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CARBON FIBER FABRIC AND ITS POTENTIAL FOR USE IN OBJECTS CONSERVATION

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Carbon fiber fabric is a high-performance woven cloth made from carbon filament. It is widely known for its applications in the aerospace, auto, marine, and sporting equipment industries. While high-strength carbon fibers became commercially available in the 1960s and more broadly obtainable for consumer use in the 1990s, we have yet to see this versatile material reach its full potential within the field of objects conservation. Carbon fiber fabric is designed to be used in concert with a resin system to create rigid parts that have a modulus of elasticity comparable to steel. These polymer-reinforced carbon composites are fabricated from layers of carbon fiber cloth laminated together with epoxy. One notable benefit to the conservator is that, while laying up the fabric and resin, the material can be made to conform to almost any shape. The cured composite can be quite thin and is as strong as steel but a fraction of the weight. Carbon fiber composites are ideally suited to applications in which strength, stiffness, lower weight, and outstanding fatigue characteristics are critical requirements, making them particularly well suited for fabricating object supports and mounts. This paper will introduce carbon fiber fabric as a strong, lightweight material that has the potential to replace steel or brass in many conservation mounting applications and will explore ways that carbon fiber fabric has been used in the Department of Objects Conservation at The Metropolitan Museum of Art. Also included is an overview of the material's history and manufacture. Details on how to choose materials and methods for working with carbon fiber fabric are featured.

KEYWORDS: Carbon fiber, Carbon fiber composite, Conservation, Mounts, Aluminum honeycomb

1. INTRODUCTION

Carbon fiber (CF) fabric, once a specialized material reserved for the aeronautics and aerospace industries, is now regularly encountered in daily life. Commercially, it is valued for its lustrous good looks and has been embraced by architects as well as designers of furniture and decorative arts. Carbon fiber composites (CFCs) are becoming more common in sporting equipment and have been adopted by the sailing industry, in which carbon fiber is used in the fabrication of hulls, booms, masts, and even the sails themselves. One of the advantages of carbon fiber composites is that they can be fabricated in virtually any shape or size.

Though widely considered a space-age product, the first carbon fibers were created by Thomas Edison, who patented the material in 1880 for use as a filament in his incandescent lightbulb (Harholdt 2003). Edison's technique involved burning cotton threads in a vacuum until they were fully carbonized, resulting in a material that could make an ideal lightbulb filament due to its heat tolerance and inherent ability to conduct electricity. Edison's carbon fibers, however, had little tensile strength, one of the many ways they differed from modern carbon fibers.

Carbon fiber fabric is a woven cloth made up of thousands of filaments; each filament is composed of primarily carbon atoms that are more or less aligned along the axis of the fiber. It is important to note here that the terms "graphite fiber" and "carbon fiber" are often used interchangeably, but this is a misuse of the terms. "Graphite" refers to a material with a specific molecular structure in which sheets of aromatic carbon atoms are regularly stacked so that they overlap with a carbon atom at the center of each ring. The most commonly available carbon fibers are rarely produced with a graphitic structural alignment. True graphite fibers, which are produced for highly specialized purposes, universally have mechanical characteristics that far exceed those of standard carbon fiber, hence the importance of using the correct terminology when discussing these materials (Lavin 2001).

2. MANUFACTURING PROCESS

Just as Edison used a cotton thread to create his carbon fiber filament, modern carbon fibers are also manufactured from precursors. Historically, rayon was the first precursor used to create high-tensile-strength carbon fibers. Today's CFs are created in a highly controlled manufacturing process and are derived primarily from one of two precursor materials: petroleum pitch (originating from coal tar and petroleum products) or polyacrylonitrile (PAN). The most recently developed feedstock is hydrocarbon gas, which is used to make vapor-grown fibers (Bahl et al. 1998). PAN-based fibers, however, dominate the world carbon fiber market. The first viable production method with this precursor was developed in Japan in the early 1960s and further refined in the United States by Union Carbide as well as the Royal Aircraft Establishment, or RAE, in the United Kingdom (Langley 1971; Bahl et al. 1998).

The first step in manufacturing carbon fibers from PAN is to spin fibers from vats of the precursor, which can be accomplished in a variety of ways—one method is high-speed extrusion of the polymer into a solvent bath (Morgan 2005). The resulting PAN fiber typically goes through a steam heating and stretching process. The fiber then undergoes an oxidation step, which changes the color of the fiber from white to gold, then copper, and eventually to black (fig. 1). This heating process drives off PAN's pendant nitrile groups, ultimately converting the material to a cyclic molecular structure. This is a highly exothermic reaction, which provides an opportunity to recover energy that can be recycled in other parts of the processing (Lavin 2001).

Next, the fibers pass through multiple oxidation stages, adding oxygen atoms to the carbon rings. This step ultimately reaches 200°C and raises the melting point of the fibers. Then, they pass through two furnaces (heated to 1,000°C, and then to 1,500°C) that carbonize the fibers, driving off volatile noncarbon atoms. At this stage, large randomly oriented, aromatic sheets of carbon start to form. The fibers then go through a surface treatment process that roughens the exterior texture to make it compatible with resins, ensuring excellent adhesion during the fabrication of composites. Finally, the fibers are sized with a proprietary polymer, making them easier to process into spools, and then are woven into fabric (Lavin 2001; Oak Ridge National Laboratory 2011).

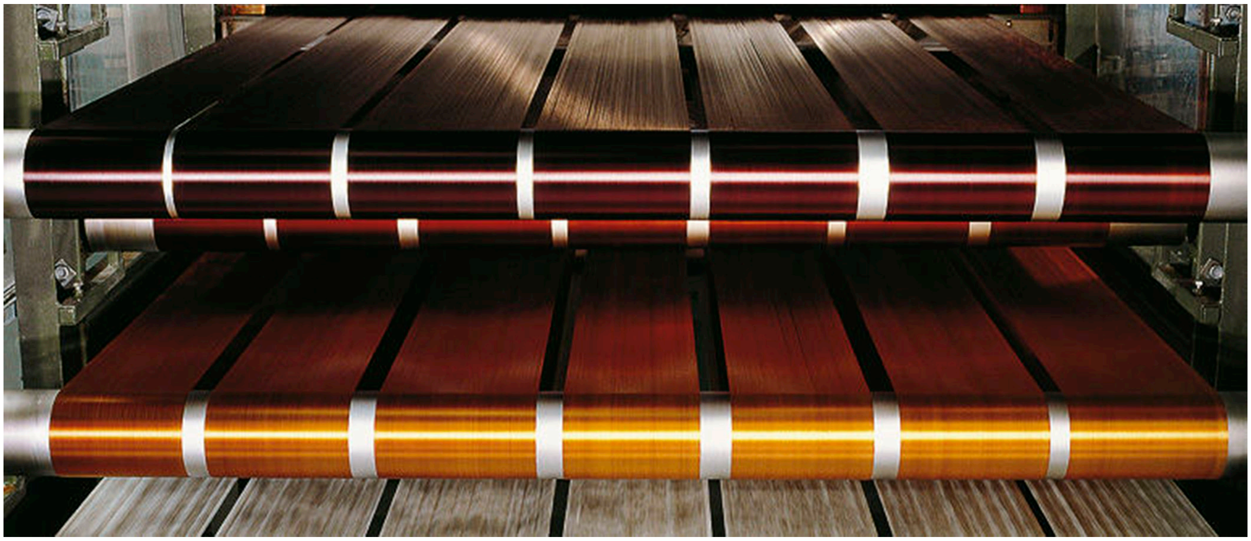

Fig. 1. Polyacrylonitrile (PAN) fibers going through the oxidation process; as PAN fibers oxidize, they change from white to copper, then finally to black (Courtesy of StellaViegas.com.br)

3. MATERIAL CHARACTERISTICS OF CARBON FIBER

The result of the thermal conversion process described earlier is a carbon filament ranging from 5 to 10 µm in diameter—a fraction of the thickness of a human hair (fig. 2). This tiny fiber has extraordinary characteristics. While the mechanical properties of CF can vary based on manufacturer, precursor, and specific manufacturing techniques, carbon fiber can be described generally as having a stiffness-to-weight ratio that makes it twice as stiff and five times stronger than steel (Gross 2003; Quinn 2010).

Such strength comparisons are commonly reported, but describing carbon fibers in general terms in relation to steel may be misleading. The typical material characteristics used to describe the strength of carbon fiber are tensile strength, a measure of the pulling force a fiber can withstand before it fails, and Young's (or elastic) modulus, which measures the stiffness of a material, or its ability to resist elongation under load. Carbon fibers can be manufactured with a range of tensile strength and moduli. For example, it is possible to create a fiber with high tensile strength and low modulus. A low modulus would be necessary when flexibility is needed, while high modulus would be sought when bending or deflection is not desired (Morgan 2005). For these reasons, it is inaccurate to make broad characterizations stating that CF is "n" orders of magnitude stronger than steel. It is more accurate to say that most CFs match or beat the strength and stiffness of steel.

Strength aside, one of the most desirable features of carbon fiber is its high strength-to-weight ratio. Carbon fibers are universally significantly lighter than steel, making them appropriate for a wide variety of applications for which low weight is required (Gross 2003). Carbon fiber is also chemically resistant and does not corrode the way metals do. It has high temperature tolerance and a low coefficient of thermal expansion, making CF ideal for the construction of spacecraft. Carbon fibers are not subject to creep or fatigue failure, as metals are. Finally, CF is electrically conductive, as Edison discovered nearly 140 years ago.

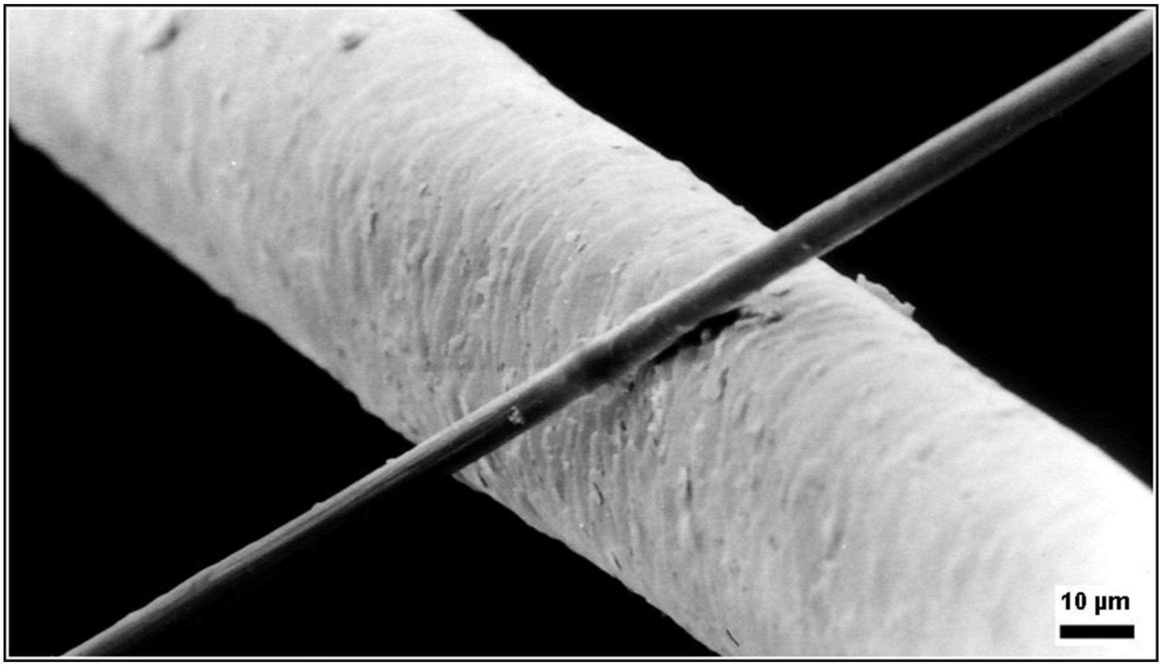

Fig. 2. Carbon fiber filament (top) compared to a human hair (bottom) (Courtesy of Wikimedia Commons)

4. CHOOSING MATERIALS

The material characteristics of carbon fiber are fully realized only when they are carried in a matrix, creating a laminated composite of fiber and resin, or CFC. There is a plethora of fabric weights and weaves on the market, but being aware of common industry terms will help the user to select appropriate materials (fig. 3). A "filament" is a single strand of carbon fiber; thousands of filaments make a "fiber," or "yarn." "Tow" is the material used to weave carbon fiber fabrics as well as a standalone product made available on spools. Fibers are described by the number of filaments present: for example, "3K tow" indicates that there are 3,000 filaments in the fiber. With regard to describing weaves, the CF industry refers to the fibers running in the warp direction as "ends" and those running in the weft, or "fill" direction, as "picks." Ends and picks are measured per linear inch. Thus, a 12 × 12 fabric has 12 fibers in the end direction and 12 fibers in the picks direction. The addition of "3K" in front of 12 × 12 would mean that each of those fibers has 3,000 filaments each (see fig. 3).

4.1 Fabric

FibreGlast is one of many companies selling carbon fiber fabric; they maintain a helpful website with a "learning center" section that includes white papers and videos to inform their customers. As this article was being written, FibreGlast had no fewer than 15 different fabrics available for purchase. Most conservators will find that FibreGlast's 6K 5HS satin weave cloth and carbon fiber tape will likely suit the needs of most relevant projects. The 6K 5HS satin weave is a versatile fabric available in wide rolls. This fabric is more easily draped over complex shapes than plain weave fabric, and it builds up quickly to create structural parts with virtually no flexibility. Carbon fiber tape is not adhesive backed but is called "tape" because it is woven to width with a selvage to prevent unraveling, one of the inconveniences of slippery carbon fibers. The tape format is convenient if a project requires many narrow strips of fabric. When layering with a laminating epoxy, the plain weave tape wets out quickly and handles easily. Only three layers are typically necessary to produce useful nonstructural pieces, and it is particularly convenient for joining prefabricated parts together.

Prefabricated components are a convenient option for building structures that have regular geometries, as they are available in a wide variety of shapes, such as right angles, C channel, I beam, round or square tubes, and rods. These structural components can be cut with a band saw and then assembled using carbon fiber tape and epoxy. Many online companies offer these components, including CarbonFiberTubeShop.com, McMaster-Carr, Dragon Plate, GraphiteStore.com, and Rock West Composites.

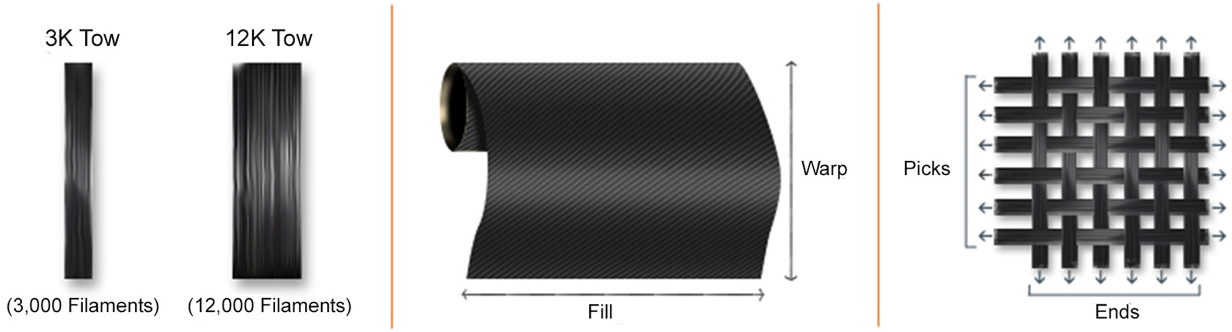

Fig. 3. Terminology of carbon fiber fabric (Courtesy of FibreGlast.com)

4.2 Resins

The three most commonly available laminating resins are polyester, vinyl ester, and epoxy. Polyester is widely used in the composite industry because it is less expensive and more forgiving than epoxy; it is typically paired with fiberglass fabric. Vinyl esters are low-viscosity resins and are well suited for vacuum infusion of composites. Despite the conveniences of other resins, epoxy is the best option for conservation projects because it outperforms polyester and vinyl ester resins in strength and dimensional stability. Epoxy is the most expensive resin of the three options. For the best results, conservators should always use the laminating resin recommended by their CF vendor. For example, when using FibreGlast's fabrics, best results will be achieved when using their FibreGlast 2000 epoxy system specifically designed for laminating CF fabric.

WEST System 105 epoxy is commonly used to make composite parts; however, the reader should be aware that it was not developed for the production of carbon fiber laminates. WEST System was designed to serve the boat-building industry and was specifically made for laminating fiberglass to wood. This brand of epoxy has a lower heat deflection temperature than FibreGlast's resin, which means that CFCs made with WEST System epoxy could potentially soften and sag with direct and extended exposure to sunlight.

5. EXAMPLES OF CARBON FIBER FABRIC IN OBJECTS CONSERVATION

The following examples illustrate some of the ways that carbon fiber fabric has been used in the Department of Objects Conservation at The Metropolitan Museum of Art. This broad overview will help to provide some understanding of CF's versatility and will potentially spark the imagination of conservators to find new and innovative ways to use this material.

5.1 Tullio Armature

Tullio Lombardo's *Adam* is a Renaissance marble sculpture that broke into hundreds of pieces when the pedestal beneath it collapsed in 2002. The conservation project that followed lasted over 10 years and was a time of fruitful research and innovation (Riccardelli et al. 2014). In the early phases of the project, conservators needed a way to hold the individual fragments of the sculpture in an external treatment armature designed to aid in the assembly of the sculpture. After trying various materials, CF proved strong enough to support the marble fragments and sufficiently versatile to allow fabrication in the conservation lab without the need for special equipment (fig. 4).

5.1.1 Torso Corset

The largest piece of the damaged sculpture was the torso, weighing approximately 172 kg (380 lb.). A carbon fiber "corset" was conceived, equipped with a wide flange that would allow the torso to be suspended from an overhead bridge crane. A full-scale model of the torso (the result of three-dimensional laser scanning and computer numerical controlled [CNC] milling) was used as the form on which the corset was fabricated. To account for the thickness of a cushioned lining inside the strap, the torso model was first prepared with a layer of Volara followed by tight layers of protective stretch wrap plastic (fig. 5a). Strips of 6K 5HS satin weave fabric were cut to fit around the torso. Then, the fabric was laid down on the form, layer by layer, each time applying a coating of FibreGlast System 2000 laminating epoxy (the same epoxy was used for all of the examples in this paper). Finally, the whole was wrapped with more stretch wrap plastic, ensuring that the carbon fiber and epoxy would cure perfectly conformed to the shape of the torso (fig. 5b).

Fig. 4. Fragments of Tullio Lombardo's *Adam* supported by an external armature; the black straps around torso and legs are carbon fiber supports (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

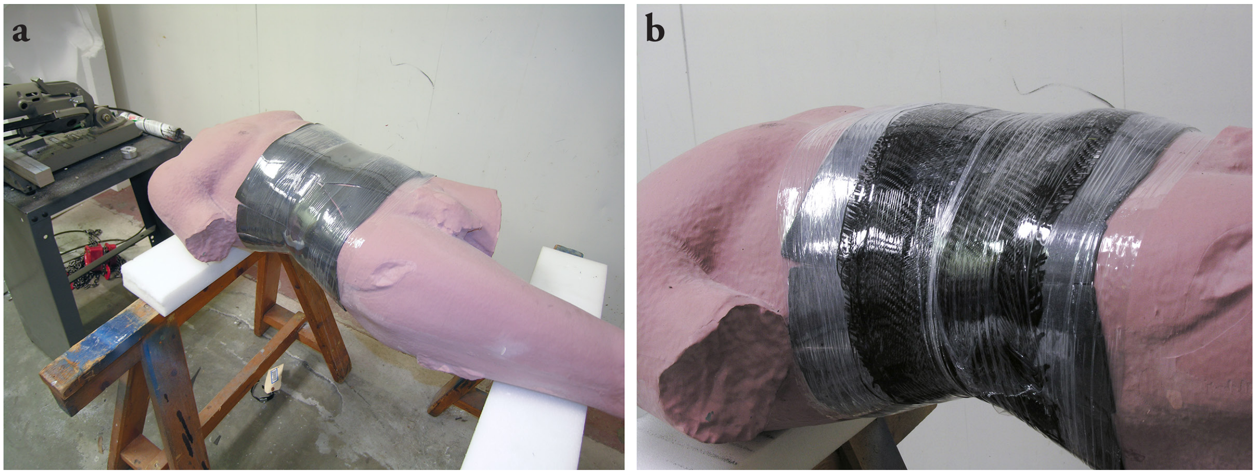

Fig. 5. (a) Computer numerical controlled (CNC)–milled torso form prepared with Volara and stretch wrap plastic. (b) Four layers of 6K 5HS satin weave fabric laminated with epoxy, then compressed with stretch wrap (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

Next, as a separate part, a flange that extends horizontally from the corset was created by simply laying down on a flat surface protected with silicone Mylar several layers of fabric in a ring form. The flange was bisected and then attached to the right and left sides of the cured corset while still attached to the torso model using strips of CF tape and epoxy (fig. 6). Once the flange was well attached, a thin hacksaw blade was used to make cuts at the front and back of the whole assembly, releasing it from the torso form. The corset at this point was rough, far from being finished. The cured form was then shaped on a belt sander. Laminating carbon fiber fabric is messy, and it is common for epoxy to drip and pool around the edges of the fabric, inevitably resulting in dangerously sharp protrusions of fibers embedded in epoxy. It is essential to use personal protective equipment (PPE)—including eye protection, dust mask, and gloves—when cutting or sanding carbon fiber fabric.

After the flange was attached, additional vertical "buttresses" were secured to the corset to provide more structural support. These parts consist of separately made sheets of laminated carbon fiber, cut to fit on a band saw, and then attached with a few layers of carbon fiber tape and epoxy. Several layers of fabric were added to the corset overall to increase the stiffness of the form. The completed torso corset, shaped and sanded to be free of sharp edges, was tightened in place by means of two knob-and-bolt assemblies that passed through the front and rear buttresses. The entire assembly was suspended from an overhead bridge crane by means of threaded rods (fig. 7).

5.1.2 Leg Straps

Carbon fiber was also used to make the straps that held *Adam*'s leg fragments in place. As with the torso, full-scale models of the major fragments served as the forms on which the straps were made. The leg straps were built up with carbon fiber similarly to the corset but without the need for flanges or structural reinforcement. Another difference from the torso corset was that hardware connectors and closures were built into the leg straps. By incorporating flange nuts into the layers of carbon fiber, the straps could be connected to a rigid external framework by means of ball joints, adding some articulation to the setup. The straps were tightened around the fragments by means of hose clamps embedded into the layers of carbon fiber fabric (fig. 8). The resulting straps were rigid enough to support the stone fragments but still had enough flexibility to be removed at the end of use without the need to cut them off the sculpture.

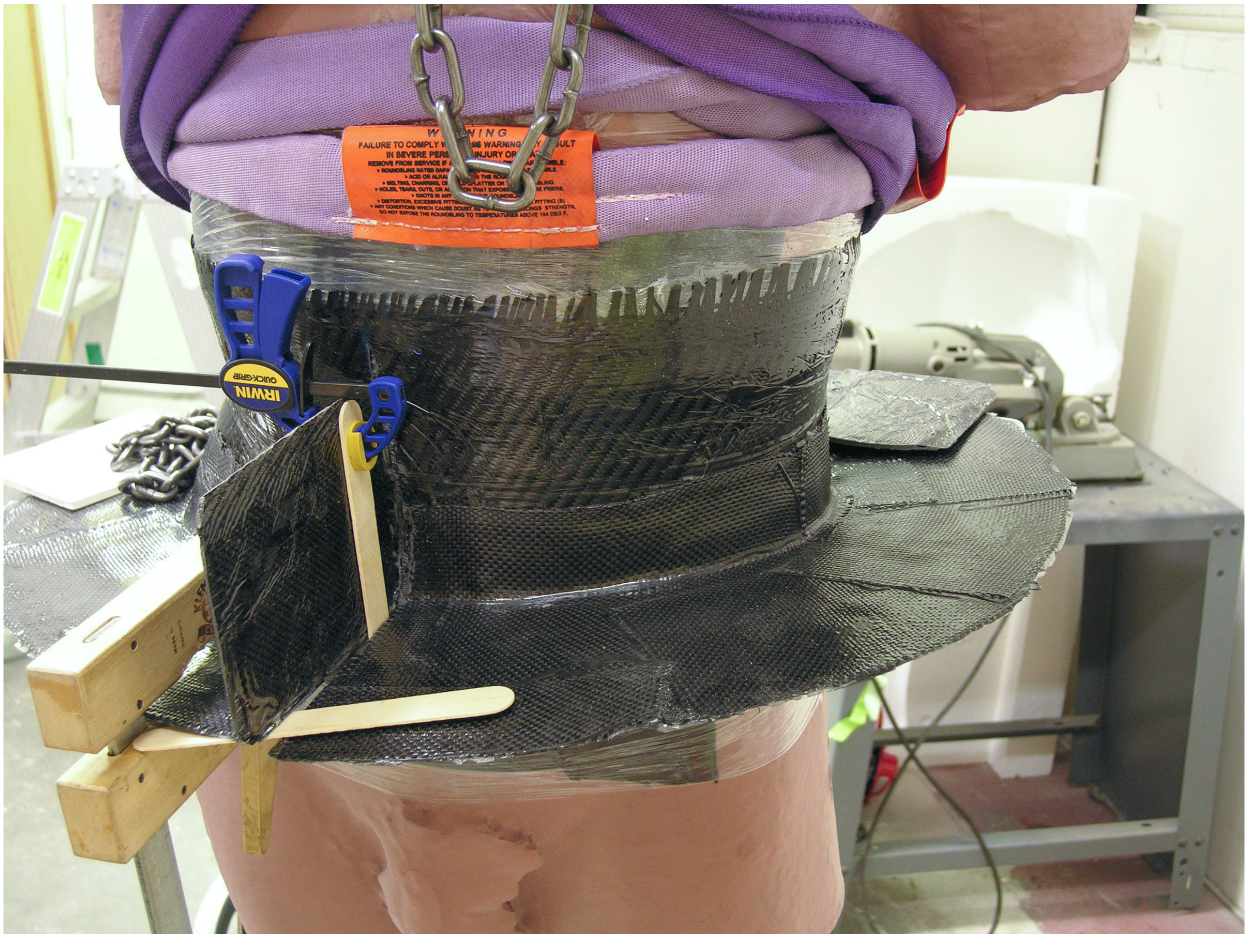

Fig. 6. Attaching a previously fabricated flange to the inner corset using additional layers of plain weave carbon fiber fabric (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

The corset and leg straps were critical components of the external armature used throughout *Adam*'s reconstruction, serving as a support system that allowed assembly and reassembly of the fragments as needed, and was capable of holding the fragments in precise positions for long periods while the chosen acrylic resin adhesive reached full strength. The sculpture was fully assembled in its armature each time adhesive was applied to a join, providing the opportunity to closely monitor the alignment of the fragments. Riccardelli et al. (2014) provide a detailed account of how the external Tullio armature was developed and used.

5.2 *Prudence* Tondo Mounting System

Prudence is a glazed terracotta architectural relief made by Andrea della Robbia in 1475. Fifteen sections comprise the tondo—eight in the colorful garland and seven making up the inner tondo relief. This impressive piece is 164.5 cm (5-1/2 ft.) in diameter and weighs 350 kg (775 lb.). In 2016, the tondo was removed from a deteriorating iron and cement support and remounted in preparation for travel to two exhibition venues (Riccardelli and Walker 2019). One of the main tasks of the project was to create a mounting system that would support each of the tondo's sections individually without the use of adhesives or mortar. The weight of many of the sections surpassed 36 kg (80 lb.) and were deemed too

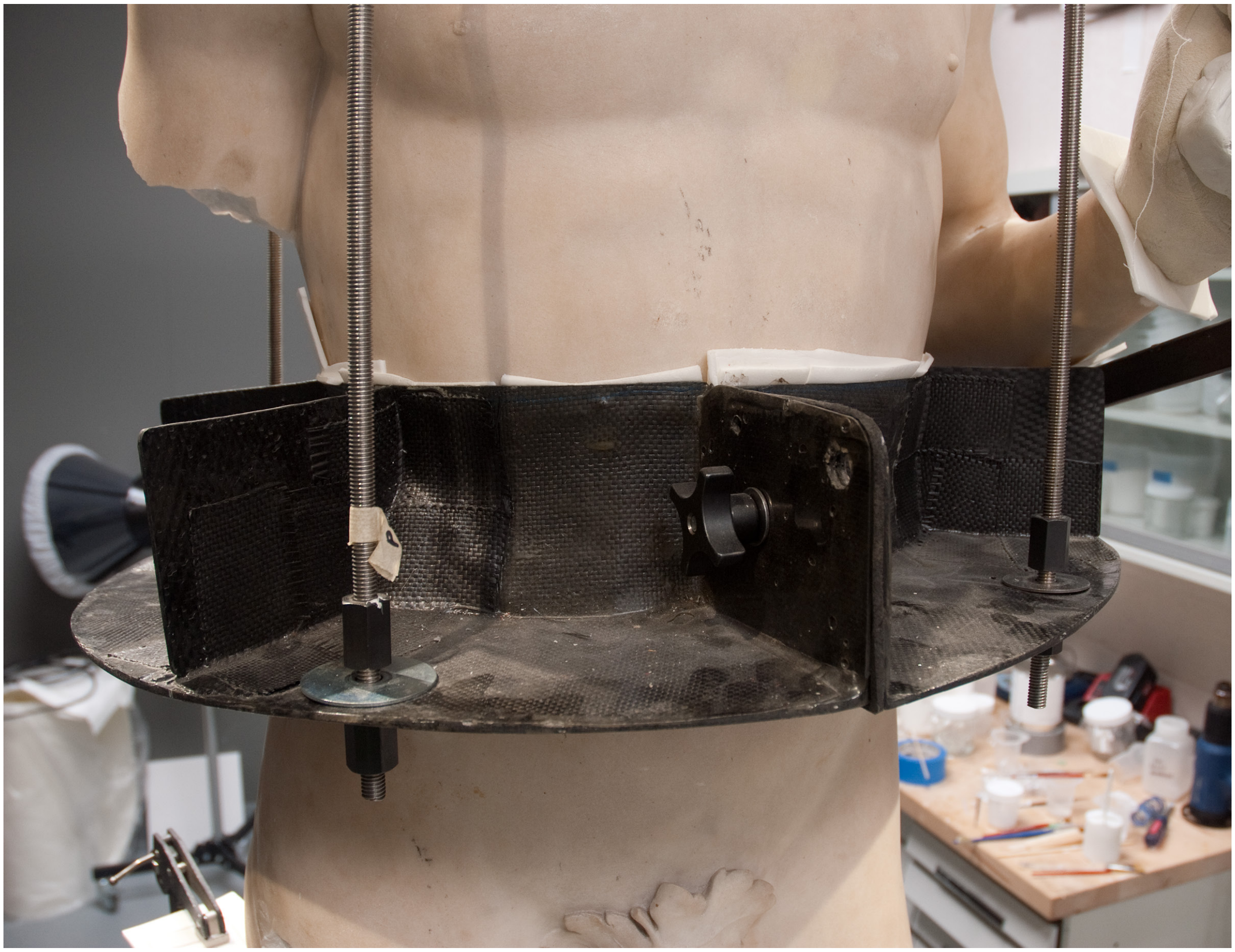

Fig. 7. Completed torso corset with additional buttresses and hanging hardware. Bolts and knobs were used to pressure fit the corset around the torso. (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

heavy for brass strap mounts normally made by the Department of Objects Conservation's preparators. The use of steel mounts was ruled out, as the logistics of fabrication by The Met's metal shop would have proven too complicated and time-consuming. Furthermore, heavy steel mounts would not have been aesthetically acceptable. Carbon fiber once again proved to be a versatile, lightweight solution to our needs and was used to create customized mounting clips that fit into a specialized backing panel (figs. 9a, 9b).

The foundation of *Prudence*'s mount is an aluminum honeycomb backing panel custom-fabricated for the project, designed with a diameter slightly smaller than the assembled tondo so that it would not be visible when installed on the gallery wall. Each section of the tondo is held individually by three carbon fiber clips that are mechanically attached to this backing panel. Into the base of each clip, a metal weld nut (a threaded cylinder with a flange at one end) was embedded, allowing it to seat into holes drilled into the panel. The clips are held in place with bolts, fed through from the back of the panel into the nuts (fig. 10). The addition of fender washers under each hex head prevents localized crushing of the honeycomb panel as the bolts are tightened.

Fig. 8. Detail of *Adam*'s left knee in the external armature. Hose clamps embedded into the carbon fiber layers allowed the strap to be tightened around the fragment or loosened to remove the strap at the end of the treatment; flange nuts in the strap allowed attachment of ball joints that connected to a rigid external framework. (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

5.2.1 Creating the Prudence *Clips*

Carbon fiber can conform to almost any shape, but it must be molded under some pressure to ensure the best conformation between the fabric and the substrate. Commercially, this is achieved with vacuum bagging, but such equipment and expertise was not available for the *Prudence* project. Furthermore, due to the vacuum pressure required and potential difficulty in controlling the flow of resin, this technique might not be appropriate for use on many art objects. On the armature straps for *Adam*, stretch wrap plastic was used to compress the layers of carbon fiber fabric and epoxy while it cured. For *Prudence*, the object's contours were much more complicated, necessitating the use of a two-part molding system to compress the carbon fiber and epoxy as it cured. The inner part of the mold was created with a quick-set silicone dental putty (Delikit VPS putty) rolled out into a thick slab and pressed around the section to cure (fig. 11a&b). Then, an exterior "mother mold" was made from hard Ethafoam 900 (fig. 11c). The

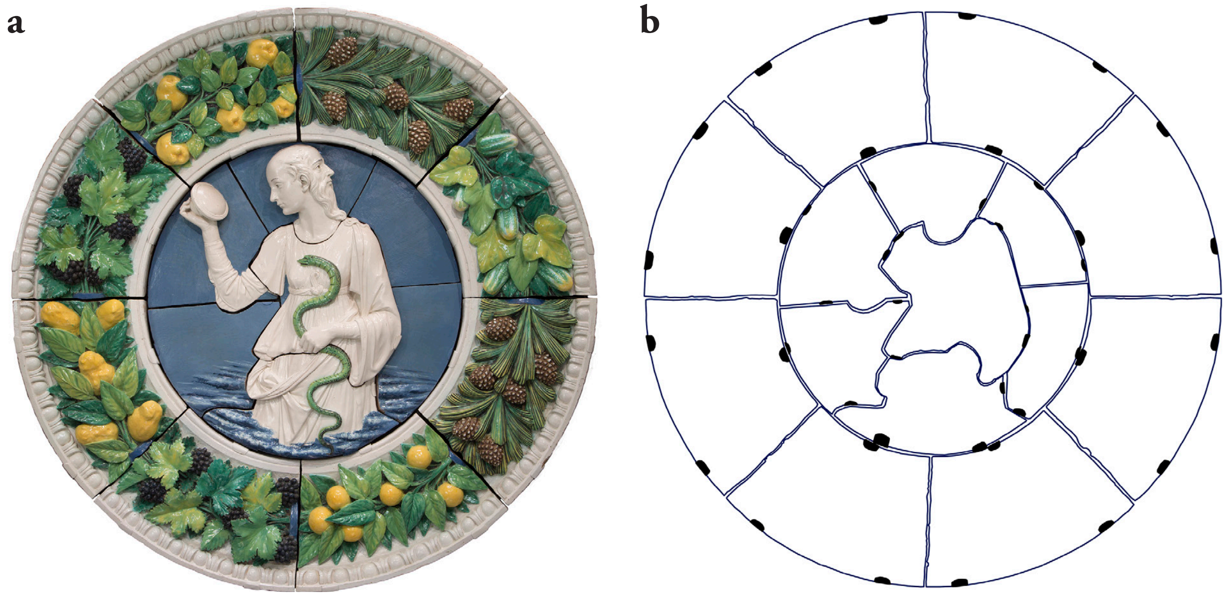

Fig. 9. (a) The tondo after treatment and mounting. *Prudence*, Andrea della Robbia, ca. 1475, glazed terracotta, 164.5 cm diameter, 21.116. Purchase, Joseph Pulitzer Bequest, 1921. (b) Diagram of carbon fiber clips used to hold the tondo's sections. (Courtesy C. Riccardelli, ©The Metropolitan Museum of Art)

inner mold ensured excellent conformation of the CF to the surface, while the outer Ethafoam provided a firm support against the inner mold to distribute pressure from clamps.

As with most multistep processes, thorough preparation made the job of laminating much more efficient. Precutting all of the required CF before getting started was an essential step (fig. 12). Because carbon

Fig. 10. Cross-sectional view of a garland section on the *Prudence* mounting system (Courtesy C. Riccardelli, ©The Metropolitan Museum of Art)

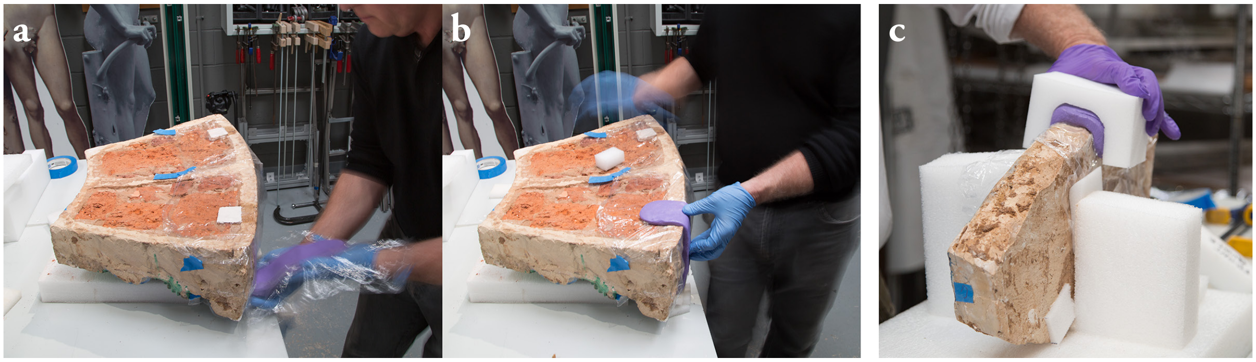

Fig. 11. (a&b) Creating internal mold of a garland section using silicone dental putty. (c) Ethafoam "mother mold" in place around a section of the inner tondo (Courtesy of W. Walker, ©The Metropolitan Museum of Art)

Fig. 12. Precutting the carbon fiber fabric into strips in preparation for layering with epoxy (Courtesy of D. Hausdorf, ©The Metropolitan Museum of Art)

fiber fabric is slick and the weave unravels easily, a rotary cutter, commonly sold in fabric stores, was effective for cutting the material. While the fabric appears soft to the touch, it is highly recommended for those handling the cloth to use PPE, as tiny, loose filaments generated while cutting can work their way into the skin and nose and are extremely irritating. For each round of lamination, we found it useful to prepare the workspace with a sheet of plastic wrap (taped down on all edges), which provided a convenient work surface that was quick to clean up. Prior to mixing the epoxy, we went over a mental checklist of prepared supplies and rehearsed all of the steps in the process.

With the mold forms of the tondo sections complete, fabric cut, and the workspace prepared, we could begin laminating the cloth and epoxy. A small batch of epoxy was mixed (enough for two clips). Then, the strips of fabric were laid down, one layer at a time, each time brushing on epoxy and tamping it through the fabric with a brush to saturate all of the fibers with resin (fig. 13a). Inexpensive "chip brushes" with natural bristles were ideal for this purpose. As the layers were built up, we found it helpful to lay down a temporary layer of plastic wrap, and to firmly squeegee the fabric and epoxy with a scraper of some kind. A stiff plastic ceramic rib worked well for this task (fig. 13b). Taking time to do this extra step mid-way through the process helped to ensure the cloth was thoroughly wetted with epoxy.

Next, we incorporated a weld nut into the carbon fiber layers. It was necessary to create a hole in the fabric using a sharpened pencil prior to pushing the nut through (fig. 14a). To prevent epoxy from flowing into the threads of the weld nut, a temporary nylon set screw was inserted into the nut along with some Orvus paste as a release agent. Additional layers of fabric were added on top of the flange in order to securely integrate it into the clip (figs. 14b, 14c). In all, seven layers of 6K 5HS satin weave fabric were used for each of the *Prudence* mounting clips.

After all layers were assembled, the plastic wrap that had been functioning as the work surface was carefully folded around the material, making a protective package to assist in moving the slippery, sticky material. This package was then laid into the silicone component of the mold (fig. 15a). With the surface of the object protected with layers of plastic wrap, the prepared carbon fiber and silicone mold were carefully put in the predetermined location, the Ethafoam "mother mold" was added, and then was clamped tightly (figs. 15b, 15c).

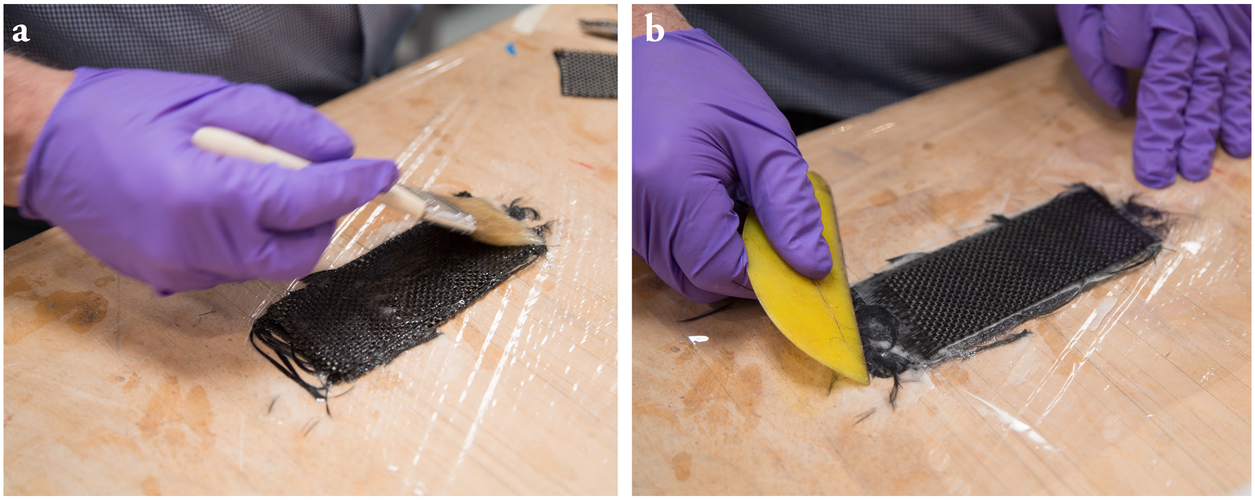

Fig. 13. (a) Brushing epoxy onto carbon fiber fabric. (b) Squeegeeing the layers to ensure saturation of the fibers (Courtesy of W. Walker, ©The Metropolitan Museum of Art)

Fig. 14. (a) Insertion of weld nut hardware into the cloth; a nylon set screw prevented epoxy from flowing into the threads. (b) Flange of weld nut on top of carbon fiber layers. (c) Additional carbon fiber layers added on top of weld nut's flange. (Courtesy of W. Walker, ©The Metropolitan Museum of Art)

Fig. 15. (a) Layers of carbon fiber fabric and epoxy enclosed in plastic wrap package, laid into silicone inner mold. (b) Clamping while epoxy cures. (c) Detail showing clamping pressure on molds and carbon fiber. (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

After the epoxy had cured a minimum of 12 hours, the molds could be removed from the object, revealing a strip of hardened carbon fiber fabric perfectly conformed to the shape of the object (fig. 16a). The clips were strong and stiff, but still flexible enough to remove from the object using a bit of leverage applied from the bottom of the clip. The clips were then shaped on a belt sander to remove excess material and rough edges. Thin acrylic felt padding was applied to the inner surfaces of the clips before they were returned to the object (fig. 16b). A finishing step was to paint the clips to match the surrounding terracotta or glaze. While labor intensive, using carbon fiber fabric on this project produced strong, lightweight, low-profile supports that were barely visible either from the front or side of the object (figs. 9a, 16c).

5.3 Turtle Shell Mask Support

Carbon fiber fabric can be built up to create strong and lightweight supports for heavy objects, but it can also be used on more delicate objects. In 2007, Amy Jones Abbe (now of Jones Abbe Art Conservation, LLC) treated a turtle shell mask in preparation for the reinstallation of The Met's Oceanic galleries. The piece, which originates from an island in the Torres Strait, separating Australia from New Guinea, is made of more than a dozen large sheets of turtle shell that have been bent, pierced, and lashed together with vegetable-fiber cord. This combination forms a mask representing a human face superimposed on a frigate bird. The turtle shell sheet that formed the bird's right wing had broken, a problem that had been only partially addressed in the past by the use of an external mount to hold it in place. After Amy realigned and joined the break, she proceeded to reinforce the cantilevered wing with a thin, slightly flexible integral support. Carbon fiber fabric was an ideal material for this purpose.

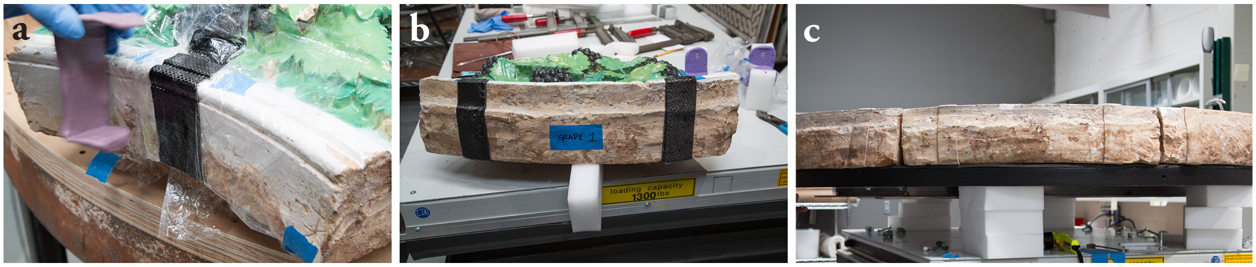

Fig. 16. (a) Rough carbon fiber clip after removing molds. (b) Clips on one of the garland sections, after shaping but before painting. (c) Tondo viewed from the side, showing painted clips (Courtesy of C. Riccardelli, ©The Metropolitan Museum of Art)

To make the supports conform to the shape of the object, a silicone cast was made of the underside of the wing. From that, a two-part plaster mold was created. Because one surface of the support would be in direct contact with the turtle shell, Amy chose EPO-TEK 301-2 as the laminating epoxy for the first layer of fabric, presuming that it might provide a more archival surface on that face of the support. Furthermore, because the weight to be supported by this CF part was minimal and contained within a museum environment, the use of an alternative resin did not raise concern. The first layer of 6K 5HS satin weave CF fabric and epoxy (along with plastic wrap barrier layers) was placed into the prepared plaster mold and then clamped shut. After curing, the mold was opened, and two more layers of CF fabric were added using the FibreGlast 2000 system. The completed strips, about 1.5 cm wide, were shaped and sanded smooth, and then attached across the break using Paraloid B-72 (figs. 18a, 18b). The supports were positioned so that they overlapped primarily in the dark-brown mottling of the turtle shell, with the intention that they would only minimally interfere with the transparency of the material. When the mask is viewed at eye level, the support is barely noticeable even with light transmitting through the wing. The ability to create a lightweight, thin, yet stiff support was the advantage to using CF in this treatment.

Fig. 17. (a) Turtle shell mask before treatment; the bird's right wing was broken and unsupported; mask (Buk, Krar, or Kara); Torres Strait Islands; mid- to late 19th century; turtle shell, wood, cassowary feathers, fiber, resin, shell, paint; 54.6 × 63.5 × 57.8 cm. 1978.412.1510. The Michael C. Rockefeller Memorial Collection, Purchase, Nelson A. Rockefeller Gift, 1967. (b) Detail of broken wing before treatment. ((a) ©The Metropolitan Museum of Art; (b) Courtesy of A. J. Abbe ©The Metropolitan Museum of Art)

Fig. 18. (a) Carbon fiber supports after molding and shaping. (b) Supports attached to underside of the wing. (Courtesy of A. J. Abbe, ©The Metropolitan Museum of Art)

5.4 Upholstery Supports

The Met's upholstery conservator, Nancy Britton, has been using CF fabric for more than 15 years, and has devised clever techniques to use the material to make rigid frameworks for upholstery. A good, basic example of her technique can be found in a Klismos chair, made in Philadelphia around 1815 (figs. 19a, 19b). For this half over-the-rail chair, Nancy made a cap system that slips over the rails without the need to insert metal fasteners into the wood. Traditional upholstery techniques cause irreparable damage to wooden furniture elements from repeated use of metal fasteners such as tacks or staples, leaving tacking rabbets riddled with holes. Conversely, upholstery conservation methods aim to be noninvasive and employ techniques that avoid insertion of fasteners as much as possible. Nancy's cap

Fig. 19. (a) Chair with new show cover removed. (b) Show cover in place with decorative nail heads. Side Chair, Philadelphia, 1815–1830, ash and pine, 58.7 × 46.4 × 54 cm. 63.143. Anonymous Gift, 1963 (Courtesy of N. Britton, ©The Metropolitan Museum of Art)

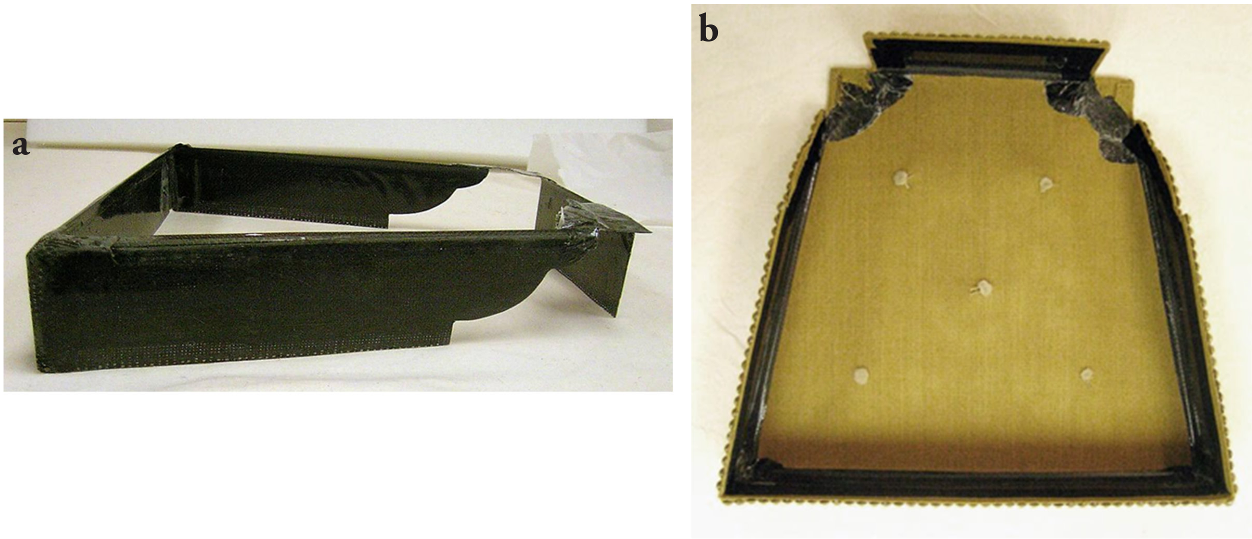

Fig. 20. (a) Upholstery cap frame created from prefabricated right-angle carbon fiber components. (b) Cap with reproduction fabric attached using PVA adhesive. (Courtesy of N. Britton, ©The Metropolitan Museum of Art)

system is completely reversible and easy to remove to provide access to examine the structure of the chair or if the textile needs to be replaced.

On the seat of the Klismos chair, a carbon fiber shell with an open top was made using a combination of prefabricated right-angle components and carbon fiber fabric (fig. 20a). In this case, Nancy left the seat open to allow for the tufting process, which required access to both sides of the fabric. The wool reproduction fabric and padding adhered over the edges of the frame using PVA adhesive, which bonded well with the sanded surface of the CF shell (fig. 20b). Then, tufting was completed using loop Velcro discs that functioned as the stops for silk tufts on the top of the show cover. The final step was to attach reproduction nail heads around the edge of the show cover—these were cast in tinted epoxy and then painted with mica pigments (see fig. 19b). The thin and stiff properties of CF were advantages in this treatment.

6. CONCLUSIONS: MAKING THE CHOICE TO USE CARBON FIBER FABRIC

While high-strength carbon fibers became commercially available in the 1960s and more broadly obtainable for consumer use in the 1990s, we have yet to see this versatile material reach its full potential within the field of objects conservation. With knowledge of the projects shared earlier and the understanding of how to fabricate composites, carbon fiber fabric will undoubtedly inspire conservators to find new and clever ways to incorporate the material into their practice. However, there are many factors to take into consideration before deciding whether CF fabric is the correct material for a project.

Consider your budget. Carbon fiber is expensive. The mid-weight fabric purchased for the *Prudence* mounting project was $220 for a 2.75-m (3-yd.) roll in 2016. A 45.72-m (50-yd.) roll of 5-cm (2-in.) wide carbon fiber tape cost $260 in 2016. Depending on how many layers of lamination are required for a project, the yardage is consumed quickly, and expenses can soar.

Consider whether your project requires the stiffness of carbon fiber fabric. If creating a conforming backing support for a relatively small object, an alternative material, fiberglass fabric, might be sufficient for the project. Fiberglass is laminated in a similar fashion to CF, but is significantly cheaper. On the other hand, there are times when a project calls for a material that is stiff and extremely thin, such as in the case of the turtle shell mask and the upholstery cap shell. Carbon fiber fabric was well suited to fit the needs of these projects.

Consider the environment in which CF components will be displayed. If the location is outdoors, will the composite be in direct contact with or contain metal components? Despite all of the impressive properties of CFCs, carbon fiber is situated very high on the galvanic scale (above stainless steel and titanium); its conductivity must be taken into consideration when using it in contact with metals. Due to its extreme conductivity, when a less-noble metal is electrically connected to a carbon fiber composite, it is susceptible to galvanic corrosion. These conditions are exaggerated when the CF has a large surface area and is coupled with a small metallic part, such as a bolt (Yari 2017). In some of the projects described earlier, metal hardware was incorporated into mounting straps, but in those instances, the CFCs were in use within a stable museum environment, posing little to no risk of corrosion. If CFCs are determined to be ideal for an outdoor installation in contact with metals, there are ways to control galvanic corrosion. One simple solution is to disconnect the electrical connection between CF and metal by laminating an electrically insulating material, such as a fiberglass fabric, between those parts. Another method for managing galvanic corrosion might be to use nonconductive fasteners made from nylon or fiber-reinforced plastic.

Consider the use of CF and epoxy in close proximity to sensitive materials. FibreGlast 2000 epoxy resin catalyzed with 2060 hardener was evaluated by The Met's Department of Scientific Research (DSR) in 2017, following their 20170922_OT protocol, a variant of their 20170606_OT protocol as described on the *AIC Wiki* (Buscarino et al. 2017).[1] Duplicate jars heated for 28 days at 60°C resulted in a "Permanent" rating for all coupons. The lead coupon exhibited some darkening; however, the control leads darkened as well. These results indicate that the material may be used indefinitely in the presence of art, though the DSR recommends that the material be retested using their 20171116_OT protocol, in which the control lead coupons more typically remain untarnished (Buscarino et al. 2018). It is important to note that this Oddy testing protocol does not place the specimen in contact with the metal coupons. Therefore, if a project requires that CFCs be in direct contact with sensitive materials, further testing using a contact protocol should be performed before moving forward with the project.

Carefully consider the risks of using alternative resins. A question that conservators often raise about carbon fiber is, "Can it be laminated with other resins? Can I use B-72?" The use of resins other than those specifically designed to laminate carbon fiber fabric is not recommended. With over 60 years of research and development devoted to perfecting the bond between resin and fiber, the resins specified by CF manufacturers can be counted on to perform as stated. If the wrong resin is used to make a carbon fiber composite, the material characteristics of the product will be completely different from what is reported in the literature.

Carbon fiber has grown in popularity not only with aeronautical engineers and boat builders but also in more artistic fields, such as decorative arts, furniture design, and musical instruments. These extraordinary fibers continue to be essential in high-performance applications for everything from airplanes to automobiles, satellites to sporting goods, and artificial limbs. Certainly, the beauty of the material is seductive. Carbon fiber fabric was essential to the success of the conservation projects described in this article. Taking into consideration all of the strengths and drawbacks of carbon fiber fabric, with practice and planning, many conservators will find that carbon fiber is a versatile material with infinite possibilities.

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NOTE

1. FibreGlast 2000 resin was prepared with the 2060 catalyst and allowed to cure for four days in a mold prior to cutting it into 2-mm thick pieces and placing 2 g of material and a mini-vial containing 0.5 mL water into to a Pyrex screw-top jar. Lead, copper, and silver coupons were inserted into a silicone stopper; then, the stopper was inserted into the neck of the jar. A Viton O-ring was fitted into the screw-top as a secondary seal before continuing with the remainder of DSR's 20170922_OT procedure (Buscarino et al. 2017). The Met has since updated their protocol to 20171116_OT, which replaces the silicone stopper with a laser-sintered nylon coupon holder (Buscarino et al. 2018).

REFERENCES

Bahl, O. P., Zengmin Shen, J. Gerard Lavin, and Roger A. Ross. 1998. "Manufacture of Carbon Fibers." In *Carbon Fibers*, ed. J.-B. Donnet et al. New York: Marcel Deckker. 1–6.

Buscarino, Isabella C., Catherine H. Stephens, and Eric M. Breitung. 2017. "Oddy Test Protocol at the Metropolitan Museum of Art (The Met). Current Version: 20170606_OT and former version 20160416_OT." *AIC Wiki, Oddy Test Protocols.* http://www.conservation-wiki.com/wiki/Oddy_Test_Protocols#Metropolitan_Museum_of_Art_.28MMA.29_Protocol

—. 2018. "Oddy Test Protocol at the Metropolitan Museum of Art (The Met). Current Version: 20171116_OT." *AIC Wiki, Oddy Test Protocols.* www.conservation-wiki.com/wiki/Oddy_Test_Protocols#Metropolitan_Museum_of_Art_.28MMA.29_Protocol

Gross, Jason. 2003. *National Historic Chemical Landmark: High Performance Carbon Fibers*. Washington, DC: American Chemical Society. https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/carbonfibers.html#first-carbon-fibers

Harholdt, Katie. 2003. "Carbon Fiber, Past and Future." *Industrial Fabric Products Review* 88 (4): 14–16.

Langley, Marcus. 1971. "Carbon Fibers—The First Five Years." *FLIGHT International* September 9: 406–408.

Lavin, J. Gerard. 2001. "Carbon Fibers." In *High-performance Fibres*, ed. J. W. S. Hearle. Boca Raton, FL: CRC Press. 156–90.

Morgan, Peter. 2005. *Carbon Fibers and Their Composites*. Boca Raton, FL: Taylor & Francis.

Oak Ridge National Laboratory. 2011. *Carbon Fiber: Conventional Carbon Fiber Conversion*. YouTube video, 1:30. Posted June 7, 2011. https://youtu.be/c3SZiRYJzH8.

Quinn, Bradley. 2010. *Textile Futures: Fashion, Design and Technology*. New York: Berg.

Riccardelli, Carolyn, Jack Soultanian, Michael Morris, Lawrence Becker, George Wheeler, and Ronald Street. 2014. "The Treatment of Tullio Lombardo's *Adam*: A New Approach to the Conservation of Monumental Marble Sculpture." *Metropolitan Museum Journal* 49: 48–114.

Riccardelli, Carolyn and Wendy Walker. 2019. "The Treatment of Two Terracotta Architectural Reliefs by Andrea della Robbia at The Metropolitan Museum of Art." *Objects Specialty Group Postprints, Volume Twenty-Four, 2017*. Washington, DC: American Institute for Conservation (AIC). 24: In press.

Yari, Mehdi. 2017. "Galvanic Corrosion of Metals Connected to Carbon Fiber Reinforced Polymers." *Corrosionpedia*. Accessed October 6, 2017. https://www.corrosionpedia.com/galvanic-corrosion-of-metals-connected-to-carbon-fiber-reinforced-polymers/2/1556.

SOURCES OF MATERIALS

Aluminum Honeycomb Panels
Composite Panel Solutions (No longer in business)
7167 Rte. #353
Cattaraugus, NY 14719

Carbon Fiber Fabric and Laminating Resins
FibreGlast
385 Carr Drive
Brookville, OH 45309
http://www.fibreglast.com/

Delikit VPS putty, regular set
Net 32 Dental Supplies
250 Towne Village Dr.
Cary, NC 27513
https://www.net32.com/

Ethafoam 900 (commonly called 9-pound Ethafoam)
Sealed Air
301 Mayhill Street
Saddle River, NJ 07663
www.ethafoam.com

EPO-TEK 301-2
Epoxy Technology, Inc.
14 Fortune Dr.
Billerica, MA 01821
https://www.epotek.com/

Paraloid B-72
  Manufactured by Dow Chemical Company
  Talas
  330 Morgan Ave.
  Brooklyn, NY 11211
  https://www.talasonline.com

Weld nuts, flange nuts, hose clamps, chip brushes
  McMaster Carr
  PO Box 5370
  Princeton, NJ 08543
  https://www.mcmaster.com/

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