a veil or preformed particles) changes the failure mechanism to crack deflection. At the onset of a delamination event, crack propagation is slowed by the material present in the interface. A reduction of in-plane strength and modulus may be observed, however, the veil interleaf approach is attractive in that the toughening material need only be applied where it is required from a design perspective. This is particularly attractive for a structure such as a composite jet engine fan blade where the application demands high strength and modulus, however resistance to impact damage is also critical for safe operation.

The purpose of this paper was to evaluate the influence a thermoplastic polyurethane veil, applied as an interleaf, on static material properties and ballistic impact damage resistance of a fan blade leading edge subcomponent structure. A correlation could not be made between the moderate benefit observed through static tests and the significant reduction of impact damage observed in the impact tests.

2 EXPERIMENTAL

2.1 Static Test Coupon

Hexcel's IM7/8552 prepreg was used for initial evaluation of the interleave concept due to material availability; and test panels for static testing were fabricated from this prepreg. The areal weight of the unidirectional prepreg tape was 160 g/m² (gsm), with a 35% resin content. Material technical data for this material may be obtained from Hexcel[13].

The melt spun thermoplastic polyurethane (TPU) veil used for interleave material, was manufactured at Hills, Inc of Melbourne, FL. The veil was prepared in both 15 gsm and 45 gsm areal weights.

As progress was made toward the subcomponent structure, a composite fan blade leading edge, a prepreg material relevant to this application was procured. IM7/8551-7 is a state-of-the-art prepreg material for composite structures that require high damage tolerance[14]. This material was used for leading edge subcomponent fabrication and ballistic impact testing.

2.2 Panel Fabrication

Flat panels for static testing were fabricated and tested following vacuum bagging and cure procedures recommended by the Hexcel for IM7/8552. The ply configuration of panels fabricated for tension and compression was [0/90/90/0]_{2s}, and was intended to maximize interply stress concentration at the 0/90 interface. The TPU veil was incorporated into the panel at the cross-ply, therefore 8 layers of veil per each 16 ply laminate. Mode I and Mode II laminates were fabricated with a [0]₂₄ ply configuration and included a Teflon crack initiator, 6.35 cm in length, at the mid-plane. A single layer of veil material was incorporated at the mid-plane for these tests.

2.3 Leading Edge Subcomponent Fabrication

A simple subcomponent impact test article was designed to represent the leading edge of a fan blade as documented in Reference 15. The IM7/8551-7 pre-impregnated tape was cut according to the ply lay-up and configuration specifications for the subcomponent. An aluminum tool was custom designed to fabricate the leading edge specimen described in this paper. The mold was a mated 7075 Aluminum die, which was fitted with a vacuum pump venting attachment and a channel to capture excess resin flow (Fig. 1). All blade coupons were processed in an autoclave and followed the vendor recommended cure cycle. Cured blades dimensions were 15.24 cm (6 in) wide by 45.7 cm (18 in) long and, following removal from the tool, were machined on the 45.7 cm (18 in) sides for a smooth surface to secure in the impact test fixture.

In an effort to protect the leading edge from extensive break-out damage during impact, leading edge protection was applied in the form of an industrial aluminum foil adhesive tape. The aluminum foil tape was 0.25 mm (0.01 in) thick and 5.1 cm (2 in) wide and added approximately 20 g of mass to the edge of the blade. The adhesive tape was placed 2.5 cm (1 in) from the leading edge on the concave side of the blade, rolled over onto the convex side, then smoothed and flattened. A fully prepared test article is shown (Fig. 2).

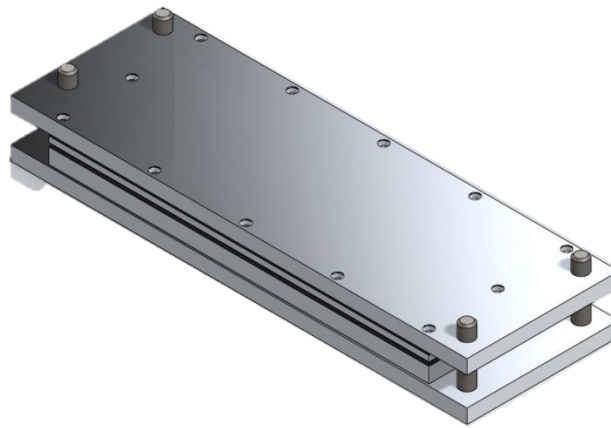


Figure 1. 3-D model of mated die mold



Figure 2: Prepared leading edge test article

2.4 Static Tests

All static tests were performed according to standard test methods and under room temperature, dry conditions. Tension and compression specimens were fabricated with a $[0/90/90/0]_{2s}$ ply configuration and tests followed, respectively; ASTM D 3039, “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials”, and ASTM D 3410, “Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading”. Mode I and Mode II fracture toughness tests followed, respectively; ASTM D 5528, “Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites”, and JIS K 7086, “Testing Methods for Interlaminar Fracture Toughness of Carbon Fiber Reinforced Plastics”.

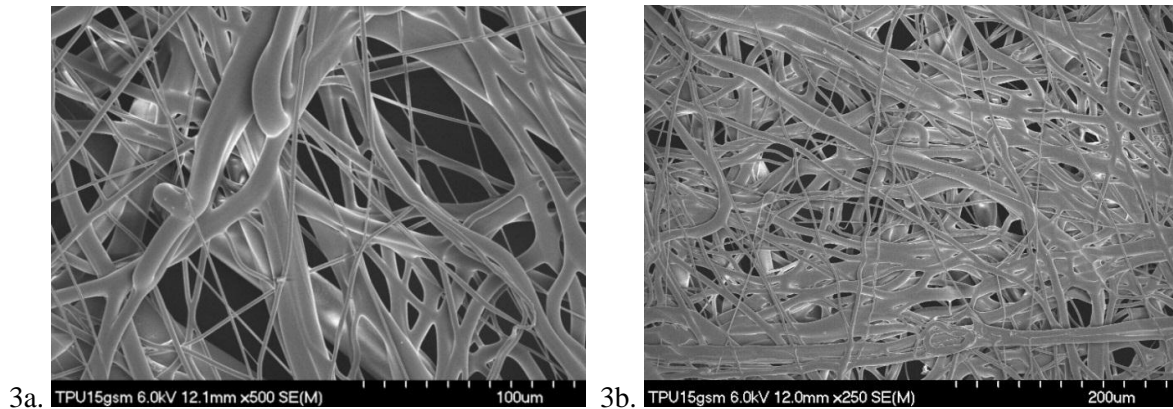
2.5 Ballistic Impact Test

Impact tests were performed in the Ballistics Impact Laboratory at NASA Glenn Research Center to simulate the material response to bird strike at the leading edge. Impact tests utilized a single-stage gas gun, consisting of a 7 m barrel and a 0.35 m^2 pressure vessel. The pressure vessel was loaded to a pressure of 1.2 MPa (175 psi), and the pressure was released using a burst disk. The projectile was housed in a cylindrical sabot for protection at the initial pressure release. Both were accelerated through the barrel by the release of pressure. The sabot was halted at the end of the barrel by a sabot arrestor and the projectile continued into the test specimen. High speed cameras were used to capture the impact of the projectile on the test article and determine the estimated speed. These tests were performed at speeds of approximately 305 m/s (1000 ft/s). A gelatin bird simulant was used as the

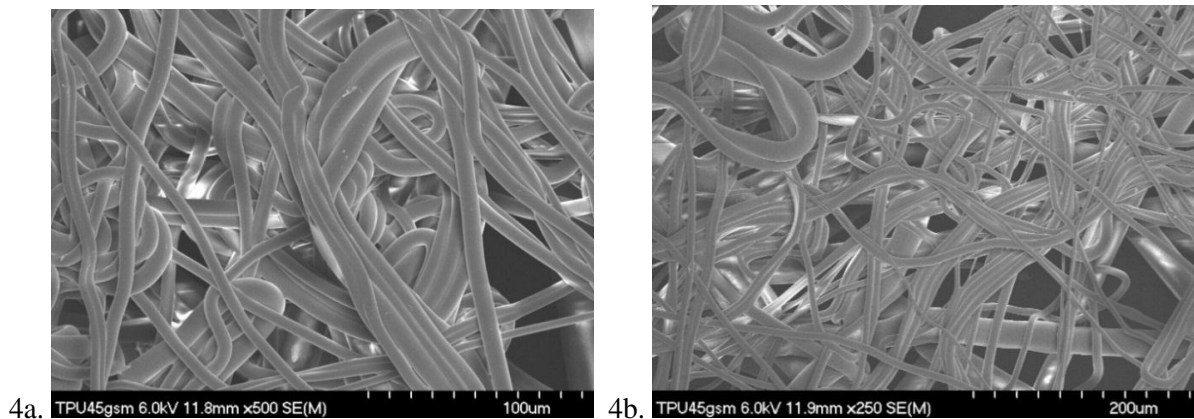
projectile, containing ballistic grade gelatin and microspheres to approximate the density of a bird; $\sim 0.9484 \text{ g/cm}^3$. The molded projectile was cylindrical, with a length of 7.6 cm (3 in) and diameter of 3.2 cm (1.25 in) and a mass of 50g. The projectile impacted the leading edge of the subcomponent at an angle representative of a bird strike. The procedure for making the bird simulant and the orientations of the projectile and blade are presented in Reference 15.

3 RESULTS AND DISCUSSION

Two separate veil areal weights, 15gsm and 45gsm, were evaluated. Representative SEM images (Figs 3, 4), show variation in fiber packing within regions of the 15 gsm (Figs 3a-3b) and the 45 gsm material (Figs 4a-4b). Literature has reported an increase in fracture toughness with increasing interleave thickness[16], however, tension and compression strength tended to decrease with increased areal weight, i.e., thickness. Thus, moving forward with fracture toughness and blade subcomponent work only the 15 gsm material was used.

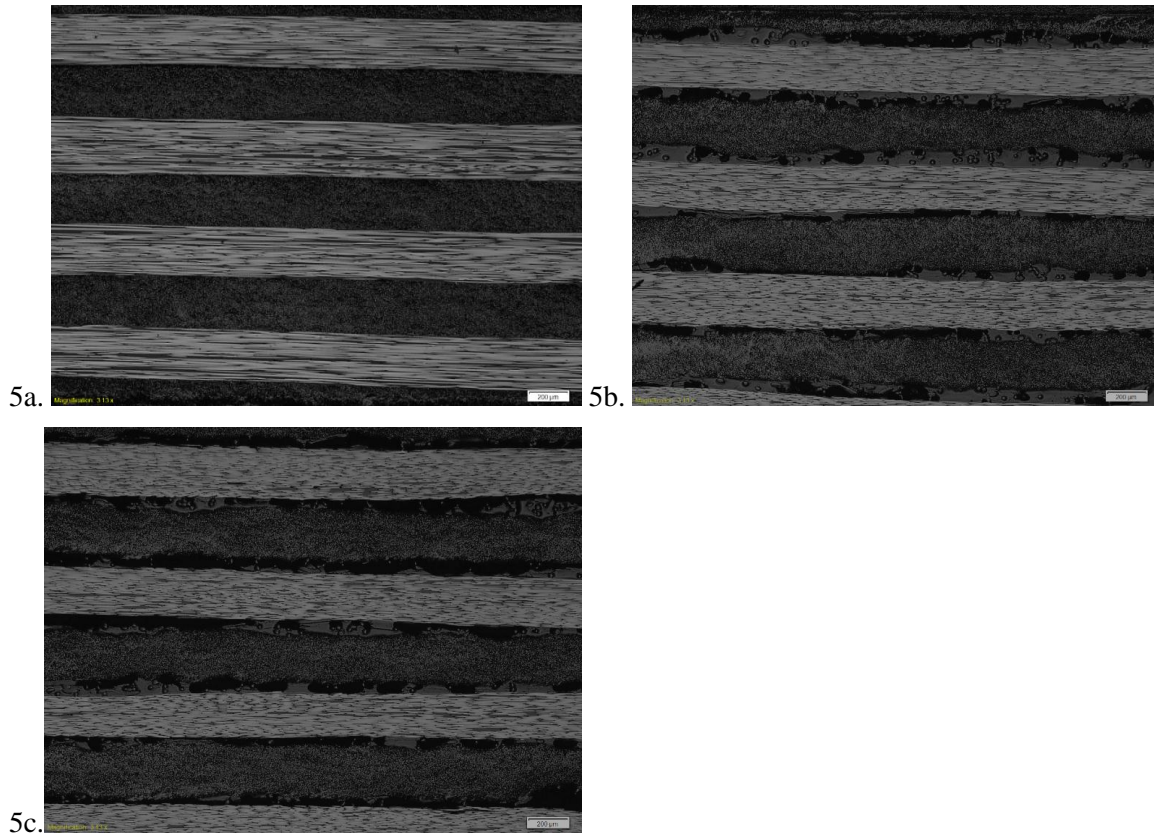


Figures 3a-b illustrate the variation in fiber diameter and packing within the 15 gsm veil.



Figures 4a and 4b illustrate the variation in fiber diameter and packing within the 45 gsm veil.

The process to cure the material was not modified following incorporation of the veil within the laminate. Optical microscopy of the cured panel cross-section (Figs 5a-5c) showed excessive voids at the interface, due to the added porous material, (Figs 5b and 5c). Voids are seen as the black areas at the ply interfaces. Future cure studies are recommended to mitigate consolidation issues such as void formation. A distinct increase of interlaminar interface thickness was also observed, from $\sim 5 \mu\text{m}$ in the baseline composite, to $10\text{-}70 \mu\text{m}$ in the 15 gsm veil coupon, and $30\text{-}70 \mu\text{m}$ in the 45 gsm veil coupon.



Figures 5a-5c: Optical Microscopy of the cross-section of a- baseline composite, b- 15 gsm interleave, and c- 45 gsm interleave coupon.

Static tests were performed to evaluate the influence of the interleaved TPU on fracture toughness and the associated reduction of in-plane properties. A portion of the commonly reported drop in tensile strength is attributed to a reduction in fiber volume fraction that results from the added interleave material. The tension/compression coupons fabricated for this study incorporated an interleave material at eight of the sixteen ply interfaces. The fiber volume for each laminate, as measured by acid digestion, is listed in Table 1. The average 10% increase in thickness resulted in calculated 6% reduction of fiber volume in the interleaved coupons.

Table 1: Average coupon thickness and fiber volume of baseline and interleaved laminates.

| Material | Thickness (mm) | Fiber Vol (%) |
|-----------------|----------------|---------------|
| Baseline | 2.25 | 58% |
| 15 gsm TPU Veil | 2.45 | 54% |
| 45 gsm TPU Veil | 2.53 | 52% |

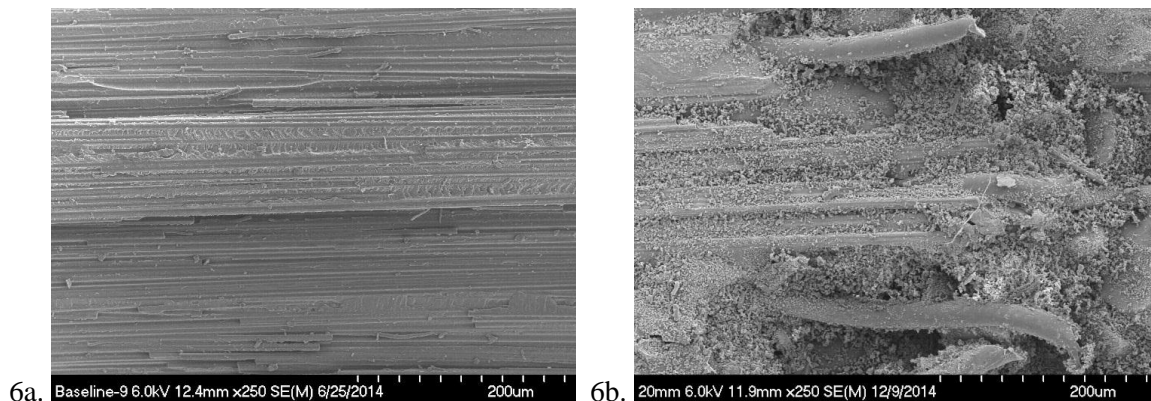
The results of the static tests are summarized in Table 2 and show a reduction of in-plane strength and modulus that can only partly be accounted for through normalization by fiber volume. Data presented is as measured and not normalized to fiber volume.

Table 2: Mechanical test data for baseline and interleaved coupons.

| In-Plane Results | Test Strength [std dev] (ksi) | Modulus [std dev] (Msi) | Fracture Toughness | G _{IC} (J/m ²) | G _{IIC} (kJ/m ²) |
|-------------------------|-------------------------------|-------------------------|-------------------------|-------------------------------------|---------------------------------------|
| Tension | | | DCB | | |
| Baseline | 179 [6] | 12.2 [0.5] | Baseline | 182 [6] | |
| TPU interleave (15 gsm) | 154 [3] | 10.9 [0.3] | TPU interleave (15 gsm) | 320 [43] | |
| TPU interleave (45 gsm) | 108 [6] | 10.6 [2] | | | |
| Compression | | | ENF | | |
| Baseline | 102.4 [7.3] | 10.7 [0.1] | Baseline | | 3.15 [0.04] |
| TPU interleave (15 gsm) | 56.7 [5.1] | 9.1 [0.4] | TPU interleave (15 gsm) | | 3.32 [0.06] |
| TPU interleave (45 gsm) | 45.1 [3.0] | 9.5 [0.9] | | | |

The tensile strength of the 15 gsm interleaved material was reduced by only 13%, with thermoplastic present at 50% of the interfaces. This is an anticipated consequence of the reduction of fiber volume and the void content at the interface. The much larger (40%) reduction of tensile strength following interleave with 45 gsm material is due in part to the greater content of low strength thermoplastic, and in part to increased wet-out issues at composite interfaces where the material was present. The compression strength was decreased due to the reduced stiffness of the polymeric material surrounding the fiber. The dominant failure mechanism in compression is fiber buckling, which occurs at a reduced compressive stress as matrix modulus decreases.

Mode I fracture toughness tests showed a 40% increase in G_{IC} following addition of the TPU veil. The mechanism of improvement has been attributed to crack deflection, where the veil increases the path length of crack propagation. This is illustrated in the images of the fracture surfaces Figs (6a and 6b). Figure 6a show matrix failure in the baseline material, and a clean fracture surface. The failure of the toughened panels, Figure 6b, is obscured from the debris left from the interleave, but an increased amount of fiber pull out is observed. The benefit to Mode II fracture toughness was negligible; 5%.



Figures 6a-b: Mode I fracture surface of 6a- baseline panel, 6b- 15 gsm interleave.

3.1 Composite Fan Blade Leading Edge Subcomponent

Baseline and thermoplastic polyurethane (TPU) veil toughened blades were prepared to evaluate the effects of increased interlaminar strain-release capability of the structure on impact resistance. The toughening veil was 22.9 cm (9 in) long and placed in the midsection of the blade length (Fig 7). Three layers of TPU were added to the blade in the locations labeled in Fig. 8. Two of the layers were 7.6 cm (3 in) wide and the other was 5.1 cm (2 in) wide. The veil placement was chosen to cover a significant portion of ply terminations; reducing free edge stresses.

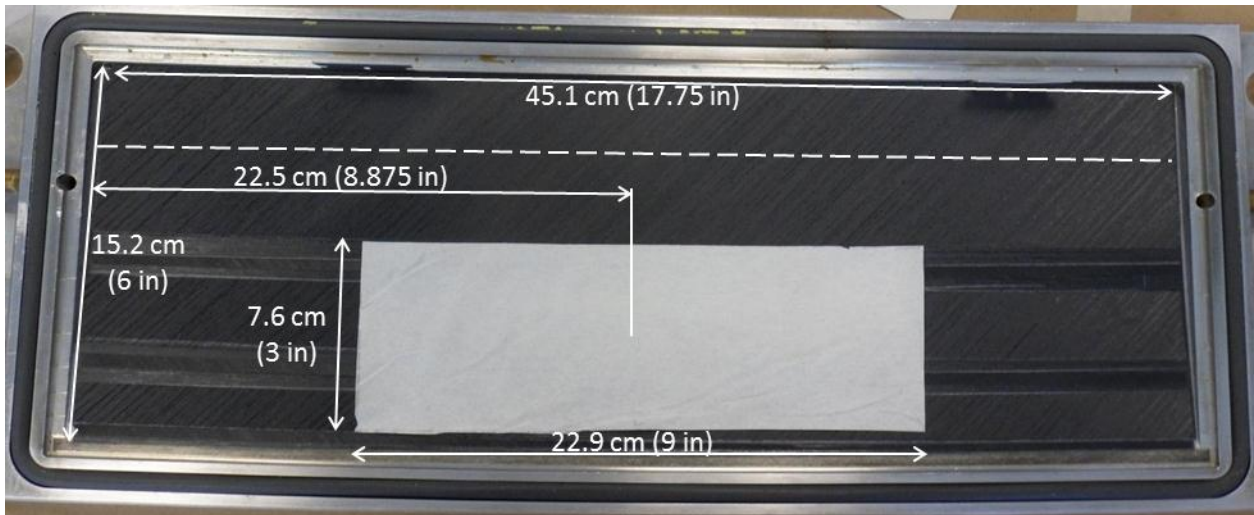


Figure 7. Location of 7.6 cm (3in) polyurethane veil layer.

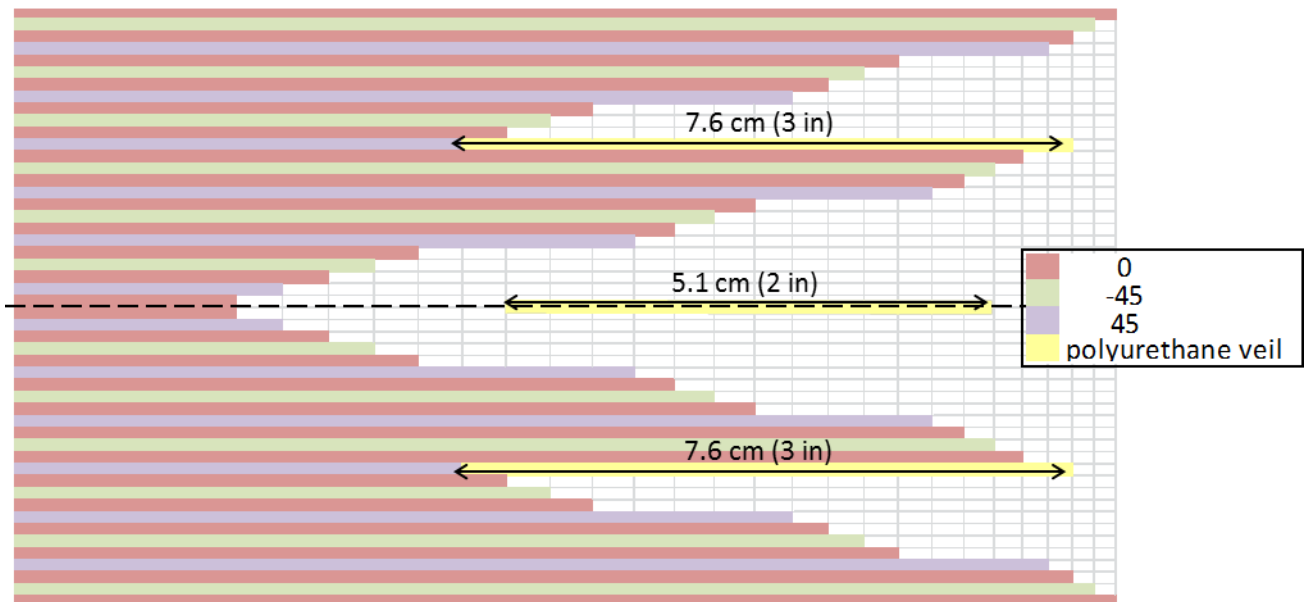


Figure 8. Polyurethane veil toughened specimen.

The results of the impact test are shown (Fig. 9). Impact of the baseline blade (C006) led to considerable damage at the leading edge, with complete break-out at the impact location. There was no break-out of material for the veil toughened blades (C008) and no delamination at the leading edge was noted; in the interleave region. In both tests, a small delamination was observed near one end of the leading edge in an unmodified region due to flexural wave reflection. This failure mode was observed in other leading edge tests and is considered an artifact of boundary conditions, occurring

after the initial impact. Permanent deformation at the leading edge of the blade tip in actual fan blades is common in bird strike events.



Figure 9. Photos of baseline (left) and toughened (right) panels after impact

3.2 Damage Inspection

Thermography images were used to characterize the impact-induced damage to the blade, (Figs 10a – 10b). The thermal image in Figure 10a indicates that damage to the baseline blade was limited to break-out at the impact site. The dark area along the leading edge is an artifact of the test, due to the thinness of the blade at the leading edge. In the toughened blade the leading edge maintained its integrity, allowing a greater amount of energy to be transferred into the blade, resulting in increased overall deformation in the form of large oscillatory flexing. The increased bending of the blade appeared to result in some delamination just beyond the placement of the toughening veil, as evidenced by the thermal image of the toughened blade (Fig. 10b). Increased flexing and bending was observed in the toughened blade, relative to the baseline, in high speed videos of the experiments. As a result, the mid-blade delamination appeared to only occur in the ‘toughened’ blade.

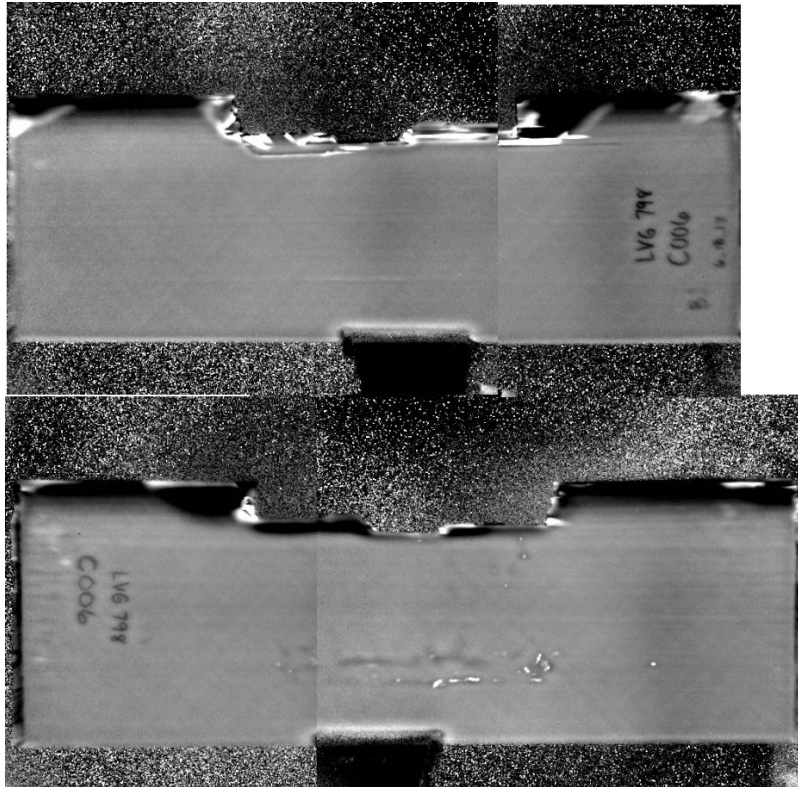


Figure 10a. Thermography images of the baseline composite blade. Upper image corresponds to the back surface and the lower image corresponds to the front surface.

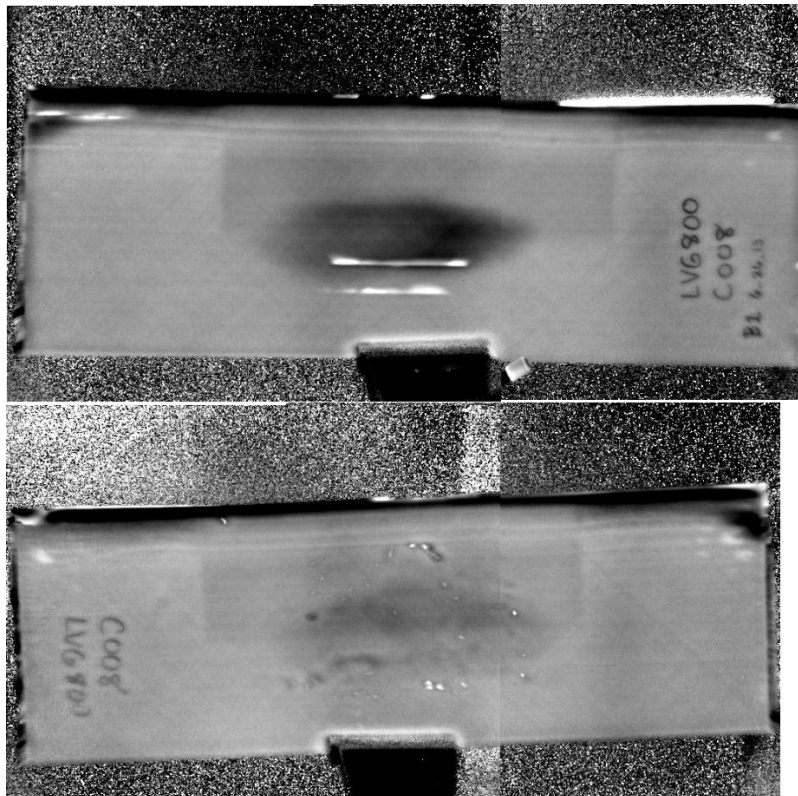


Figure 10b. Thermography images of the thermoplastic veil incorporated blade. Upper image corresponds to the back surface and the lower image corresponds to the front surface.

4 CONCLUSIONS

A thermoplastic polyurethane veil was incorporated into flat panels and a fan blade leading edge subcomponent to evaluate the influence on static response and impact damage resistance of the material. Incorporation of the veil material resulted in voids within the veil material between plies. Static testing demonstrated a reduction of in-plane material strength and modulus, possibly caused by the void formation. However Mode I fracture toughness was improved by ~40% as a result of a change from a smooth to rough fracture path.

A simplified composite blade subcomponent was designed, fabricated, and impact tested to simulate a bird strike event. The interleave approach lead to a significant reduction in damage on impact.

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