In-situ Processing of Thermoplastic Composites for Large-scale Structures

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INTRODUCTION

Around for many, many years, composite materials have been on a long and interesting evolution. Although rarely recognized, the origin of man-made (or engineered) composites actually has its roots in architecture. From Egyptian times, straw has been used as an additive to the clay brick-making process providing both strength (resistance to cracking) as well as the ability to speed drying of the clay and reduce the occurrence of loss during the firing process. By the mid twentieth century, aggressive investment and development of fiber reinforced plastics for the emerging aerospace industry marked a period of tremendous progress for these materials – particularly marked by impressive gains in performance. The use of composite materials has been steadily growing ever since as the various benefits of these materials (most notably their high-strength and light-weight) have been utilized in many industries. The materials are now synonymous with aerospace, where weight savings are critical. Here today, advanced manufacturing technologies are being used to build composite structures for high performance applications such as Lockheed Martin's F-35 Lightning II (The Joint Strike Fighter) and Boeing Commercial Aircraft's 787. Here, composites are being used to replace aluminum and steel due to their high strength-to-weight ratio.

MATERIALS

Composite materials, for the purpose of this discussion, are comprised of continuous fibers held together with a polymer matrix. The fibers principally influence mechanical properties (i.e. provide high strength), while the resin protects and stabilizes the fibers while transferring the load from one fiber to another. The most commonly used fibers are glass and carbon. From a purely economic standpoint, E-glass (electrical grade) holds the most potential for use in architectural type applications. S-glass (structural grade) and standard modulus carbon fibers provide higher strength, but are more expensive.

The matrix that binds the fibers together can either be a thermoset or thermoplastic polymer. Thermosets (such as epoxies) require a chemical cure. Conventional thermoset processing requires a labor and energy intensive process. Typically, the preform is made by hand layup. The part must then be vacuum bagged and cured in an autoclave cycle. Expensive tooling and consumable bagging materials add to the cost of the approach. Additionally, many thermosets involve toxic chemical components, particularly before and during the cure cycle and require refrigeration of the raw materials prior to processing.

On the other hand, thermoplastics can be melt-bonded to form a structure. The material can be melted and reformed. Common thermoplastics include polyethylene (PE), polypropylene (PP), Nylon (PA), and polyetheretherketone (PEEK). Thermoplastic composites are more damage tolerant, fatigue resistant, corrosion resistant, non-toxic, recyclable, and allow fusion bonding with other melt miscible thermoplastic structures.

The raw material can come in the form of a prepreg tape, meaning the fibers are pre-impregnated with the thermoplastic resin. This is done off line at the material supplier's facility. Because the material is a thermoplastic, there are no shelf life or "out time" issues. The raw material can be stored at room temperature for an indefinite amount of time, as opposed to thermoset materials which require relatively strict storage temperatures and have a limited shelf life (these issues are driven by the fact that thermoset prepreg has resin in its uncured state – therefore you have handling issues related to preventing the onset of the chemical reaction that produces the cross-linking or cure).

FABRICATION PROCESS

Automated layup techniques provide an out of autoclave cure. With automated fiber placement, thermoplastic material is heated and consolidated in-situ, or as it is being fabricated. The end result is a structure that does not require any post-processing. This is critical for large and/or thick-walled structures. Issues arise for large or thick-walled thermoset materials during the cure cycle. For large parts, limitations on autoclave size and concerns over matching CTE (coefficient of thermal expansion) of the part and tool complicate large part fabrication. For thick parts, the temperature gradient in the wall that develops as the part is heating and cooling can cause cracking, most often between the plies of material. These cracks are most frequently of the interlaminar type. This situation is further exacerbated by the differential stage of cure created by the gradients in temperature. By using an in-situ process with thermoplastic resin, we can eliminate this step and reduce the thermally induced residual stresses created. Automated fiber placement technology allows fibers to be oriented in any direction, allowing structures to be fabricated to a fully optimized design to carry specific loads.

A basic schematic of the automated fiber placement process is depicted in Figure 1 below. A hot gas torch provides the heat source for melting the incoming composite tape. A compaction roller applies pressure and consolidates each layer. A robotic platform positions the fiber placement head along the mandrel surface to automatically layup the composite structure. The temperature, compaction force, and process speed parameters are actively monitored and controlled throughout the process.

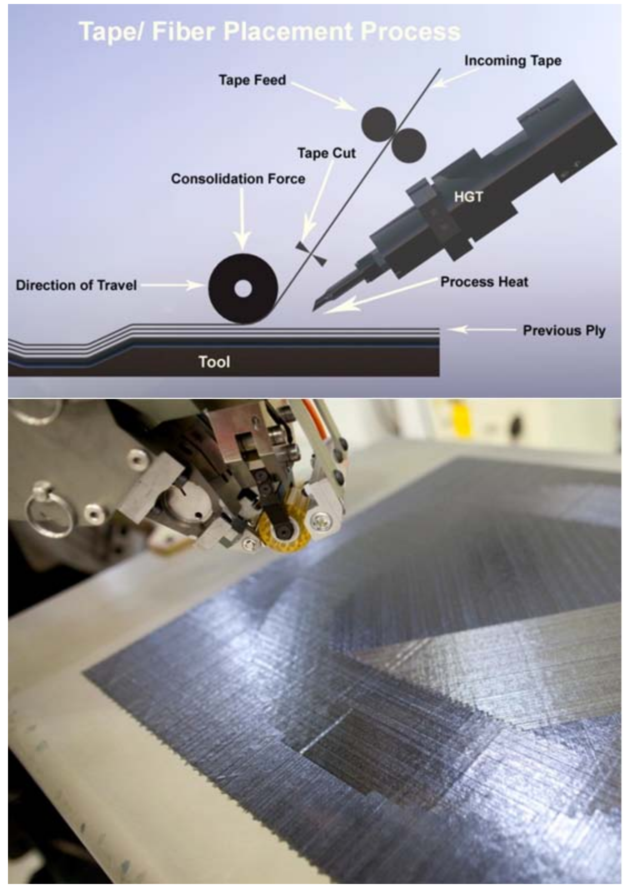

Figure 1. Schematic and photo of the automated fiber placement process.

The first layer of material is most often placed on to a "cold" tool (cold relative to the processing temperature of the thermoplastic). After which, subsequent layers are placed on top of the previous layers to form the laminate of desired thickness and fiber orientation. Each new layer is melt bonded to the previous layer. The laminate is built to the desired specifications and then is removed from the tooling. At this point, the laminate is considered complete. There is no post processing needed. The part is then trimmed to the desired geometry and is ready for use.

COMPOSITE STRUCTURE

Composite structures can be found in many aerospace applications, as reducing weight is critical in this field. Automated fiber placement of thermoplastics allows for the integration of stiffeners into a structure so that no additional fasteners or adhesives are required. Figure 2 below shows a carbon fiber reinforced composite tub (or sub-floor, the bottom section of the fuselage structure) for the H-60 Blackhawk helicopter. Composite 'I' beams and 'T' stiffeners were manufactured and assembled into a tool. The top and bottom composite skins were fiber placed over the stringers to produce a lightweight, high strength, enhanced fatigue resistant replacement for an aluminum structure. The result is a complete, integrally bonded composite structure. Composite floor sections and panels can offer increased damage tolerance, corrosion resistance, longer service life, lighter weight, and greater durability than many conventional building materials.

Figure 2. Carbon fiber composite sub-floor for the H-60 Blackhawk helicopter.

The use of thermoplastic composites for primary aircraft structures can also be seen in the parts shown in the Figure 3 below (each are thermoplastic composite structures made with Automated Dynamics' in-situ fiber placement process). The integrally stiffened tail boom structure (shown upper left), is about 24 inch diameter by 60 inch length. The structure that is seen in the upper right portion of the figure is about 24 inches by 48 inches in cross-section. These structures demonstrated a successful bond between the prefabricated thermoplastic internal stiffeners and the thermoplastic skin with no secondary adhesives or mechanical fasteners. To accomplish this, many of the stiffeners were manufactured using a typical commodity process such as compression molding or continuous compression molding. These parts were then trimmed to size and fitted into a metallic tool which allowed the composite skin to be melt bonded over the top of the stiffeners with a fully automated robotic process. The result is a single piece composite structure that is able to replace thousands of metal stiffeners, sheet metal skin sections, and fasteners (typically 2-piece titanium rivets).

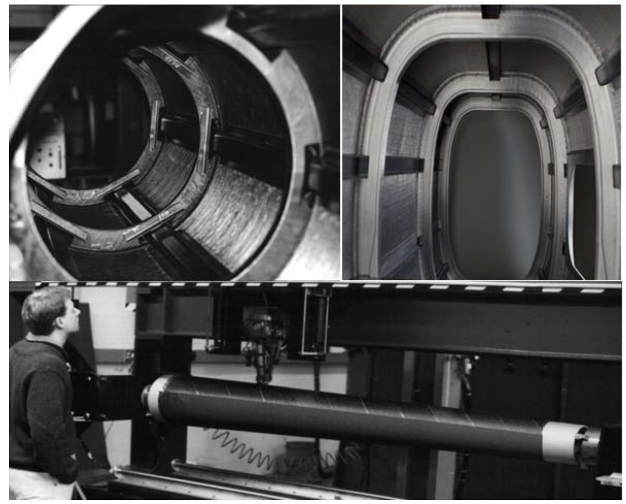

Figure 3. Internally stiffened thermoplastic composite tail boom.

In the architecture market, automated fiber placement was recently implemented to build a prototype structural beam with fiberglass composites, shown in Figure 4 below. The key aspect of the program was to leverage the advantages of unidirectional composites to make a beam that used minimal material. The beam was designed to demonstrate the capabilities of automated fiber placement, while maintaining the desired aesthetic components. A custom program was generated to create the complex pattern. Finite Element Analysis (FEA) quantified the loading and stress concentrations to allow for an efficient design. Fiber placement processing played a critical role in this design, because it allowed for the production of a part that had fiber paths with orientations that varied as the stress level varied along the length of the part.

The beam design was able to meet the program goals for sustainability. The aim was to reduce the total embodied energy of the building materials. Since the structure is fabricated with less material and weight, it reduces waste and energy used in construction. The light weight material also means that fuel consumption and costs for delivery are reduced. This work was done with Mike Silver Architects and Rafael Vinoly Architects.

ARCHITECTURAL INTEGRATION CHALLENGES

While there are many advantages to using automated fiber placement of thermoplastics for large-

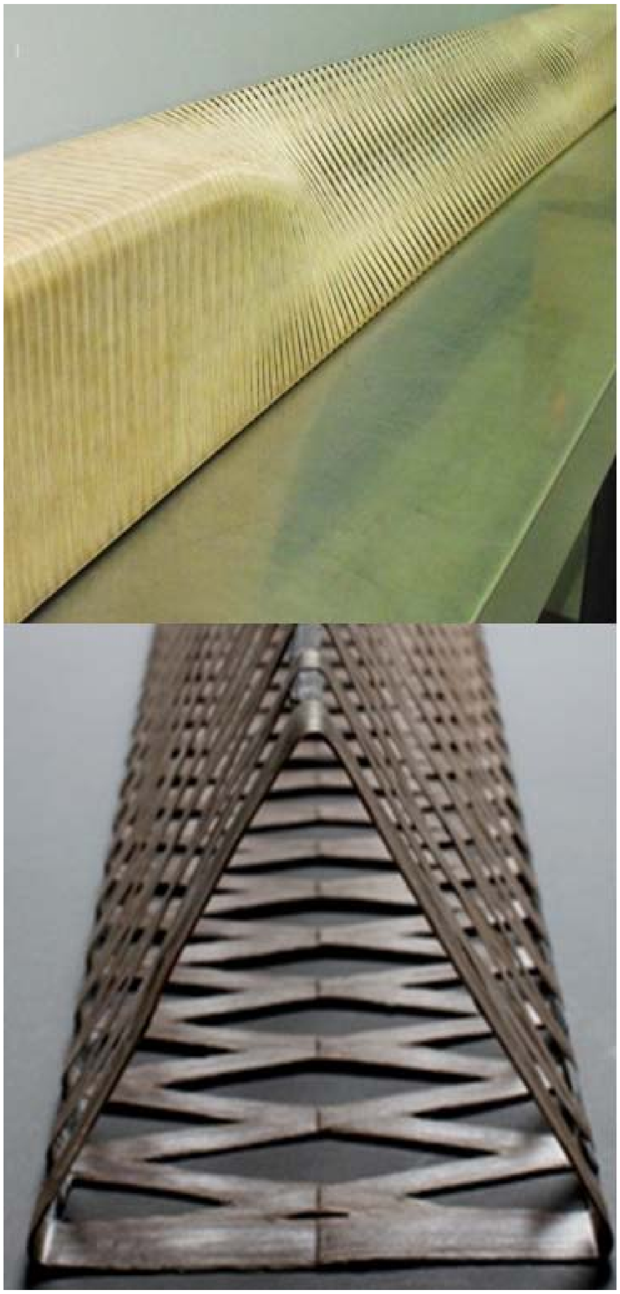

Figure 4. Fiberglass composite beams for a ceiling support concept.

scale applications such as architectural, there remain a few challenges in commercialization of composite structures. One obvious concern would be how to meet fire code requirements found in most building codes. Initially, however, maybe thermoplastic composites should be compared to wood. An initial starting place would be applications where composites can replace wood. In this situation, FST (Fire, Smoke, and Toxicity) performance is comparable and the economic penalty for shifting to more exotic solutions does not come into play. Higher temperature composites are available, but are limiting due to cost. Solutions like high temperature thermoset materials are in the marketplace but have processing complications that make it challenging to create affordable large scale structures. Higher temperature materials such as ceramic matrix composites exist and can certainly provide all of the temperature (and fire) resistance required to replace structural steel, but to date are not far enough down the development path and are not yet used widely enough to bring the price into an area where they can be economically practical for these types of applications. Development of higher temperature composites that will meet the economic constraints is an option, and is in progress but will need time before it is ready to be compatible with the needs of the marketplace.

Another challenge with composite structures is inspection criteria. Impact damage on the surface of a composite part may not leave visual damage. However, there could be significant internal damage – damage that compromises the performance of the component in certain specific loading situations. Defects may also be introduced during manufacturing (i.e. introduction of foreign objects, causing voids), which are also not apparent through a visual inspection. Non-destructive evaluation techniques can be difficult and expensive to implement, especially with large or thick-walled structures. While the technology certainly exists to be able to overcome this obstacle, only a slow but steady demand in the marketplace will bring about the evolution of the methods, equipment, and overall capabilities needed to support structures of this geometry.

Maybe the largest hurdle we face in moving composite structures forward in architectural applications is industry acceptance of a "new" material and the associated knowledge and design tools and methods that will need to accompany them. Since these materials are not widely used in the industry, there is a lack of understanding and comfort with them. Composites require a different design approach. The material science behind understanding their performance is more complicated that what is typically found with materials such as metal, and to fully take advantage of their unique properties new design approaches will be needed. It takes time to qualify and gain wide-spread implementation of composites in any new market – this one will be no exception.

PATH FORWARD

Automated fiber placement of thermoplastic composites provides the opportunity for a novel approach in architectural structures. The automated technique allows for the layup design to be tailored to the required mechanical loads, it yields very precise and high performance parts, and does so in an extremely reliable and repeatable manner. Best yet, it is able to do so while minimizing associated labor costs and environmental footprint associated with many high-performance materials solutions. Thermoplastic composites offer many advantages, including light-weight, high strength, damage tolerant, fatigue resistant, and corrosion resistant. The key to success penetrating this market will be further testing and qualification of materials, design approaches, and processes to gain industry acceptance of composites.

Today, fiber placement equipment exists to do some of this work, but not enough of it is in the academic community where we can begin the process of learning how to most appropriately integrate this into the design process for the industry. Only though implementation at this educational stage will there be the opportunity to drive the changes needed to shift the accepted approaches used in designing structures. Automated Dynamics has worked with Universities to help develop a method for introducing these materials to the design process and has just recently released an automated workcell specifically developed for use in the academic environment. By making access to the technology both affordable and scaled such that it would be compatible with a studio design environment, we hope to be able to encourage further integration of these materials and process into the marketplace. The ultimate goal will be to expose the next generation of design professionals to the tools and understanding needed to change the design approach and integrate these materials into structures at the earliest design levels.

Figure 5. Automated Dynamics' production (left) and lab-scale (right) fiber placement equipment.