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Influence of Fiber Volume and Alignment on Impact Resistance of Braided Carbon Fiber/Epoxy Composites

Sandi G. Miller and Gary D. Roberts
Glenn Research Center, Cleveland, Ohio

Paula J. Heimann and Linda S. McCorkle
Ohio Aerospace Institute, Brook Park, Ohio

Richard E. Martin
Cleveland State University, Cleveland, Ohio

J. Michael Pereira and Robert K. Goldberg
Glenn Research Center, Cleveland, Ohio

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Sandi G. Miller and Gary D. Roberts
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Paula J. Heimann and Linda S. McCorkle
Ohio Aerospace Institute
Brook Park, Ohio 44142

Richard E. Martin
Cleveland State University
Cleveland, Ohio 44115

J. Michael Pereira and Robert K. Goldberg
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

The effect of axial tow alignment within a laminate ply stack on the impact penetration threshold for a series of composite panels was evaluated; specifically, the effect of a lateral shift in alignment to induce fiber nesting. Panels were fabricated from braided T700S carbon fiber and TenCate Advanced Composites's TC275-1 epoxy resin prepreg. Axial tows in each ply were aligned, offset, or rotated to evaluate the influence of such parameters on impact penetration resistance. Panel-to-panel variation in thickness, resin content, and fiber volume ratio were measured. Ultimately, process-related deviations drove penetration limits on impact. Influence of axial tow alignment was difficult to discern outside of the processing-induced variations between panels.

Introduction

The application of advanced composite structures continues to rise across multiple platforms, including primary structures for aeronautics, space, automotive, and marine vehicles. Textile composites have often been evaluated as a reinforcing fiber because of the low fabrication cost, easy handling, and high structural performance (Refs. 1 and 2). Composite insertion into a primary structure requires an understanding of process-induced variation within the component as well as development of the corresponding analytical models. Because of the anisotropic and inhomogeneous nature of carbon-fiber-reinforced composites, parameters controlling mechanical properties are numerous and include fiber architecture, fiber properties, matrix properties, and so forth. Such constituent parameters influence material performance, and all are subject to manufacturing variability (Ref. 3).

Previous reports have detailed the influence on tensile strength of variation in braid architecture and thickness near mold-line defects in tubes manufactured by resin infusion into a triaxially braided preform (Ref. 4). Previous work has also identified a possible effect of axial tow alignment on impact penetration velocity.

In this work, ply layup and process-related variation in composite panels made with a triaxially braided prepreg were evaluated. Axial tows were intentionally aligned, offset, or rotated ("clocked") relative to each successive layer. This stacking sequence would generate an opportunity for nesting in the offset panel that would not be readily available within the aligned panel. Separately, a set of low-fiber-volume (LFV) panels were fabricated to elucidate the influence of fiber/resin content on the penetration threshold.

Experimental

QISO-H-59 braided carbon fiber fabric was manufactured at A&P Technology, Inc., in Cincinnati, Ohio, and impregnated with TC275-1 epoxy resin by TenCate Advanced Composites. QISO-H-59 braid was manufactured using T700S fiber with a 0°, ±60° fiber angle. Fiber areal weight was 536 g/m^2 and the resin content was 38 wt%. Cured ply thickness at 55 percent fiber volume was 0.54 mm (0.021 in.).

Laminates were prepared with either a $[0]_6$ ply configuration or a rotated arrangement [0, 30, 60, 90, 120, 180]. The $[0]_6$ panels were varied through either an alignment of, or lateral shift in the axial (0°) tows between successive plies. Panel dimensions of 30.5 by 30.5 cm (12 by 12 in.) were used because of limitation in autoclave size.

A separate panel set was fabricated by A&P Technology and used a QISO braided prepreg fabricated to a higher resin content relative to the NASA panels. The LFV panels had a $[0]_6$ layup but were manufactured with a random axial tow arrangement (no control over interply stacking alignment). The 30.5- by 30.5-cm impact panels were machined from parent 61- by 61-cm (24- by 24-in.) panels to limit panel-to-panel process variation.

Panels were consolidated in accordance with an autoclave cure cycle recommended by TenCate: heat at 1.1 °C (2 °F) per minute to 107 °C (225 °F), dwell for 1 h, ramp to 177 °C (350 °F) at 1.1 °C (2 °F) per minute and dwell for 2 h (Ref. 5). Void content was evaluated by acid digestion. Fiber alignment was imaged through optical photomicroscopy. Panel quality was evaluated by pulse echo C-scan and indication-free panels were subjected to ballistic impact. C-scan was used after impact to evaluate damage area.

The penetration threshold for each set of panels was measured using the ASTM D8101/D8101M test method (Ref. 6). In these tests the composite panels are supported in a circular fixture and impacted by a 50-g blunt Aluminum 2024 projectile using a gas gun (Figure 1). The blunt impact allows a larger strain energy density to accumulate in a large area of the material prior to penetration compared to a sharp impactor that would induct failure by local through-thickness shearing. The penetration threshold was determined by conducting tests over a range of velocities that resulted in some projectiles penetrating through the panels and some not penetrating, thereby bounding the threshold.

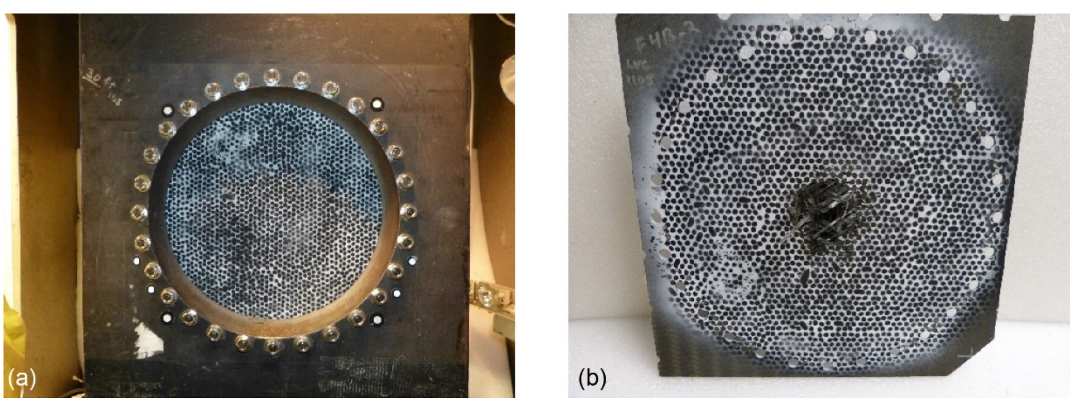

Figure 1.—Braided carbon fiber/epoxy composite impact test panel. (a) Mounted in impact fixture. (b) After projectile penetration.

Results and Discussion

The aligned and offset fiber arrangements of each panel were characterized by optical microscopy (Figure 2 and Figure 3, respectively). Dark areas within each cross-sectional view correspond to fiber ends within axial tows. Light areas are representative of the ±60 fiber tows. Photomicrographs depict the variation in axial tow alignment between test articles as well as illustrate an overall high panel quality and low void content. Resin pockets were observed within all panels, typically concentrated around a tow end.

Axial tow alignment is called out in Figure 2. Efforts to align axial tows were only partially successful. The dashed red box shows a width approximating an axial tow width. Plies 2, 3, 5, and 6 are aligned and lie mostly within this box. However, plies 1 and 4 are shifted and lie mostly outside of the box. This is a result of difficulty in aligning all locations within every ply during layup and shifting of plies during cure.

The photomicrograph in Figure 3 calls out the offset arrangment of the axial tows within sequential plies. Again, the dashed red box represents approximately the width of an axial fiber tow. An attempt was made to offset each layer by one half of the axial tow spacing. This should have resulted in tows 2, 4, and 6 being vertically aligned and tows 1, 3, and 5 also vertically aligned, with the odd-numbered tows being horizontally offset from the even-numbered tows by one-half of the tow spacing. This layup was nearly achieved in Figure 3 except for ply 3. Ply 3 should be aligned with plies 1 and 5 instead of with the even-numbered plies. With the misplacement or shifting of a single ply (ply 3), Figure 2 and Figure 3 are very similar, having four plies that appear to be aligned and two plies offset. This illustrates the difficulty in fabricating model materials in which plies are either perfectly aligned or offset at every location within a panel. This limits the ability to determine the potential difference in impact penetration threshold for panels with perfectly aligned versus perfectly shifted layups.

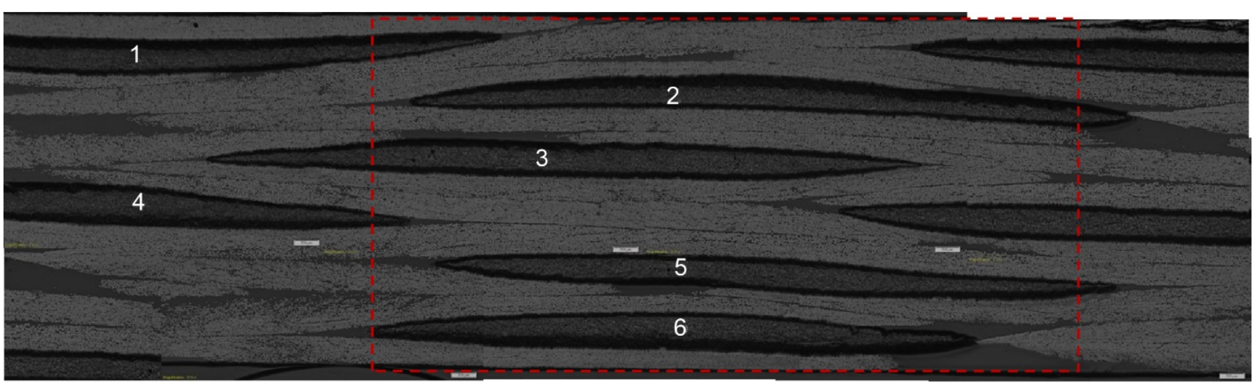

Figure 2.—Photomicrograph of cross section of $[0]_6$ laminate, representing alignment of axial tows.

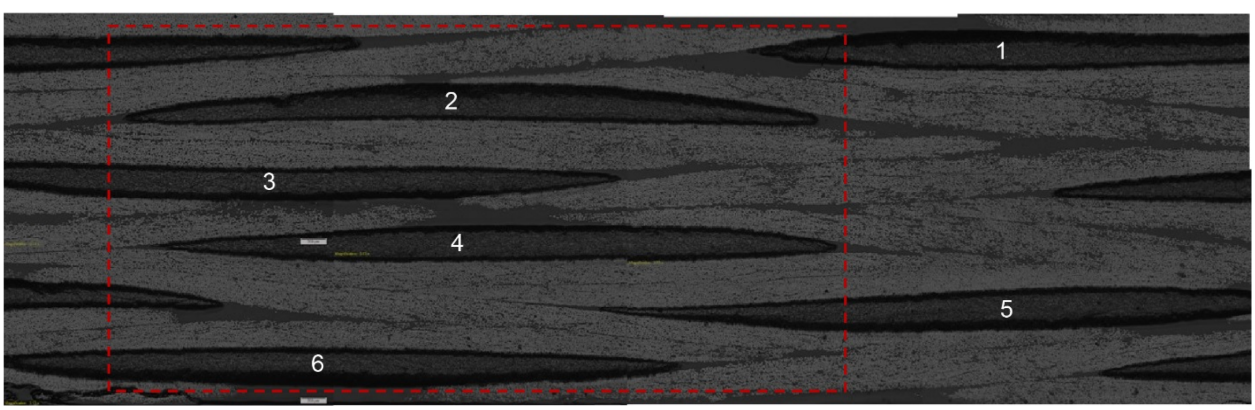

Figure 3.—Cross section of $[0]_6$ braided carbon fiber/epoxy laminate, representing alignment of axial tows.

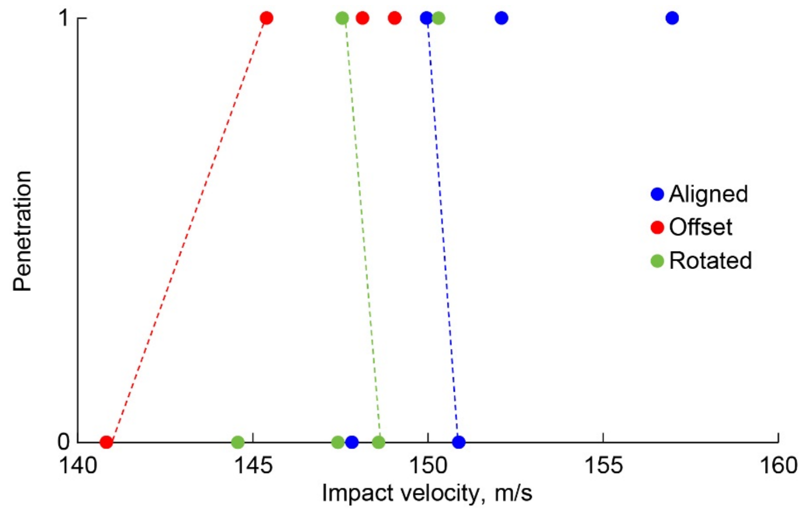

Figure 4.—Penetration as function of projectile impact velocity for braided carbon fiber/epoxy composites with different fiber alignments.

A plot of penetration threshold as related to fiber alignment is shown in Figure 4, with a value of 0 representative of no penetration and a value of 1 corresponding to projectile penetration through the panel. There are not enough data to calculate a true penetration velocity with statistical significance. Instead, a dashed line is drawn between points having the highest velocity for an unpenetrated test (a y-axis value of 0) and the lowest velocity for a penetrated test (a y-axis value of 1) to provide an estimate of penetration threshold. The estimated penetration threshold for the offset layup was lower than that of the aligned and rotated layups; however, the difference is small (~5 m/s). With a small variance and limited data it is not possible to determine if these differences are statistically significant and, if so, if they are related to the axial fiber alignment or to other factors. Other possible variables influencing penetration threshold include panel-to-panel variation in thickness, resin content, and fiber volume fraction.

Panel thicknesses, subsequent fiber volume, and corresponding impact data are outlined in Table I.

Processing parameters were kept constant throughout fabrication of individual panels. As a result, the measured variation in panel thickness and corresponding fiber volume was small; within each panel set and between fiber orientations.

A separate set of panels were fabricated by A&P Technology based on a QISO braided prepreg with higher resin content and therefore lower fiber volume than the other panels. Panel thickness, constituent quantities, and impact data are listed in Table II. Figure 5 plots the penetration thresholds of the LFV panels along with those of the in-house manufactured panels.

The penetration threshold of the LFV, or high-resin-content, panels is significantly greater than that of the higher fiber volume variants. It is possible that the difference in penetration threshold is a result of material and process variations. However, all panels appeared to be very high quality with minimal voids observed by microscopy. Another possibility for the difference in penetration threshold is related to panel thickness and resin content. All panels had the same amount of fiber reinforcement. However, the LFV panels were thicker and had greater resin content (lower fiber volume fraction) than the other panels. Thicker panels would have lower in-plane material modulus because of the lower fiber volume fraction, but higher plate bending stiffness since the outer plies are a greater distance from the neutral plane. Increased resin content in the LFV would provide more material that could dissipate energy through plastic deformation. Further experimentation and analysis at the microscopic, mesoscopic, and macroscopic levels are needed to determine the relative importance of materials processing, fiber volume fraction, resin content, and ply layup on impact penetration threshold. However, the results presented here suggest that lower fiber volume fraction (higher resin content) could be beneficial for impact resistance. This differs from a common approach to design for the highest possible fiber volume fraction. Whereas high fiber volume fraction provides high in-plane material properties for fiber-dominated deformation modes, lower fiber volume fraction could be a better option for impact-resistant structure design.

This conclusion is supported by the postimpact damage areas observed by C-scan. Postimpact damage images are shown in Figure 6 to Figure 9. A large damage area was observed for all panel types, as intended when the blunt impactor is used. However, the damage area for the LFV panel was consistently larger than the damage area observed in the higher fiber volume panels, indicating a greater distribution of impact load.

TABLE I.—PANEL THICKNESS, FIBER VOLUME, AND IMPACT DATA FOR BRAIDED CARBON FIBER/EPOXY COMPOSITE PANELS WITH INTENTIONAL FIBER ALIGNMENT VARIATIONS

Alignment	Panel	Average panel thickness, in.	Fiber, vol%	Impact velocity, m/s	Penetration
Aligned	1078	0.1303	54.0	147.83	N
	1079	0.1290	54.5	156.97	Y
	1080	0.1300	54.1	152.1	Y
	1081	0.1233	57.1	150.88	N
	1082	0.1305	53.9	149.96	Y
Average		**0.1286**	**54.7**		
Offset	1083	0.1285	54.7	149.05	Y
	1084	0.1250	56.3	149.05	Y
	1086	0.1265	55.6	148.13	Y
	1087	0.1265	55.6	140.82	N
	1088	0.1313	53.6	145.39	Y
Average		**0.1276**	**55.2**		
Rotated	1090	0.1293	54.4	144.57	N
	1091	0.1290	54.5	147.55	Y
	1093	0.125	56.3	147.43	N
	1094	0.1270	55.4	148.59	N
	1095	0.1250	56.3	150.3	Y
Average		**0.1276**	**55.2**		

TABLE II.—CONSTITUENT CONCENTRATIONS AND IMPACT DATA FOR LOW-FIBER-VOLUME (LFV) BRAIDED CARBON FIBER/EPOXY COMPOSITE PANELS

Panel	Average panel thickness, in.	Fiber, vol%	Impact velocity, m/s	Penetration
1101	0.1385	50.8	169.47	N
1102	0.1388	50.7	170.69	N
1103	0.1390	50.6	174.96	Y
1104	0.1413	49.8	177.09	N
1105	0.1413	49.8	178.92	Y
Average	**0.1398**	**50.34**		

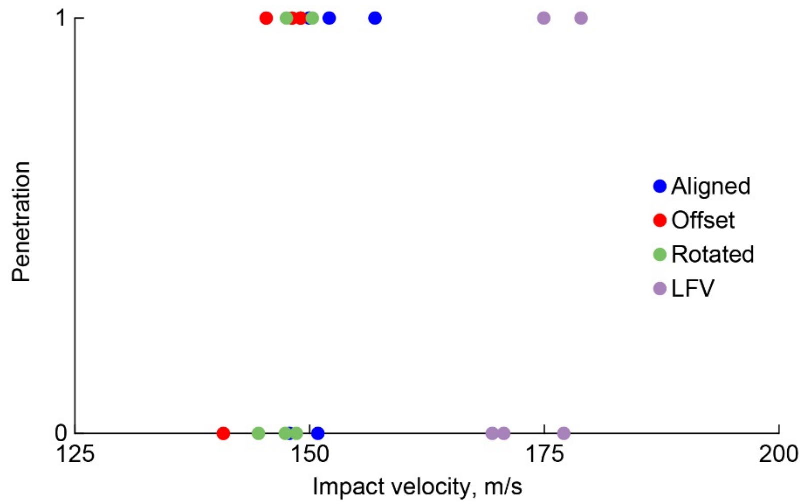

Figure 5.—Penetration as function of projectile impact velocity for braided carbon fiber/epoxy composite panels with different fiber alignments and low fiber volume (LFV).

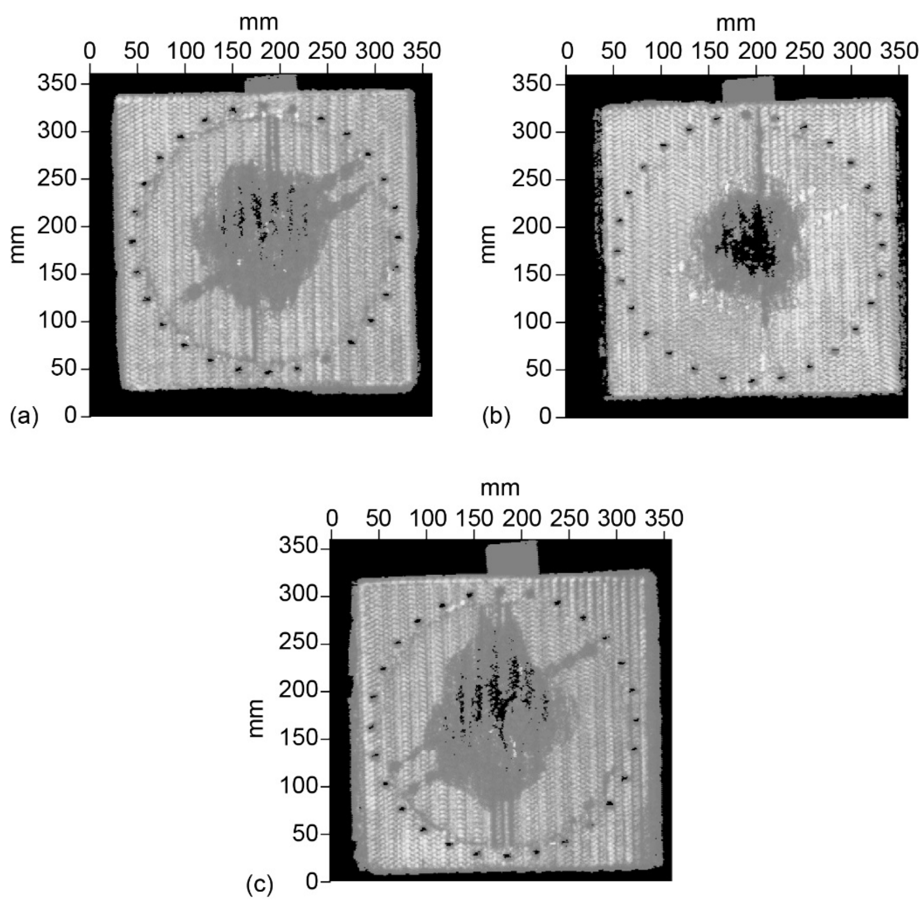

Figure 6.—Postimpact C-scan images of representative aligned braided carbon fiber/epoxy composite panels (see Table I). (a) Panel 1078. (b) Panel 1080. (c) Panel 1081.

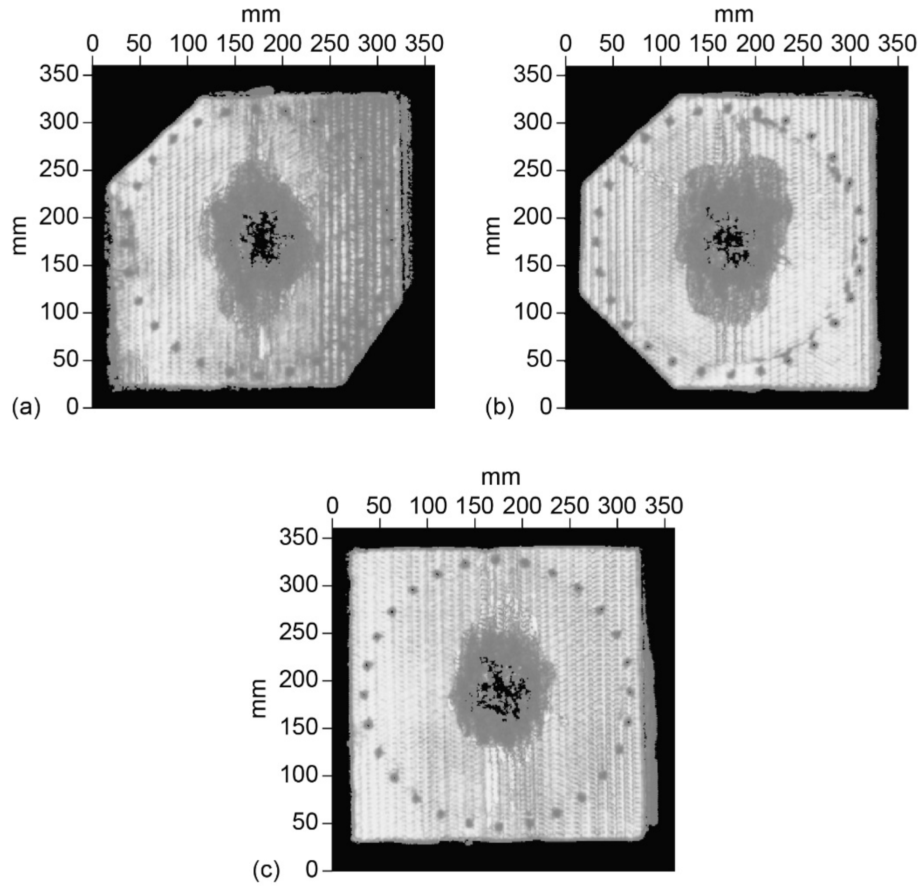

Figure 7.—Postimpact C-scan images of representative offset braided carbon fiber/epoxy composite panels (see Table I). (a) Panel 1083. (b) Panel 1084. (c) Panel 1086.

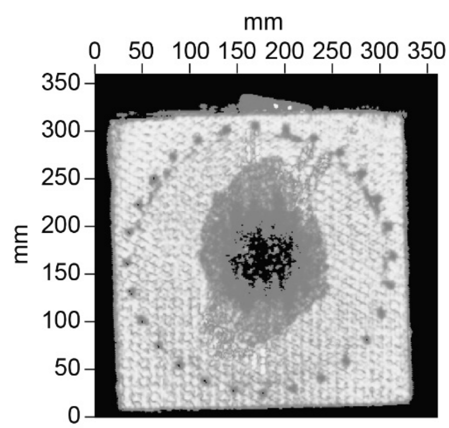

Figure 8.—Postimpact C-scan images of representative rotated braided carbon fiber/epoxy composite panel 1095 (see Table I).

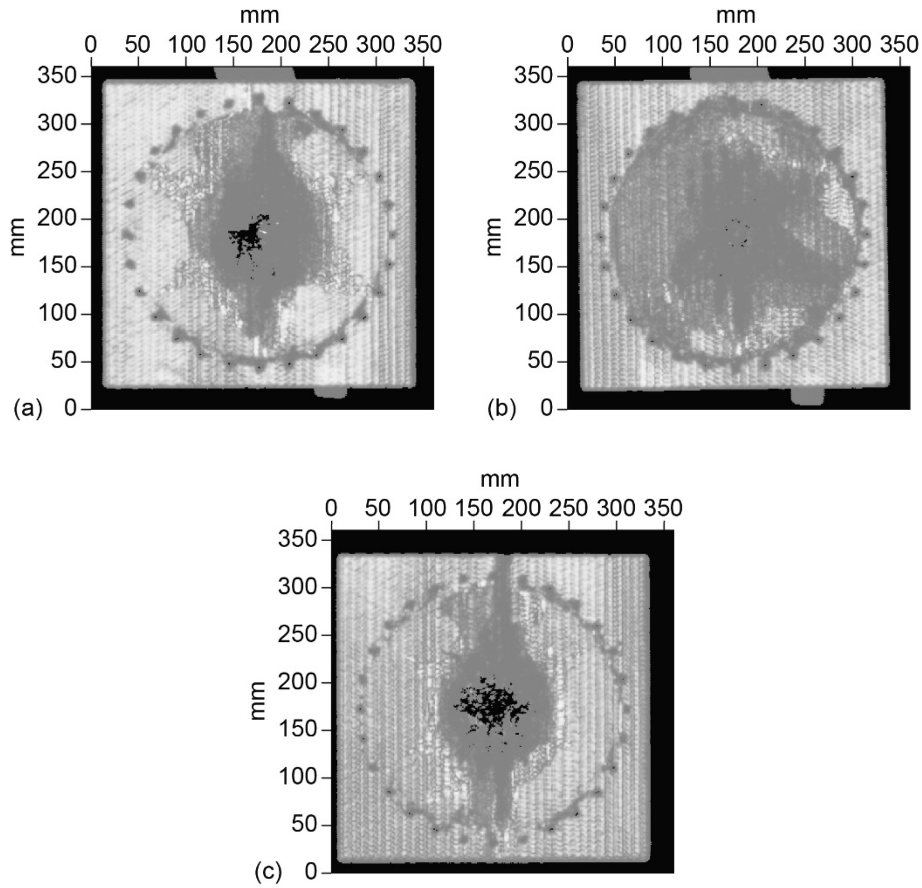

Figure 9.—Postimpact C-scan images of representative low-fiber-volume (LFV) braided carbon fiber/epoxy composite panels (see Table II). (a) Panel 1101. (b) Panel 1102. (c) Panel 1103.

A detailed analytical study could provide further insight into the effects of geometric and material variability on the impact response. A mesoscopic-scale model, where the fiber tows and resin pockets are explicitly modeled, could be used to determine how the behaviors of the individual constituents contribute to the overall impact response. In terms of the parameters discussed in this study, in an analytical model the alignment of the fiber tows relative to each other could be precisely specified, and perfectly stacked or offset fiber tow orientations could be defined exactly, which would allow for a precise determination of the effects of the fiber tow geometry and layout on the impact behavior of the material. Furthermore, simulated panels with a variety of fiber volume ratios and distribution of resin pockets could be developed, which would allow for a detailed examination on how the amount and location of resin pockets contribute to the impact response. The specific deformation and damage patterns that occur in the fiber tows and resin pockets could be examined, which would provide significant insight into what aspects of the material behavior lead to the penetration velocities and overall damage patterns observed in the experiments. For example, the effects of specified local mechanisms—such as local temperature rises in the matrix, local matrix failures, or local plasticity in the matrix—on the overall impact response could be quantified, leading to a more thorough and complete understanding of the processes that occur during an impact event.

Conclusions

A series of triaxially braided composite panels were fabricated and impacted with a blunt projectile to determine the penetration threshold as a function of fiber alignment and fiber volume. Axial tow fiber alignment was a challenge to perfect during fabrication, and in most cases an absolute aligned or offset orientation was not achieved. A rotated layup with each layer oriented at 30° relative to adjacent layers was more easily achieved. Measured panel thicknesses and calculated fiber volumes showed little variation between panels or fiber orientations. The estimated penetration threshold for the offset layup was lower than that of the aligned and rotated layups; however, the difference is small, suggesting little influence of fiber arrangement on impact penetration threshold. A series of low-fiber-volume panels clearly demonstrated this parameter was a primary driver in determining the impact penetration threshold.

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