

Fabrication of a First Article Lightweight Composite Technology Demonstrator – Exospine

by Jared M. Gardner, Larry R. Holmes, Jr., and Jerome T. Tzeng

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Fabrication of a First Article Lightweight Composite Technology Demonstrator – Exospine

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14. ABSTRACT The U.S. Army Research Laboratory (ARL) has fabricated a lightweight composite technology demonstration exospine. The composite exospine allows for load transfer off of a Soldier's shoulders and back, directly to the waist and legs, in order to reduce spine related injuries caused by the load carried during typical field maneuvers. Previous work conducted at the Center for Composite Materials, University of Delaware (UD-CCM, Newark, DE) focused on the design and optimization of the stiffness and weight of the structure through use of composite materials. Although the demonstrator is not evaluated mechanically in the scope of this work, since the work focuses only the fabrication of the article, it is expected to perform comparably to a baseline metal design from Emerald Touch Inc. (Duncanville, TX) that is capable of bearing a full loading of a typical Soldier's field gear. The demonstrator is constructed of a plain woven carbon fiber fabric, an epoxy resin matrix, and a low-density foam core. The finished first article demonstrator shows that the design is feasible for fabrication using standard composite processing methods and weighs only 263 g (9.28 oz). This report provides a detailed description of the fabrication of the exospine composite technology demonstrator.					
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1. Introduction

Injuries have become widespread and are near epidemic status in the United States (U.S.) military. The U.S. Army is experiencing an extremely large percentage of Soldier related injuries due to the equipment borne of the loads placed on the joints and spine during typical in-field and training maneuvers. Ergonomics focused on efficient load transfer of personal protective armor configurations and other equipment borne by the Soldier is of significant consideration in reducing these secondary types of injuries. Identifying solutions that can reduce injuries to the Soldier may help to greatly reduce costs and maintain the readiness and health of the U.S Army.

Injury has become the number one threat to the readiness and health of the U.S. military armed forces.

Here are some staggering 2007 Department of Defense (DOD) statistics about military injuries:

- There were 2.1 million injury-related medical visits, affecting 900,000 service members.
- Injuries were the second cause of hospitalizations, accounting for almost 110,000 days in hospital.
- Injuries were, and are, the leading cause of outpatient clinical visits.
- Musculoskeletal injuries accounted for 68% of all limited-duty days and medical profiles; they add up to an estimated 25 million limited-duty days per year.

The DOD 2007 statistics regarding military injuries state that the injury rate for the Army is 2500 reported for every 1000 Soldiers. Musculoskeletal injuries to the low back, knee, ankle and shoulders account for most of those visits. These numbers do not include injuries from Operations Enduring Freedom and Iraqi Freedom; they include only injuries from Army garrisons (1).

Previous work conducted at the Center for Composite Materials, University of Delaware (UD-CCM, Newark, DE) focused on the design and optimization of an exospine structure through use of composite materials. The design is based on a steel/aluminum structure developed previously by Dr. Michael Glenn (Emerald Touch Inc., Duncanville, TX) that is capable of bearing a full loading of a typical Soldier's field gear. The exospine is designed to transfer the loads of armor and other gear off of the shoulders and back onto the waist, thereby reducing the loads carried by the spine during typical field maneuvers. The completely assembled system called the Integrated Support Exospine (ISE) detailed in (2) contains the pelvis assembly and other components necessary for gear attachment and general use. Additional details on the background, design, support system requirements, tooling construction used for the fabrication of the demonstrator, and demonstrations of the exospine can also be found in (2).

This report gives detailed descriptions of the fabrication of the technology demonstrator by the U.S. Army Research Laboratory (ARL). The demonstrator is not evaluated mechanically in the scope of this work, since the work focuses only the fabrication of the article. However, it is expected to perform comparably to a baseline metal design from Emerald Touch Inc. that is capable of bearing a full loading of a typical Soldier's field gear. This type of lightweight composite structure offers significant design flexibility, and potential future articles may provide an ideal type of platform for maximizing functionality of Soldier systems through integrated sensing, heat management, and onboard diagnostics.

2. Experimental

2.1 Materials

Plain woven carbon fiber/epoxy prepreg and a low-density foam core were provided to ARL for the fabrication of the exospine technology demonstrator by UD-CCM.

The prepreg was ACG - MTM* 45-1/CF0526 and has a cured ply thickness of 0.201 mm. It is comprised of a toughened epoxy matrix resin, 36 weight-percent, and G30 – 500/3K plain weave carbon fiber fabric, 193 (g/m²) fabric aerial weight (FAW) (3). Information provided on the lamina level test summary attached to the prepreg material stated that the specific fiber type for this material system is a Tenax – J HTS40 E13 3K 200TEX (4). Upon examination of the as-received material, common signs of shelf life expiration of the prepreg matrix material such as dry and/or resin starved locations were observed. However, the material retained sufficient tack as necessary for successful processing of the technology demonstrator.

The core material was Divinycell[†] F50 high temperature closed cell general use foam core, for commercial aircraft interior applications (5). The batch and density report attached to the core material upon receipt stated a thickness of 3.18 mm and density of 53 kg/m³ (6). The product brochure and technical datasheets for Divinycell F50 state that it is a cold and heat formable non-hygroscopic thermoplastic, with excellent FST (fire, smoke, and toxicity) properties, good mechanical properties, and is compatible with most common processes using thermoplastic and thermoset resins including epoxies and phenolics (5, 7).

* ACG-MTM is a registered trademark of Advanced Composites Group Ltd., Derbyshire, U.K.

[†] Divinycell is a registered trademark of DIAB Group, Sweden.

2.2 Computer Aided Design

Computer-aided design (CAD) programs were utilized in the design process and for exporting of ply and core dimensions to an automated Gerber Technology DC2500 (Gerber) (Tolland, CT) cutting table.

AutoCAD* drawings were provided by Dr. John J. Tierney, scientist at UD-CCM. These drawings were recreated using Solidworks (Dassault Systemes Solidworks Corp., Waltham, MA) 3-D mechanical CAD software. Length, angle, and radius measurements were used to recreate the designs as closely to the original as possible. This was done to slightly simplify the original contours, increase symmetry in the design, and reduce the number of nodes/line segments present in the drawing for automated cutting operations. Figure 1 shows the Solidworks CAD drawings of plies 1–5, the core base and arm(s), and plies 6–10 that were used for ply and core cutting. Slight simplifications of the actual CAD drawing dimensions are shown.

2.3 Tool Preparation

A single piece male tool was provided for the fabrication of the exospine technology demonstrator by UD-CCM. The tool was constructed of high density tooling board and was surface coated with Duratec†polyester surfacing primer.

* AutoCad is a registered trademark of Autodesk, Inc., San Rafael, CA.

† Duratec is a registered trademark of Hawkeye Industries, Inc., Bloomington, CA.

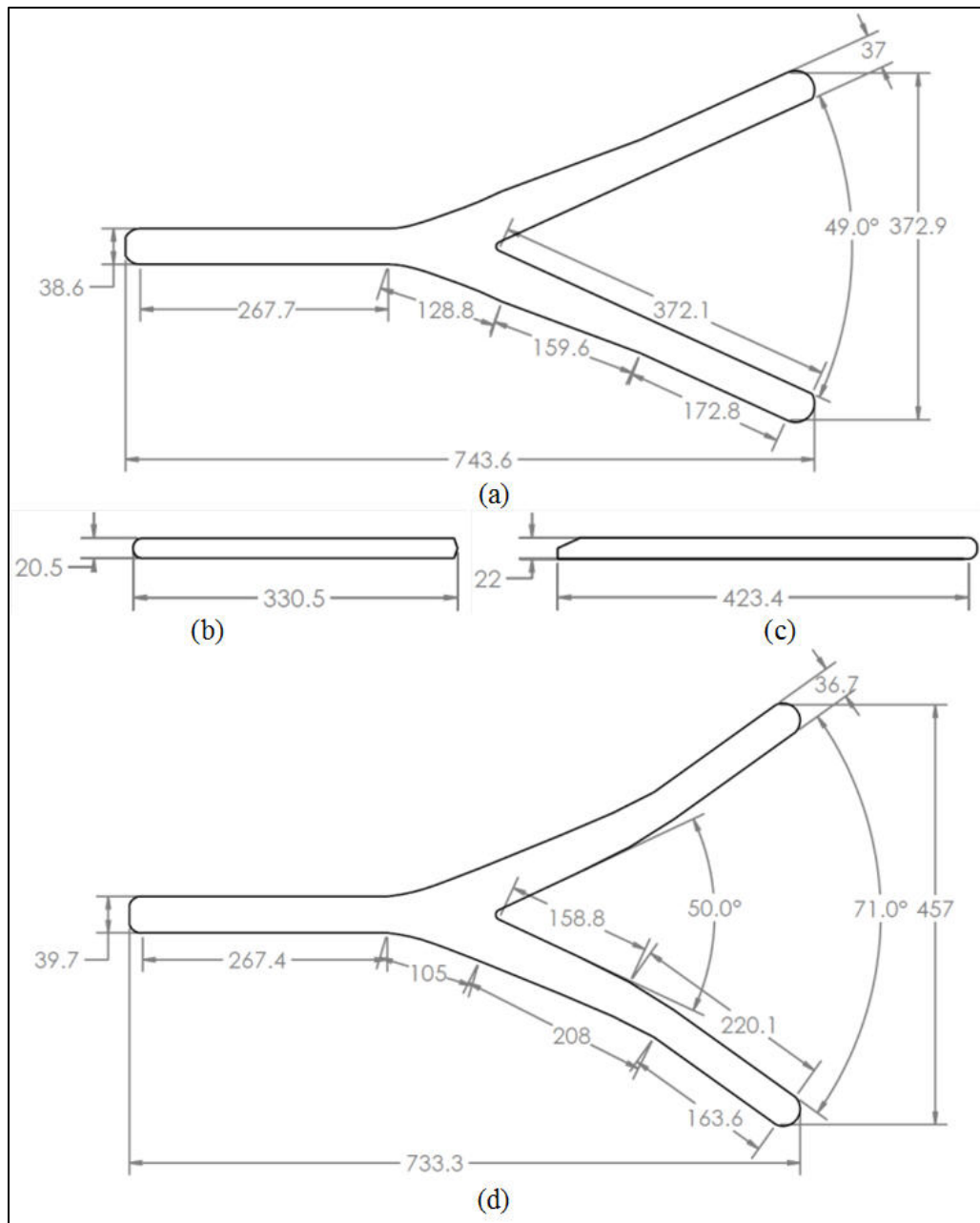


Figure 1. Solidworks CAD drawings used for cut patterns of (a) plies 1–5, (b) foam core base, (c) foam core arms, and (d) plies 6–10. All dimensions are in millimeters.

The surface of the tool was cleaned using isopropyl alcohol (IPA) before and after preparation, allowing approximately 10 min for solvent evaporation. One ply of Tooltec* CA5 PTFE coated release film was applied to the tool surface covering the contact region of the tool with the composite. The Tooltec CA5 was cut on the Gerber cutting table to 1.5 times the size of the cut pattern for plies 1–5 (figure 1(a)). The tool was vacuum bagged and placed in a convection oven for 120 min at 65.6 °C (150 °F) for curing of the Tooltec CA5. The remaining uncovered surface area of the tool was patched with the Tooltec CA5. Scribe lines, which are commonly used in tooling applications for indicating alignment and material placement, were not present on the surface of the tool. Therefore, vertical alignment marks were hand drawn along the centerline of the tool at the base, midpoint, and at various points along the centerline of each arm. A horizontal mark was also made at the base to indicate the starting point of the first fabric ply. Images of the prepared exospine tool are shown in figure 2.

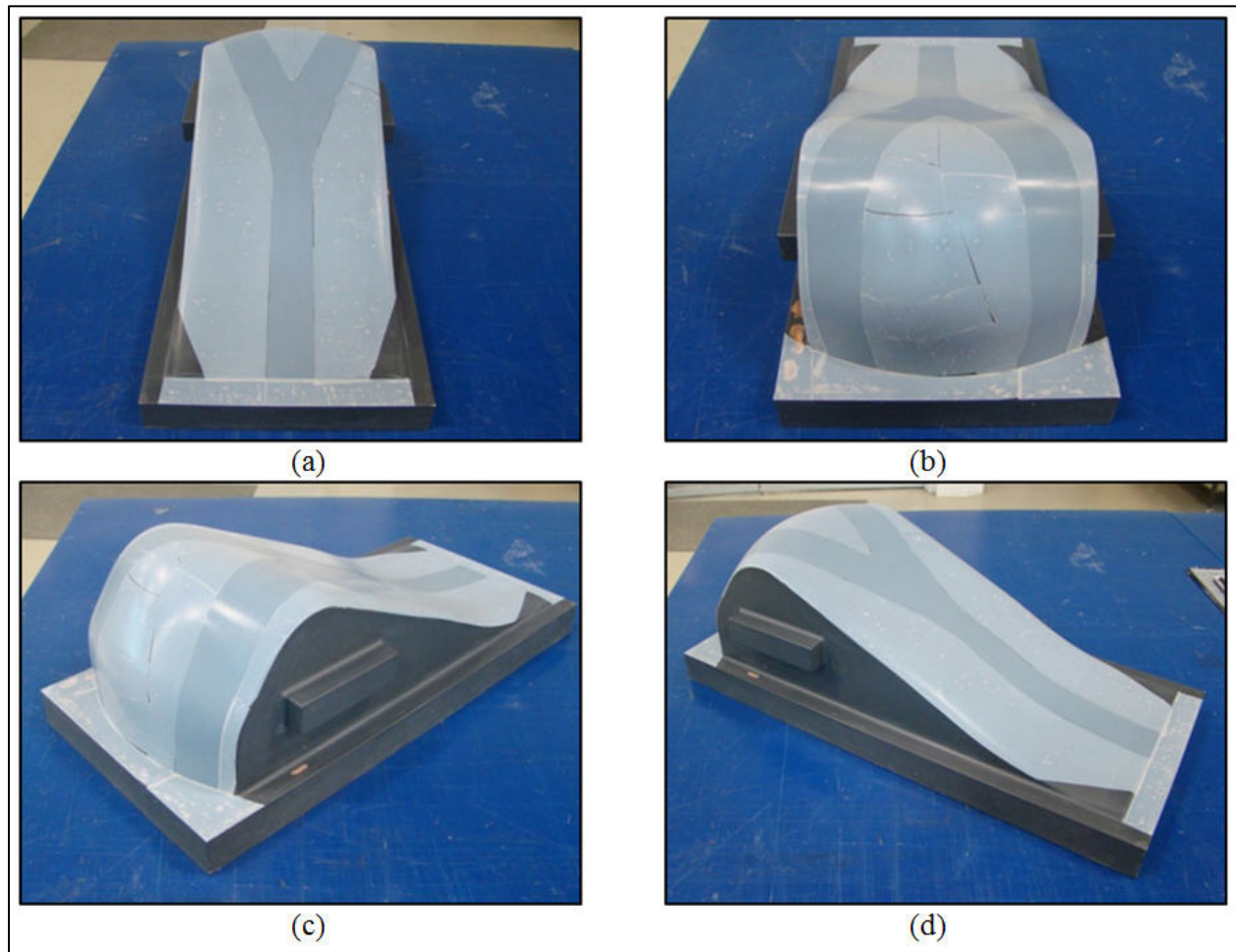


Figure 2. (a) Front, (b) back, (c) angled back, and (d) angled front views of the prepared tool.

*Tooltec is a registered trademark of Airtech International, Huntington Beach, CA.

2.4 Fabric and Core Cutting

The ply stacking sequence for this design is $[(0/90)_2, (\pm 45), (0/90)_2]_S$. Therefore, this architecture is comprised of 10 total plies and is balanced and symmetric about the core that is placed at the mid-plane between plies 5 and 6.

A ply stack was constructed after cutting with the (0/90) plies in the following locations: 1, 2, 4, 5, 6, 7, 9, and 10. The (± 45) plies were placed in the ply stack at locations: 3 and 8. The white backing side (dry side) of the prepreg fabric was oriented in the ply stack facing the tool and exterior surfaces as suggested by the manufacturer (3). The stacking sequence for the exospine construction is illustrated in table 1.

Table 1. Schematic of the ply stacking sequence for the exospine.

Ply Orientation	Ply Number	Warp Face	
0/90	10	down	↓
0/90	9		
± 45	8		
0/90	7		
0/90	6		
← --- Foam Core --- →			
0/90	5	up	↑
0/90	4		
± 45	3		
0/90	2		
0/90	1		

Using a counterclockwise warp clock (relative to the warp face and direction of the fabric), the eight (0/90) plies were cut with the long axis of the part in the 90° fabric direction, and the remaining two (± 45) plies were cut with the long axis of the part in the +45°. Figure 3 shows the ply cut directions from the fabric bolt relative to the warp face and counterclockwise warp clock.

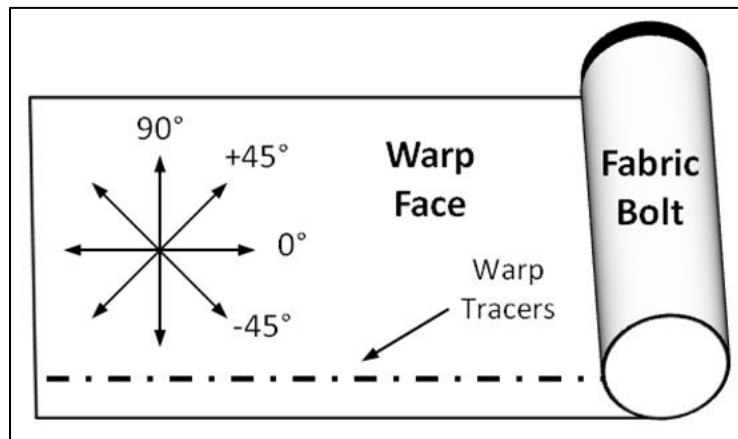


Figure 3. Fabric bolt (or fabric roll) showing warp directions and overlay of a counterclockwise warp clock.

Three cuts were made of the Divinycell F50 foam core, one for the base and two for the arms. Images of the foam core and prepreg fabric are shown during the ply cutting process in figure 4. The ply and core cut patterns generated in Solidworks were imported into the Gerber cutting table software program. The drawings required manual scaling in the Gerber software from the drawing scale to the actual pattern scale as follows: core base 1:2, core arm(s) 1:2, plies (1–5) 1:4, plies (6–10) 1:4.

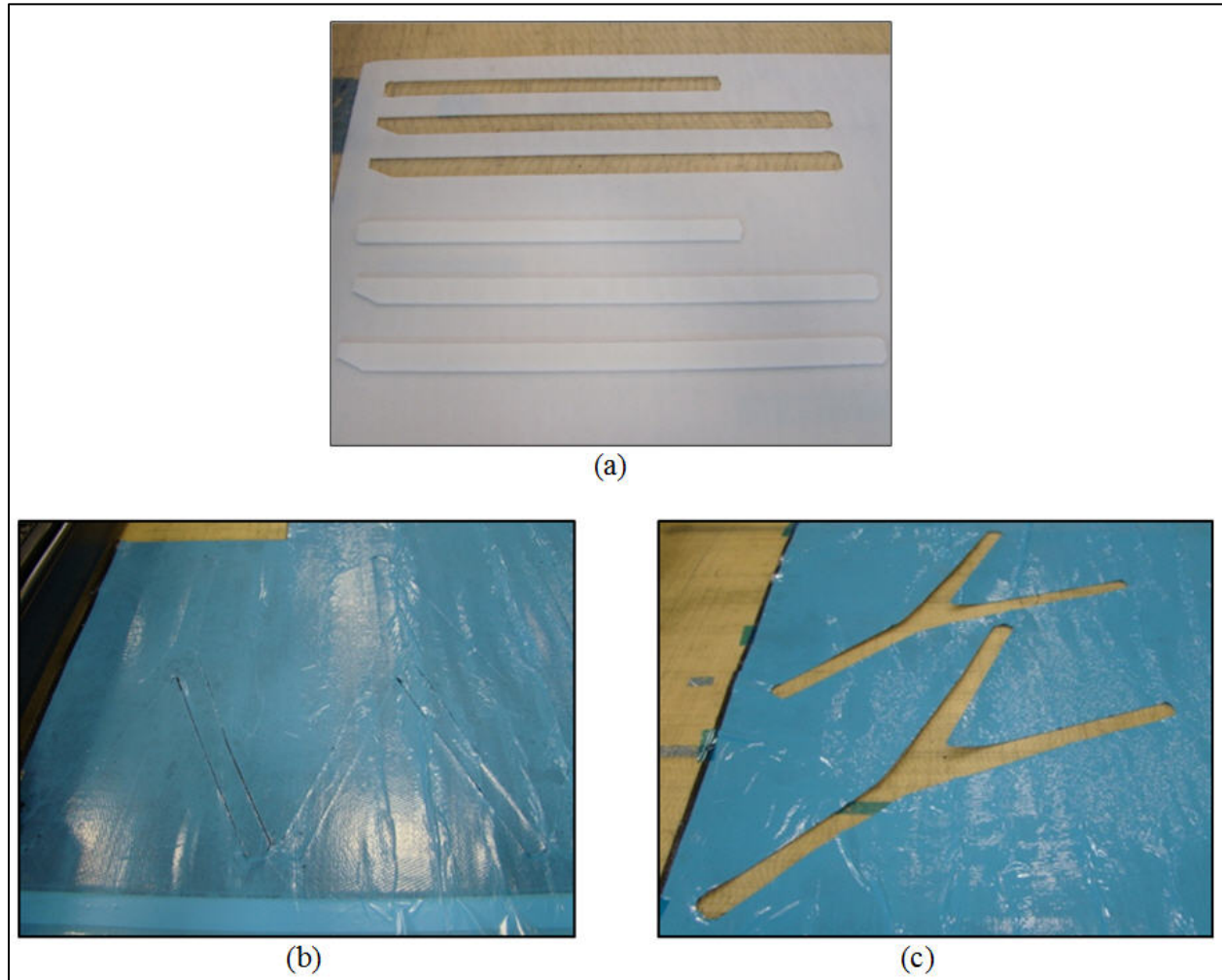


Figure 4. (a) Base and arm cuts of Divinycell F50 foam core, (b) 0/90, and (c) ± 45 ply cuts of ACG-MTM 45-1/CF0526 prepreg fabric.

3. Processing

3.1 Fabrication by Hand Layup

The composite layup was conducted by hand placing the pre-cut plies onto the surface of the tool in the exact pre-arranged order described in the previous section 2.4 of this report. The first ply was aligned with the vertical and horizontal alignment marks drawn onto the mold surface in section 2.3. The white backing was removed prior to placement of each ply. The blue release film was left on the surface of the plies during placement until completion of the tacking and forming process described next.

Shown in figure 5 is a heat gun that was used during ply placement to increase the tack of the prepreg because of the slightly resin starved nature of the as-received material. In addition, the room temperature during layup was approximately 16.7 °C (62 °F), which is 2.8 to 5.6 °C (5 to 10 °F) below average normal processing temperatures.

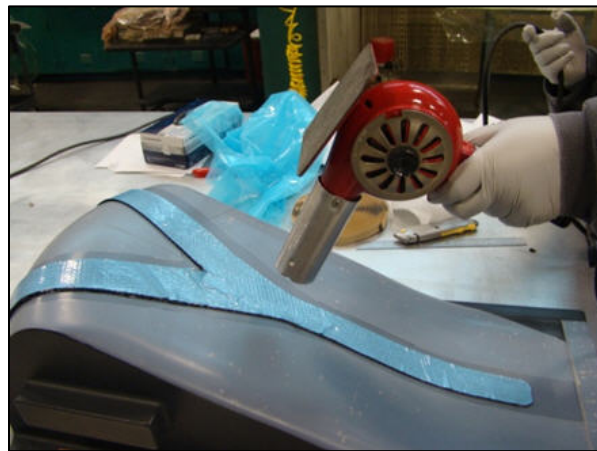


Figure 5. Ply tacking process using a heat gun.

The layup process for plies 1–3 is shown in figure 6. The callout image in figure 6b shows a close up view of the ± 45 fiber orientation.

Ply layup began at the base of the mold, working up the tool in sections approximately 1/3 of the total ply length. The heat gun was set on high, held approximately 76.2 to 101.6 mm (3 to 4 in) from the tool surface, and was moved along the length of the ply at rate of approximately 50.8 mm/s (2 in/s). After each ply section had been heated to point of slight tack, the ply was shaped and manipulated by hand, carefully working from the centerline out to the edges to conform the plies to the geometry of tool.

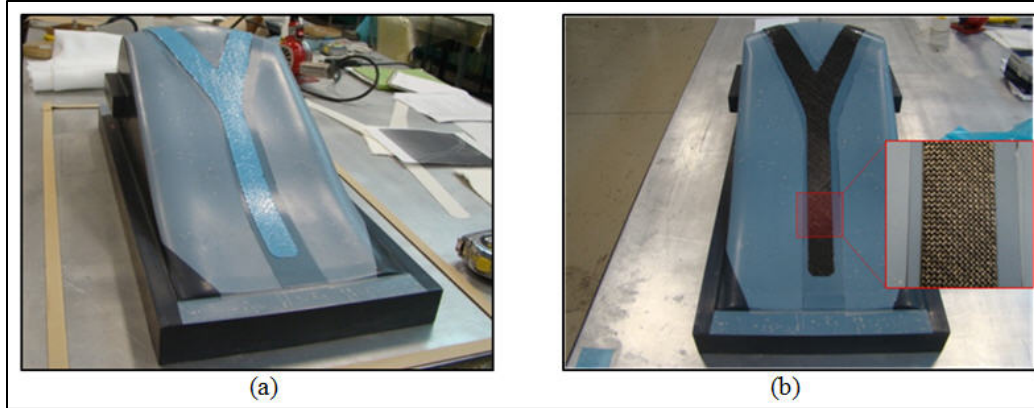


Figure 6. Layup of (a) plies 1 and 2 at 0/90, and (b) ply 3 at ± 45 .

The ply stack was debulked at plies 3, 6, and 8 during the layup process to ensure proper consolidation and conformation to the tool geometry. Prior to debulking, the ply stack was covered with a non-perforated release film, a 1/16-in thick rubber membrane (cut to 1.5 times the size of the plies), and a heavy breather cloth. The entire layup was vacuum bagged and held at approximately 22 in/Hg for 5 min during each debulk cycle. Stretchlon SL800 bagging film made by Airtech International was used for all vacuum bagging in this work. The steps of the first debulk process are shown in figure 7.

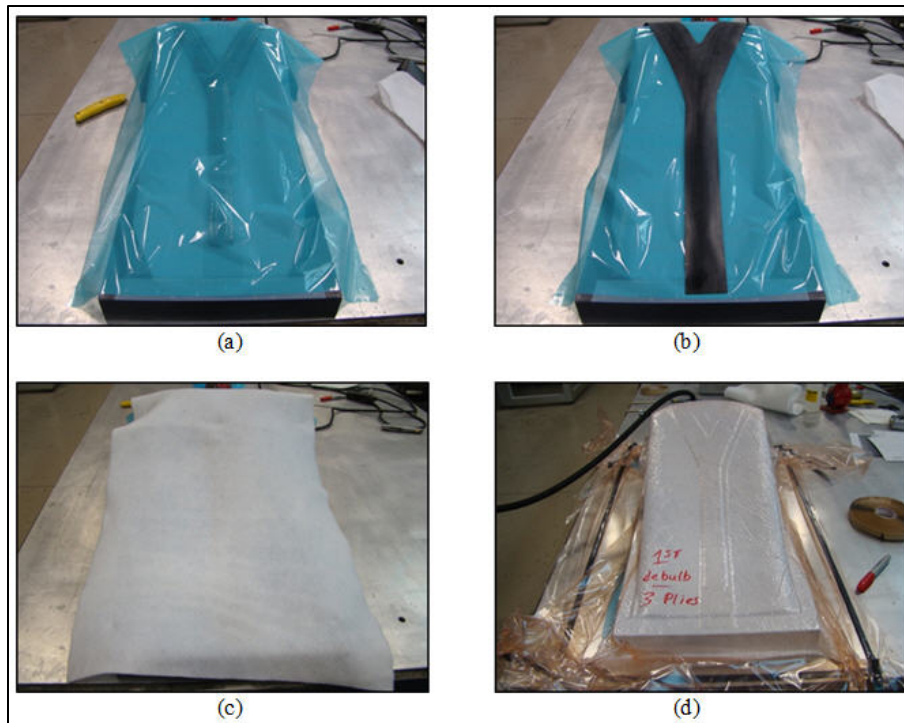


Figure 7. (a) Non-perforated release film, (b) 1/16-in rubber membrane, (c) heavy breather cloth, and (d) first debulk cycle at ply 3.

The layup process for plies 4 through 5 and the foam core are shown in figure 8. The callout images in figure 8b show close up views of the foam core from the back, top, and bottom (clockwise respectively). The starting placement location of the foam core was offset by 11.5 mm (0.45 in) from the ply edge at the base of the mold and is identified also in figure 8b.

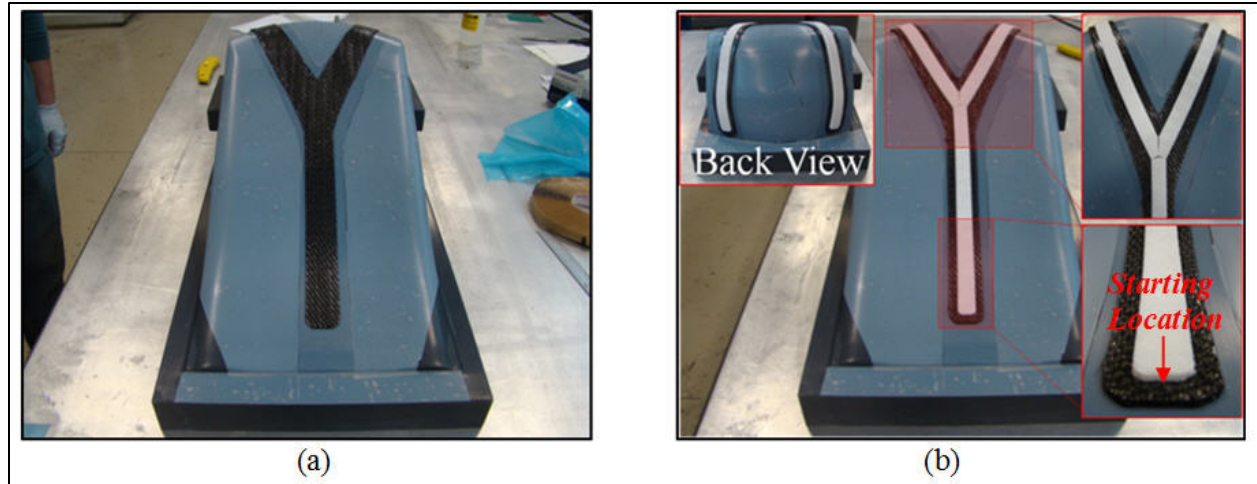


Figure 8. Layup of (a) plies 4 and 5 at 0/90, and (b) the three piece foam core.

The layup process for plies 6 through 7 and the second debulk cycle at ply 6 are shown in figure 9. A hard plastic squeegee was used to press and manipulate plies 6–10 tightly around the foam core.

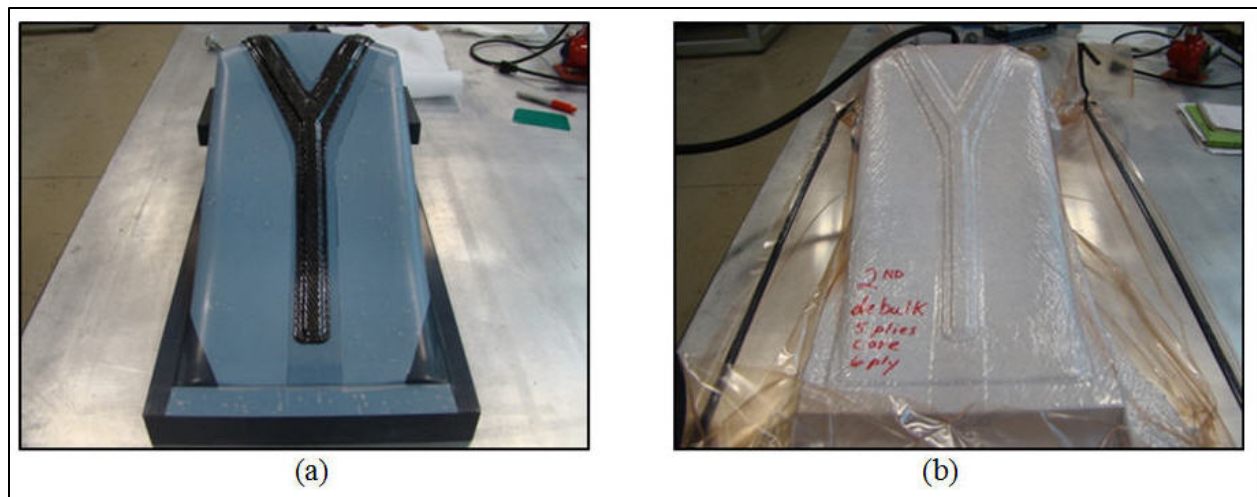


Figure 9. Layup of (a) plies 6 and 7 at 0/90, and (b) the second debulk cycle at ply 6.

The layup process for ply 8, and the third debulk cycle at ply 8 are shown in figure 10. Note that small wrinkles began to develop in ply 8 on both edges of the left arm due to ply buckling because of insufficient ply manipulation. Close up views of the wrinkles are shown in the callout images in figure 10a.

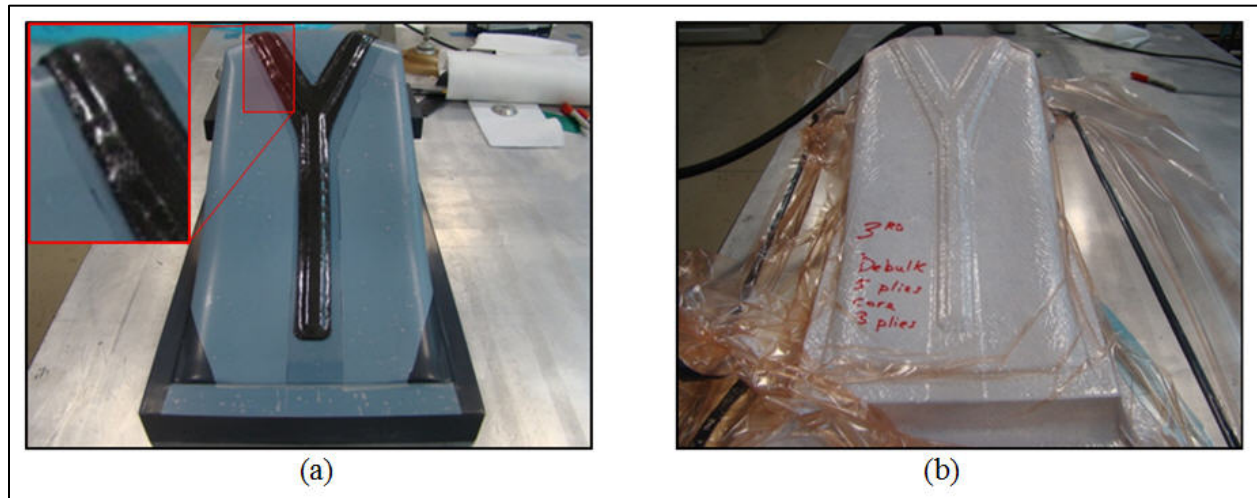


Figure 10. Layup of (a) ply 8 at ± 45 , and (b) the third debulk cycle at ply 8.

The layup process for plies 9–10 is shown in figure 11.



Figure 11. Layup of (a) plies 9 and 10 at 0/90.

Additional views of the completed layup are shown in figure 12, including back view (a), and an angle back view (b).

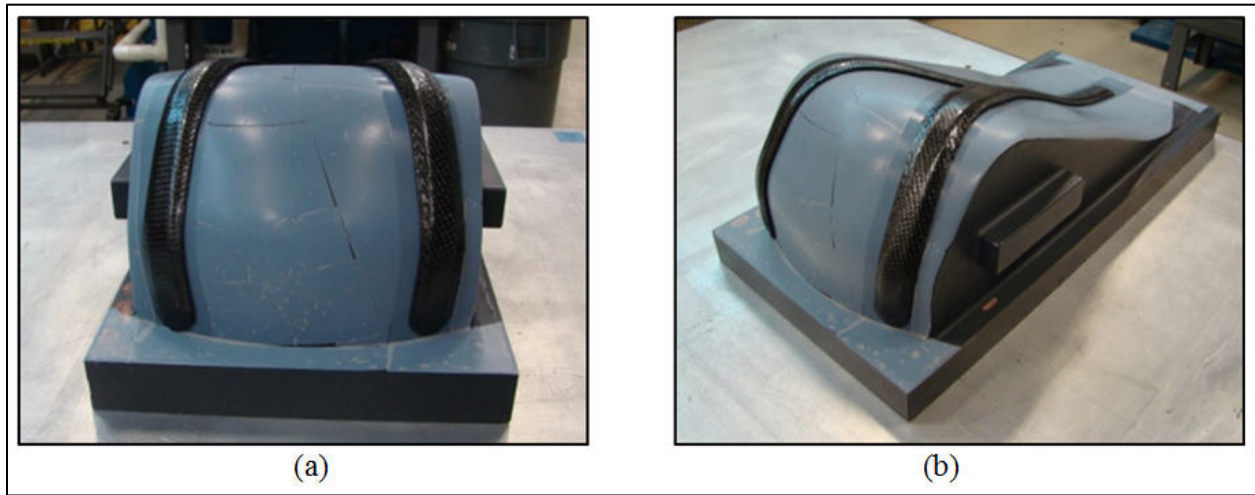


Figure 12. (a) Back, and (b) angled back views of the completed layup.

3.2 Vacuum Bag and Cure

The completed layup was covered with a non-perforated release film (sized to 1.5 times of the nominal ply cut pattern size) and the 1/16-in thick rubber membrane used in section 1.3.3. These were separately secured in place using Flashbreaker* 2 pressure sensitive polyester tape and covered by an additional ply of the non-perforated release film. The entire tool was wrapped with heavy breather cloth, overlapping the cloth at the seams. The cloth was then folded on the ends and taped in place with the Flashbreaker 2 tape. The tool was placed inside an envelope style vacuum bag, allowing sufficient excess bag for insertion of two vacuum ports into one end of the bag. Two layers of breather cloth were inserted under the back side of the tool extending approximately 460 mm (18 in) beyond the end of tool for placement under the vacuum ports. The ends of the bag were sealed using tacky tape, and the vacuum ports were inserted.

Vacuum pressure was applied slowly so that the bag could be carefully shaped to the mold and part geometry. This process eliminates bridging of the vacuum bag over edges of the part and mold geometries. Approximately 28-in Hg (14-psi) vacuum pressure was achieved, and a vacuum drop test showed less than 2 in Hg (1 psi) loss in 10 min after vacuum removal. The bagging process is shown in figures 13 and 14.

*Flashbreaker is a registered trademark of Airtech International, Huntington Beach, CA.

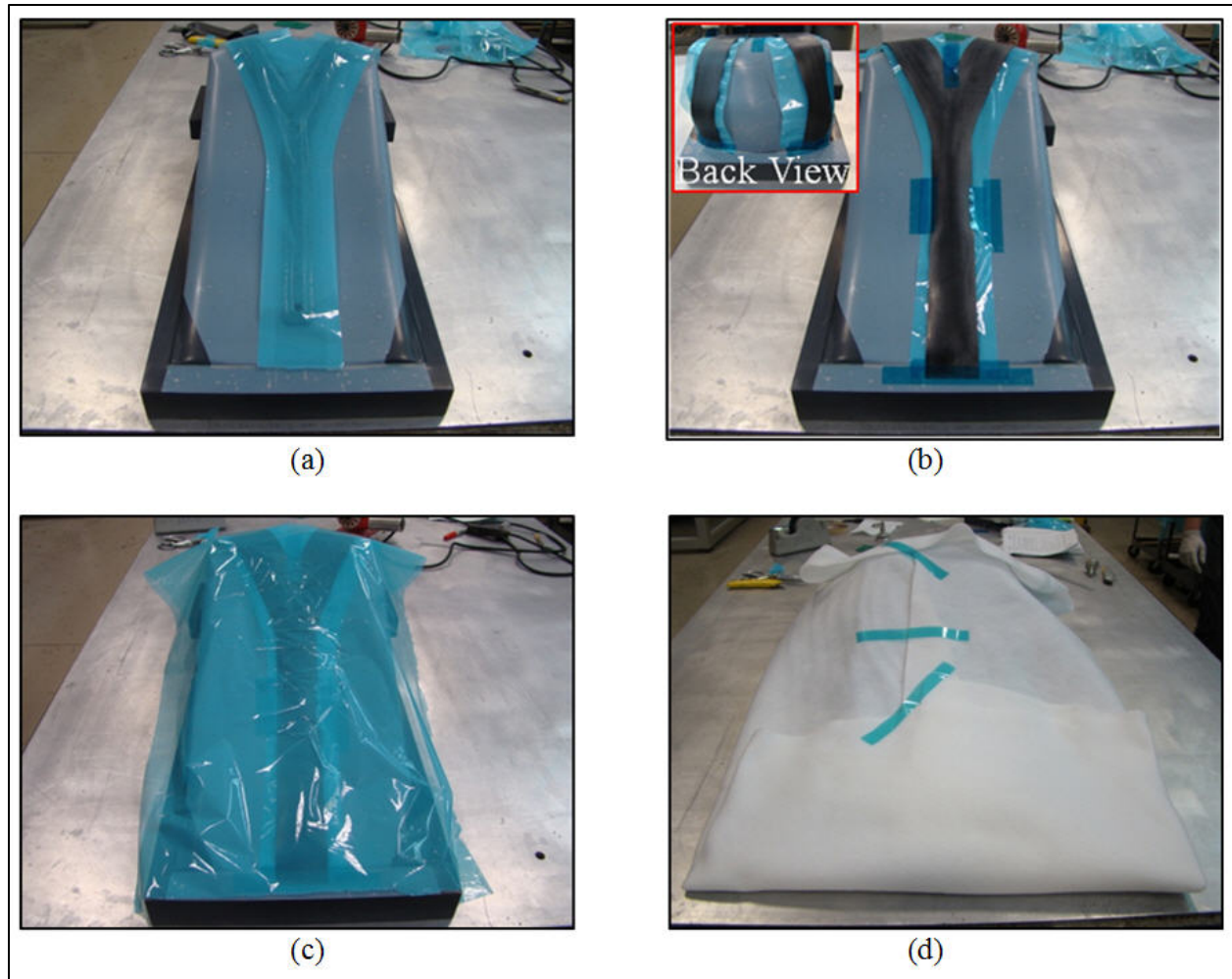


Figure 13. (a) Non-perforated release film, (b) 1/16-in rubber membrane, (c) full sheet non-perforated release film, and (d) heavy breather cloth wrapped part.

The part was placed in a convection oven and cured according the cure schedule shown in table 2.

Table 2. Cure schedule for the exospine composite technology demonstrator.

Ramp	Hold	Cool
Apply vacuum pressure 95 kPa (14 psi) 5 °C/min (9 °F/min) to 80 °C (176 °F)	20 h	Hold vacuum pressure 95 kPa (14 psi) 12 h during cool to ambient

An image of the part in the oven is shown in figure 14.

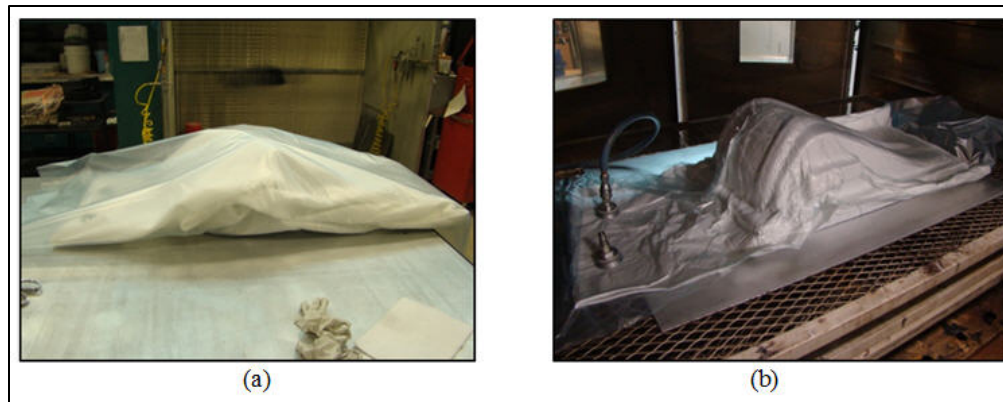


Figure 14. (a) Envelope vacuum bagging, and (b) oven cure of the part at 80 °C.

3.3 Sanding and Gel Coat Finish

The edges and ends of the part were sanded to remove resin flashing using 180-grit sandpaper. An ARL logo was printed by inkjet printer on clear film and backed with white paper using double-sided tape. The logo was then tacked to the center of the part using the two-sided tape. The part was coated with multiple coats of Krylon^{*} aerosol satin clear coat allowing 10 min drying time between successive coats. Images of the cured part and the sanded and clear coated part are shown in figure 15.

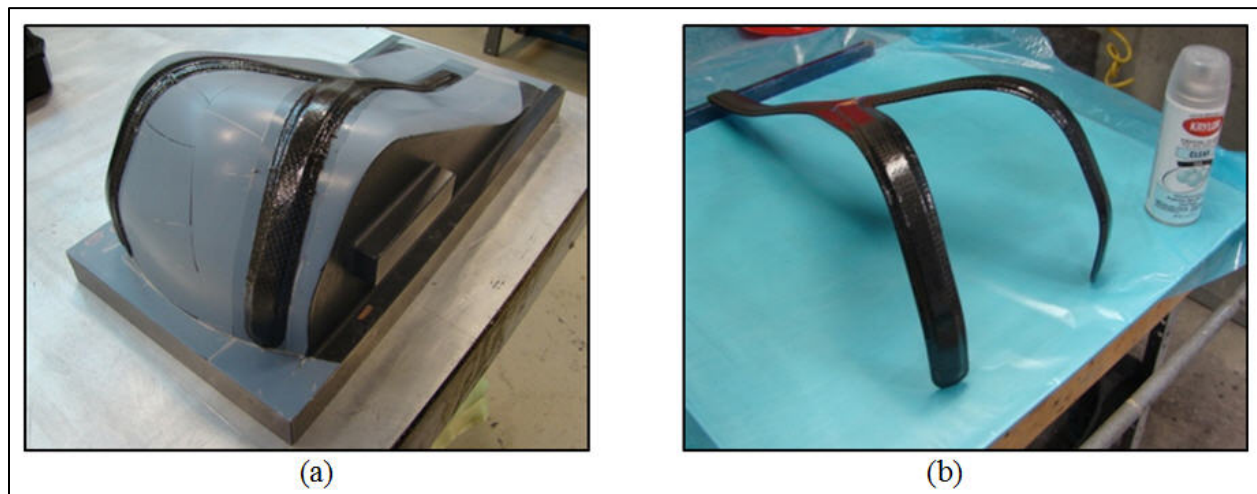


Figure 15. (a) Angled back view of the cured part, and (b) angled front view during the clear coat process.

^{*}Krylon is a registered trademark of Sherwin-Williams Co., Cleveland, OH.

4. Results

The approximate dimensions of the fully cured exospine are shown in table 3.

Table 3. Cured dimensions and mass of the exospine composite technology demonstrator.

Structure	Edge thickness mm (in)	Center thickness mm (in)	Total mass g (oz)
Exospine composite demonstrator first article	2.1 (0.08)	5.3 (0.21)	263 (9.28)

Images of the finished exospine composite technology demonstrator are shown in figure 16.

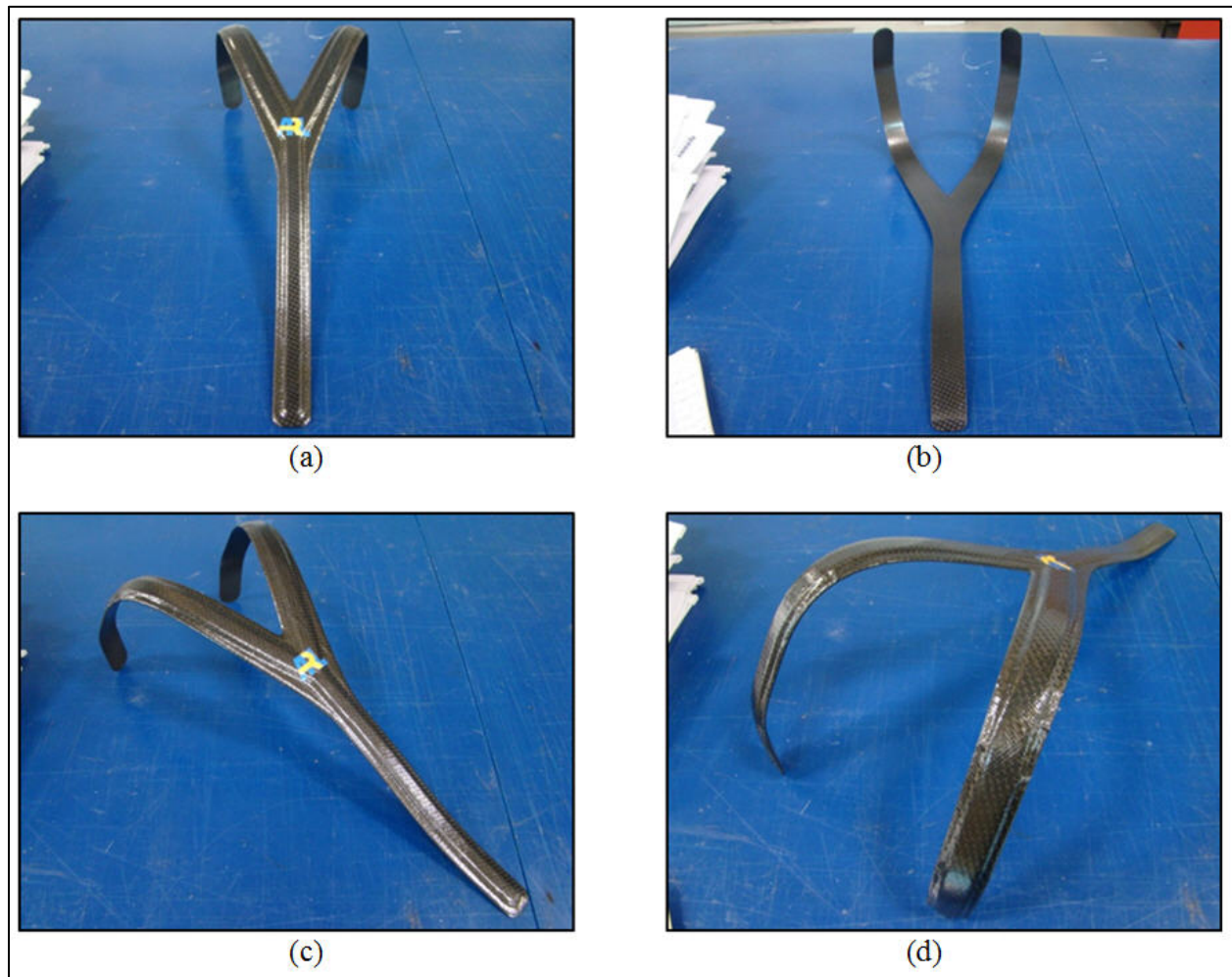


Figure 16. (a) Top, (b) bottom, (c) angled front, and (d) angled back views of the finished part.

5. Conclusions

Fabrication of a lightweight composite technology demonstration exospine was successfully completed, showing that the design is feasible for fabrication using standard composite processing methods. Data in table 3 shows that the finished article weighs only 263 g (9.28 oz) and has an excellent thickness profile of only 5.3 mm (0.21 in) at the thickest section. The article also displays accurate geometrical adherence to the tool surface after final curing. This demonstration may serve as an excellent example of a composite structural design that can be used to maximize the functionality of Soldier systems.

Suggestions for planning of future work include: use of virgin shelf life materials and tool modifications such as channeling, surface coating, and scribe lines. Suggestions for improving the fabrication process include: application of industry standards for fabric manipulation to avoid ply buckling, selection of a more appropriate finishing/gel coat, and to post-cure the composite so that a mechanical evaluation can be performed.

6. References

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
CAD	computer-aided design
DOD	Department of Defense
FAW	fabric aerial weight
FST	fire, smoke, and toxicity
IPA	isopropyl alcohol
ISE	Integrated Support Exospine
PTFE	polytetrafluoroethylene
U.S.	United States
UD-CCM	Center for Composite Materials, University of Delaware (Newark, DE)

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