

RAPID ASSEMBLY OF FIBER PREFORMS USING 3D WOVEN COMPONENTS

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ABSTRACT

3D weaving is a manufacturing technique for producing near net shape fiber preforms. These preforms can be processed into composite components using liquid molding techniques such as resin transfer molding (RTM) or the vacuum assisted process (VAP[®]). One of the main advantages of 3D woven preforms is that the touch labor required to assemble them is minimal, leading to rapid and highly automated preform construction. This paper describes an application which uses 3D woven preforms as building blocks in a more complicated fiber preform assembly. Details of the construction of the individual 3D woven preforms, their assembly into larger preforms, and estimates of labor savings relative to conventional laminated construction are discussed.

1. INTRODUCTION

The use of composite materials in aerospace structures has increased to the point that they are now commonplace in both military and commercial applications. As end users have become more comfortable with these materials, the engineering challenge has inevitably shifted from a focus on performance to a focus on cost. Final component costs can be reduced through a variety of means, though many of these are beyond the control of the design engineer. For example, raw material costs (i.e. fiber and matrix costs) can sometime be reduced by selecting lower price alternative fibers and/or resins, but this decision is often made at the vehicle level and engineers must work with the selected materials.

Another approach for reducing component cost is to focus on fabrication: reducing the amount of process waste and removing touch labor. Both of these objectives can be met using manufacturing processes that lend themselves to a high degree of automation. Resin transfer molded composites that are reinforced with 3D woven, near net shaped fiber preforms fall into this category. This paper describes work that was done to explore the construction and economics involved in utilizing 3D weaving and RTM together to support assembled composite components otherwise primarily constructed using 2D laminated composites.

1.1 3D (Jacquard) Weaving

3D weaving, also known as Jacquard weaving, is a textile process that can be used to fabricate highly shaped fiber preforms with interlocking fibers. For the purposes of this paper, the term “3D woven preform” is used to describe multi-layer textiles that have fibers which interlock two

or more layers of fabric. The basic fiber preform has fiber oriented primarily in two orthogonal directions (the “warp” direction at 0° and the “weft” direction at 90°), though these fibers can also have a through-thickness (z) component, as shown in Figure 1.

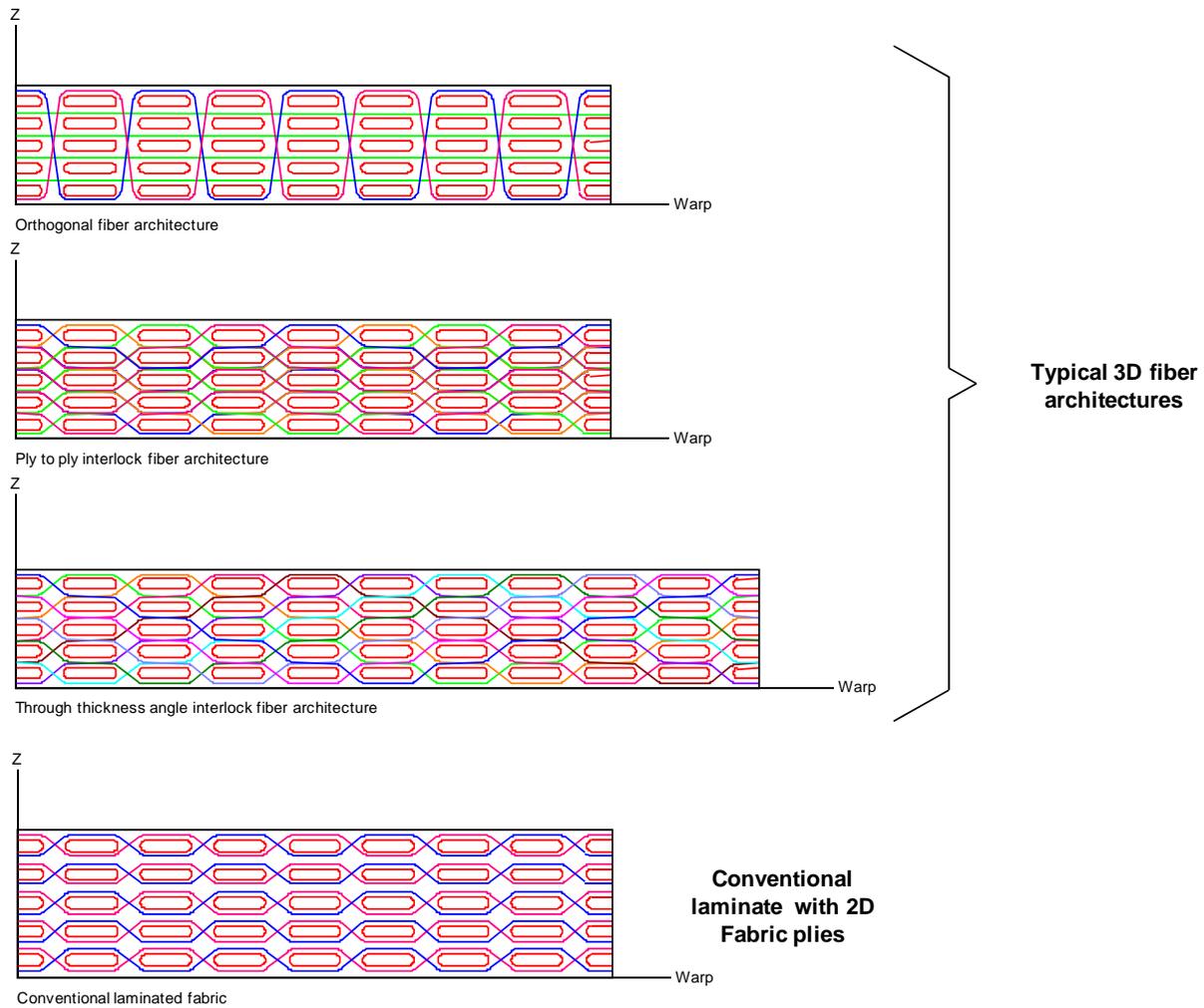


Figure 1 – Schematics of 3D woven and conventional 2D laminate fiber preforms (weft direction into page)

The ovals in Figure 1 represent fibers oriented in the weft direction and the continuous lines weaving over and under the weft fibers represent warp fibers. Note that there are unreinforced planes between the layers of fabric in the illustration for a 2D fabric laminate, but these planes do not exist for the 3D woven examples. The presence of the additional reinforcement in 3D weaving reduces the potential for delamination between adjacent layers.

3D weaving is inherently an automated process. Jacquard weaving machines are typically controlled electronically and are designed to run with minimal operator intervention. Placement

of the through thickness reinforcement is incorporated directly during the weaving process, so there is no need for any additional secondary operations.

Geometric features, such as changes in thickness, integral stiffeners, or bifurcations, can be woven directly into the preform, resulting in near net shape articles that can be ready for molding with minimal trimming or hand work. Preform geometries can vary from simple cross sectional shapes, such as Pi's or T's [1], to extremely complicated shapes, such as the airfoil geometries used in jet engine fan blades [2].

1.2 3D Woven Composites

A typical molded 3D woven fiber preform with a more complicated geometry is shown in Figure 2. In this example, a longitudinal stiffener and a series of three transverse stiffeners are integrally woven into a skin to form a stiffened panel. The skin and stiffeners are woven simultaneously to net different thicknesses and the stiffeners are woven close to their final heights. Because the entire part is woven as a single continuous preform, there is continuous fiber running from the skin into each of the stiffening elements, eliminating the need for any secondary bonding or fastening operations.



Figure 2 – Stiffened panel utilizing a 3D woven fiber preform

Compared to a conventional 2D laminate, 3D weaving minimizes process waste by eliminating the scrap material associated with nesting and cutting plies from large sheets of fabric or prepreg. Touch labor is minimized by weaving the reinforcement as a single multilayer textile, thereby eliminating the ply cutting and collating associated with the conventional laminated processes.

These types of 3D woven preforms are now both being considered and used for a wide variety of aerospace applications, including fan blades and cases for jet engines and landing gear braces for commercial airliners. Ideally, all of the reinforcement for such components could be incorporated into a single fiber preform, but this is not always possible. Differing structural requirements for various portions of a component may dictate the use of multiple preforms.

As an example, a simple I-beam in bending carries axial tension and compression loads in the flanges and shear in the web. From a performance standpoint, it is desirable to have fiber oriented in the axial direction (0° direction) in the flanges and at $\pm 45^\circ$ in the web. These conflicting requirements are difficult to achieve in a single preform.

Fortunately, significant reductions in process waste and touch labor can still be achieved by building a complex fiber preform from several smaller, simpler preforms. The remainder of this paper describes work that was done to develop a fiber preform for a sine wave web beam and establish estimates of the cost savings that can be realized through the labor reduction enabled by this approach.

1.3 Sine Wave Web Beam Fiber Preform

3D woven Pi preforms have been proposed for use as joining elements in advanced composite structures [3]. Typically, these preforms have been used as inserts that help join a web to a skin, as shown in Figure 3. The upstanding legs of the Pi allow loads to be transferred between the web and skin through double lap shear, and the flange helps to distribute pull off loads over a larger area.

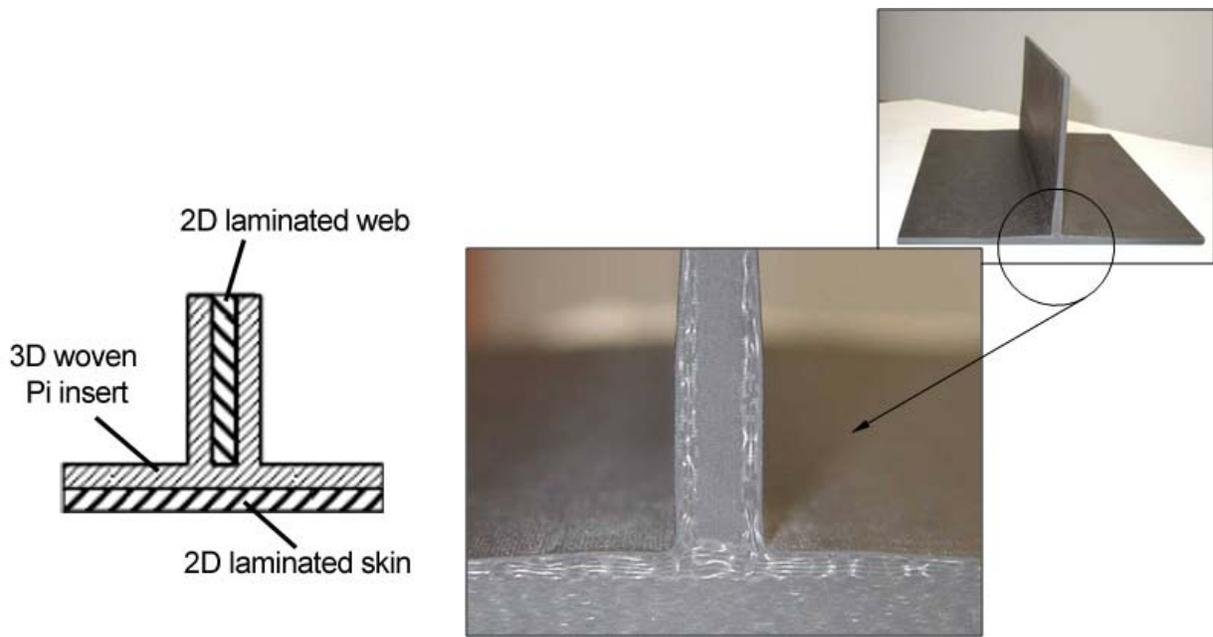


Figure 3 – Typical application of a 3D woven Pi insert

In addition to using the flange of the Pi as a means for attaching a web to a skin, it can also be used directly as the cap in a beam. Very simple and efficient I-beams using this approach have been demonstrated [4]. Beams with straight, curved, constant cross section, and variable cross section geometries have been fabricated using 3D woven Pi preforms as the caps and a conventional laminate as the webs. In these cases, the flange of the Pi can be engineered to have a high percentage of axial fiber to help carry axial and bending loads, while the web laminate can be tailored to carry transverse compression and shear loads without buckling.

This type of composite I-beam can be made to be even more efficient by using a web that is formed into the shape of a sine wave along the beam's length (depicted in Figure 4). This is because the sine wave shape provides geometrical stiffening that allows the web thickness to be reduced while the beam's performance otherwise remains the same.



Figure 4 – Prototype sine wave web beam

Such a sine wave web beam can still be produced with three relatively simple pieces (as shown in Figure 5), though weaving the Pi preforms for the caps becomes somewhat more complex. The flange of the Pi has a uniform cross section, but the intersection points between the upstanding legs and the flange is variable along the length of the Pi.

The laminated web can include bias plies ($\pm 45^\circ$ plies) to carry shear loads, and $0^\circ/90^\circ$ to carry transverse compression loads. Note, however, that the percentage of $0^\circ/90^\circ$ material can be reduced because of the geometric stiffening provided by the sine wave shape.

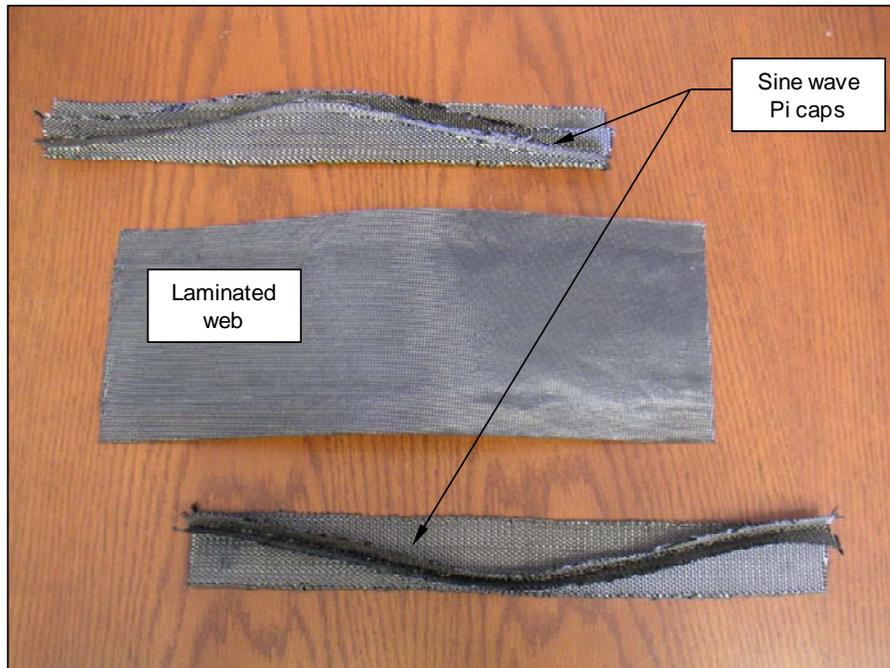


Figure 5 – Components in a sine wave web beam preform

Assembly of the final preform is very straightforward. The web is laid up as a series of simple rectangular pieces and formed into the sine wave shape. The caps are simply cut to length and placed on either edge of the web laminate. The entire preform can then be placed into a tool and resin transfer molded.

Questions that arise from utilization of 3D weaving in this type of beam construction include: where the 3D woven structure provides improvements in structural performance, does an entire component need to be 3D woven to provide structural benefits? Can some components benefit by the inclusion of both 3D and traditional 2D laminated composite structures? Is this an economical choice? Is it economical to utilize 3D weaving for only one portion of a component's fabrication?

2. COST ANALYSIS

The following sections compare the manufacturing steps and cost analysis for two sine wave beam fabrication methods. The first approach, referred to in this paper as the *prepreg* manufacturing approach, uses hand laid up prepreg cured in an autoclave to produce all components of the sine wave beam. The second process, referred to as the *preform* manufacturing approach, uses a combination of 3D woven preforms and 2D lay-ups together with the introduction of resin via the RTM process. Prior to discussing the manufacturing steps, assumptions are laid out to provide the framework of the cost analysis.

2.1 Manufacturing Assumptions

It is assumed that the weight of the two beams is held constant. In practice, the sine wave geometry increases the beam's buckling performance and reduces the web thickness. Reduced material usage directly influences the cost of the finished product. All of the material cost difference identified in this analysis is assumed to be associated with scrap material produced by each fabrication method. Again, not a truly valid assumption but the competitive nature of the aerospace industry precludes the use of actual pricing.

The construction of each beam uses intermediate modulus fiber within an epoxy resin matrix. In addition, each process is assumed mature so all improvements from learning curve are implemented. The beam has a height of 150 mm and a flange width of 50 mm. The thicknesses of the flanges and webs in each approach are identical. In practice, they would differ as the prepreg would be unidirectional. Lap joints are assumed to be satisfactory for the prepreg beam as long as the splices are spaced appropriately to permit adequate structural response.

This examination shall focus on the steps of actual fabrication, starting from ply cutting and ending with the tool prepared for the cure cycle. This particular examination shall ignore the cure cycle and thaw times for materials.

2.2 Prepreg Manufacturing Approach

For this particular manufacturing method, it is necessary to remove the prepreg from a freezer and allow it to rise to room temperature prior to use. After thawing, the prepreg roll is moved to a cutting table where both the flange and the web plies are cut. The plies are arranged into kits and moved along to a lay-up station. After being laid up by hand, the part travels to the autoclave for bagging and cure.

2.3 Prefrom Manufacturing Approach

Weaving the necessary material for the sine wave preforms – the 3D woven cap preforms and the fabric required to produce the 2D laminated web – is the first step in this production method. Upon completion of weaving, the preform is visually inspected for defects. The cap preform then goes on to secondary operations for some trimming to near net shape while the web fabric goes to a cutting table to cut the web plies.

Upon completion of the secondary operations, the 3D preform and the cut plies move to a lay-up area. Here the preform is assembled using tackifier. Once assembly is complete, the preform is loaded into the tool, which is then closed and plumbed. The last step is to inject the part. Typically, the resin is removed from the freezer and allowed thawed to room temperature while preforming operations are on-going.

3. RESULTS

The proposed manufacturing steps with estimated times are found in Table 1. These estimates indicate that utilizing the preform manufacturing approach will result in a savings of approximately 45% inw the time it takes from processing the plies until the beam is ready for

cure. Again, the assumption is that the processes are both mature and all learning curve improvements are realized.

Since the beams are of identical thickness and size, the material cost difference is realized in the amount of scrap generated during the ply cutting. Since the webs are of identical size, the assumed scrap rates are equal for both. The same cannot be said for the flanges. Splices and darts are required to accommodate the sine wave geometry. These discontinuous regions would require additional material to regain structural integrity. The additional material would increase both the prepreg ply cutting scrape rate and cycle time.

This analysis ignores the material cost of the extra thickness in the final part but does account for the increased cycle time which occurs during the prepreg manufacturing approach. The actual increased prepreg scrap is estimated to be on the order of 25 – 40%, resulting primarily from manual layout of the patterns on the cutting table. An optimized nesting program could reduce the increased scrap but not eliminate it.

Table 1 – Sine Wave Web Beam Assembly Time

| | | | | | |
|----------------------------|------|----|-----------------------|------|----|
| Prepreg | | | Preform | | |
| Cut Web Plies | 0.25 | hr | Cut Web Plies | 0.25 | hr |
| Cut Flange Plies | 0.25 | hr | Trim Flanges | 0.25 | hr |
| Kit Plies | 0.25 | hr | Kit Plies | 0.2 | hr |
| Lay-up Web | 0.25 | hr | Lay-up Web | 0.25 | hr |
| Debulk | 0.5 | hr | | | |
| Lay-up Flange | 0.5 | hr | Place Flanges in Tool | 0.75 | hr |
| Debulk | 0.5 | hr | | | |
| Lay-up Flange | 0.5 | hr | | | |
| Bag Part & Final Debulk | 1 | hr | Close & Plumb Tool | 0.75 | hr |
| | 4 | hr | | 2.45 | hr |

One cost that is difficult to estimate is the non-conformance review of beams. The prepreg items have the potential to have significantly more NCRs from fiber bridging, wrinkling, distortion, etc. from the geometry than the 3D preform which has the geometry woven into it. Based on past experience, this could be a significant cost and must be considered.

4. CONCLUSIONS

One purpose of this study was to assess if it is economically feasible to utilize 3D weaving for only one portion of a component's fabrication. Based on the reduced assembly cycle time and the reduced material scrap, 3D woven/RTM components are attractive from a cost standpoint. They also offer performance improvements as documented in Reference 5 that would further increase the possible cost savings by reducing the amount of material. Future work will examine the cost benefits against additional processes (i.e. automated tape laying).

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5. REFERENCES

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