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Final Report

Application of Resin Transfer Molding to the Manufacture of Wind Turbine Blade Substructures

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Objective

The main objective of this program is to investigate, through analytical and experimental means, the effects of processing details on the performance of a common wind turbine blade sub-component.

Justification and Approach

This project is a collaborative effort between Sandia National Laboratories (SNL) and Headwaters Composites Inc. (HCI), and is a natural extension of the turbine blade research already performed by Montana State University (MSU) and HCI of the Wind Energy Cluster under the DOE/EPSCoR program. A tremendous volume of work has been done on the fatigue performance of turbine blade materials, in increasingly complex structures. The results of these previous studies [1,2] relating to fiber architecture, fiber content, stiffener intersections, and preforming will be brought together and extended to the modeling, fabricating, and testing of a critical blade structure on a realistic scale.

The historical development of turbine blades in the U.S. has generally lacked the capability for an iterative process of detailed structural design, manufacturing, and testing at the full blade level to achieve specific structural performance, cost, and weight targets. This approach has simply been too costly for the wind industry when carried out on large blades. Yet, experience in many applications of composite structures has shown that the most efficient use of fibrous materials in complex structures can only be realized through the iterative testing and redesign of the structural details, material lay-ups, and manufacturing details, coupled with sufficiently powerful analysis tools and nondestructive evaluation. In addition to these features, a program must include personnel with extensive experience in the behavior of composite materials and structures. Typical programs that have lacked this blade development flexibility have, coupled with industry experience, produced large blades which work. However, the "shot in the dark" approach has not produced blades that perform well in full-scale structural tests when compared with reasonable expectations based on materials data. They work because they are very conservative designs.

Many wind turbine blades are made from fiberglass. The vast majority of fiberglass materials, including those used for wind turbine blades, are comprised of E-glass fibers encapsulated in an unsaturated polyester matrix. There are a number of processes currently used to manufacture composite objects ranging from hand lay-up to computer driven fiber placement equipment. The process used can have an impact on both the design and the quality of the finished product. The approach in this program is to focus on the use of one of the more sophisticated manufacturing processes, resin transfer molding (RTM), which can produce complex shapes and surfaces making it well suited to produce wind turbine blades. It is a goal of this study to provide insight on how a future design could be tailored to the capabilities of the process.

There are a number of other reasons for choosing RTM for this project. Many of the technical advantages will be stated in the following paragraphs. The fact that either initial capital costs or labor costs or both are lower than for other processes make RTM a very attractive process financially. Additionally, RTM is a closed mold process, which greatly reduces volatiles (primarily styrene) emissions. In fact, using meter-mix injection equipment can reduce these to virtually zero, reducing ventilation costs. These lower emissions also make it attractive from

environmental and regulatory standpoints. Styrene is volatile, and during open molding operations a certain amount of it escapes when the resin is applied and during the early stages of curing. At levels of 50 ppm, styrene exposure has not been found to have any neurotoxic effects. However, at levels greater than 100 ppm, symptoms such as dizziness, headaches, and fatigue can result. OSHA has made a determination, in the case of the boat building industry (also open molders of large parts), that engineering controls which would attain the 50 ppm limit would not be technologically or economically feasible [3]. The emission of volatiles is related to the area of resin exposed to the air, making these emissions quite substantial. Where large parts such as utility grade wind turbine blades are open molded, mitigation costs can be substantial.

The reduction of trim and scrap also give the RTM process improved environmental properties. Additionally, RTM is a natural process for moving from hand lay-up to a higher quality, more reliable product, particularly when produced at higher rates. It retains most of the design flexibility of hand lay-up compared with most improved quality processes.

Compared with processes like filament winding and pultrusion, also advanced processing methods, RTM has more flexibility in structural details such as skin stiffening, and compatibility with complex shapes. The use of preforms can make RTM an automated process, which can mean lower labor requirements and more repeatable results. The use of matched tooling produces very consistent dimensions with tight tolerances for improved adhesive bonding. Very smooth surfaces are possible with little or no secondary processing. The use of fiberglass or epoxy tooling can greatly speed up the tool building process, and thus, prototype development.

Although other processes are capable of producing a quality product, RTM is the only one to combine that aspect with flexibility, low cost, low emission of volatiles, and speed. The projected production rate of blades is also well suited to this process. RTM may be slow by automotive standards, but it is outstanding when used for medium runs.

Project Description

These efforts center around manufacturing a substructure, the skin/stiffener intersection (figure 1), from a relatively small (7.2 m) fiberglass blade. This structure is found in many blades, and although the selected blade is not utility grade, it possesses similar characteristics in construction and structure, and has been manufactured by HCI under the DOE/EPSCoR program, with a commonly used method known as hand lay-up. The focus on this blade size is justified by the greater potential for advances in manufacturing which can be achieved in this size range, and which can be readily adapted to larger turbine blades. Of course scale-up issues must be addressed. However, the use of RTM to manufacture large structures has been demonstrated. A variation of RTM was used in the 1940's to manufacture 40ft. hulls for the Coast Guard, and more

Figure 1 Skin/stiffener intersection.

recently, hulls from 30ft.-50ft. have been made in Europe [4]. Additionally, due to their size, smaller blades can benefit since they can economically take advantage of processes that can produce integrated components.

The skin/stiffener intersection has been selected for this study. Due to its similarity to the actual structures (figure 1) an "I" shaped section is used as an approximation to aid in the manufacturing and testing portion of this work and to allow a more generic study. The parts that are manufactured will be analyzed using modal, flexural, and fatigue tests, the results of which will be used for verification of the SNL's blade design tool, NuMAD (Numerical Manufacturing and Design).

Joints have traditionally proven troublesome in wind turbine blades. The skin/stiffener intersection, a joint common to many wind turbine blades, was selected for this study. Delamination from damage initiating in this region can lead to potential blade failure making this a potential limiting factor in blade performance [5]. This joint is on the interior of the blade, making it difficult to inspect during the assembly of the blade or to monitor in service. Thus, flaws created in manufacturing may go unnoticed, leading to possible failure. Therefore, studying how processing affects joint performance is of great interest.

Description of RTM

RTM is an extension of hand lay-up, a common method of producing wind turbine blades. In hand lay-up, fiberglass is laid into a female mold and resin is poured, sprayed, or rolled onto it. The resin is then manually distributed and worked into the reinforcement with squeegees and rollers. This method of distribution increases the possibility of shifting the fiber alignment, causing variability in the laminate. Hand lay-up uses very little in the way of equipment and as a result is a relatively inexpensive method to make composite parts. However, it is labor intensive. Some variability in the laminate can result from local shifts in the reinforcement caused by the squeegees and rollers. Additionally, the inability to consolidate the saturated fiber assembly limits the maximum fiber content and can make thickness hard to control accurately.

Resin transfer molding is a matched mold process that creates composite parts with low porosity, high fiber volume, good fiber alignment, good surface quality, and accurate dimensional and shape definition while dramatically reducing the emission of volatiles. It provides a natural extension of hand lay-up methods where higher quality is needed and higher production rates are anticipated.

As in all fiberglass molding processes the mold is critical to producing parts with good surface quality and dimensional tolerances. In RTM, a matched mold of the desired shape is employed. Due to the low pressures used in this process the mold need not be made of tool steel (as in most compression or injection molding) and can be formed from fiberglass or epoxy. This has two advantages: it greatly reduces the cost, making it accessible to blade manufacturers; and reduces the time to produce the tooling, which can allow for more design iterations and faster prototyping. This type of tooling is also capable of producing good surfaces and accurate dimensions. Furthermore, two-sided tooling provides very good control of thickness and allows stiffeners and skins to be made in one piece.

After preparing the mold for service (see drawing 1.2, page 6, for a schematic of the RTM process) it is filled with dry reinforcement and any core material and inserts as necessary. The reinforcements can be of a variety of weights and architectures, and can be layered in any fashion

so that the cavity formed by the two mold halves is filled, providing flexibility by permitting the properties to be tailored to the anticipated loading. The primary reinforcements used in RTM are made up of strands of fiberglass consisting of hundreds of individual fibers. These strands are held together by extensive stitching which serves to maintain strand integrity, alignment, spacing, and to facilitate handling. The spaces between the strands form channels approximately 0.254-0.508 mm in diameter. Multidirectional reinforcements are formed by subsequently stitching unidirectional layers together with the desired orientation, but these often are associated with poor fatigue resistance [6,7].

After loading and closing the mold, catalyzed resin is then pumped in through an inlet and the displaced air escapes through vents built into the mold. The channels formed between the discrete strands greatly aid the flow of resin through the laminate, which reduces the pressures necessary to inject the resin, particularly at high fiber volumes. The channels between the strands are filled by the flowing resin while the strands themselves are wetted out by capillary forces [8]. When resin begins flowing out of the vents the injection is stopped and the mold is sealed. Once the resin is cured, the mold is opened and the part can be removed.

This process lends itself very well to the manufacture of wind turbine blades due to ability to produce complex geometries, possibly eliminating some secondary bonding, and the surfaces required for aerodynamic quality. The precision of the RTM process in the two-sided molds allows for thinner, more controlled adhesive bondlines than is the case with processes like hand lay-up.

The major components of the process consist of the injection equipment, the mold, and bonding jigs. One of the injection machines is an air motor driven resin pump and a slave arm pump for the catalyst. This machine can precisely meter out the proper ratio of resin and catalyst over a given range depending on the size of the part, processing conditions, and the desired rate of production. This configuration also allows a variety of resin formulations and catalyst levels to be used. Once the resin and catalyst have been metered, they are forced through a static mixer, located just upstream from the inlet, to mix the two components. The other machine used is a pressure vessel. This machine delivers resin by displacement using air pressure. The resin must be catalyzed and mixed by hand, however this system allows resin that has been vented from the part to be re-injected.

The molds for the parts are also major components of this process. Due to the size of the specimens, the molds for this project are substantial (1500 lbs.). The production of large structural parts with complex geometries makes placement of the inlets and outlets important so as to insure that the mold completely fills.

Areas of Development

Due to the flow aspects, the tooling developed under this program must be properly gated and vented so as to fill completely, leaving no dry spots. This becomes more critical as the complexity of the part geometry increases. Other factors such as the volume of fiber, its location, and its architecture all affect the flow pattern making the mold design crucial. As stated earlier, RTM is a low pressure process, and relatively inexpensive tooling can be used, allowing several iterations, if necessary, to produce a final product which meets expectations.

Preforming is another area requiring further development. Preforms refer to layers of reinforcement arranged so that the fibers are properly oriented and held in place

prior to being placed into the mold. This allows the fibers to be carefully laid-up outside of the mold where inspection is much easier. The layers are commonly held together with stitching, a soluble binder, or a light coating of a tackifier.

- The performance of a wind turbine blade is highly dependent on the proper alignment and positioning of the fibers. The use of preforms becomes extremely important when producing large structures where it is easy for small fiber misalignments to go unnoticed. The following must be considered when evaluating preforming methods. The laminate must be held tightly enough to resist movement of the layers while it is being loaded into the mold. The preforms

must also be produced to allow the resin to flow properly. From a performance standpoint, as related earlier, studies done at Montana State University have shown that tight stitching of multidirectional layers can have a detrimental effect on the tensile fatigue properties of the structure at fiber volumes over 45% [6]. This problem is not related strictly to fiber volume since materials with a less stranded architecture do not exhibit this behavior even to higher fiber volumes. From a processing standpoint this means that the method of producing the preform must not inhibit the flow of the resin, which can lead to dry spots in the laminate. For example, a heavy coat of tackifier can potentially prevent the surfaces of the strands from becoming saturated. The method of preforming also influences the mechanical properties.

Figure 2 Schematic of the RTM process.

Benefits

The most obvious beneficiary of any work that improves the quality and performance of wind turbine blades is the wind industry. This project will increase the understanding of how manufacturing processes affect the performance of blades, providing insight into the advantages and pitfalls involved. Furthermore, the development and refinement of models resulting from this work will enable incorporation of these findings in future blade designs.

For SNL the primary benefit from this work comes from validation of the design tool NuMAD (currently under development at SNL). NuMAD is a front end for ANSYS®, a finite element analysis (FEA) package, allowing the user to develop 3-D models of wind turbine blades very quickly using databases of airfoils and materials. To be a useful and reliable manufacturing and design tool, NuMAD will require experimental verification for sections.

Test Cases

Three different cases were examined in the course of this study. In each case three beams were fabricated from E-glass fibers in an unsaturated polyester matrix. Polyester is the least costly material, but has shown equal mechanical properties and fatigue lifetime to vinyl ester and

epoxy matrix systems in the MSU studies [1]. At Sandia National Laboratories the I-beams were subjected to modal tests to measure their natural frequencies and mass property tests to determine beam structural properties. These tests allowed comparisons to be made between the as-built characteristics of the beams and their fabrication process.

Case 1 (A Beams)

In the first case the two flanges and web, which was made as two "c-channels" bonded back to back, were hand laid-up and adhesively bonded together to form the I-beam. Hand lay-up is a common method of manufacturing wind turbine blades, therefore these cases will serve as the baseline for the other cases.

Case 2 (B Beams)

In the second case the two flanges and web were molded together in a single piece using the RTM process (described above). This case eliminates the need for secondary bonding altogether, and represents a more complex case, which would require internal tooling to mold an entire blade. Although the tooling costs may be much greater, labor costs could be lower and preforming options could potentially offer faster cycle times and stronger parts. The mold for the RTM beams was created with the dimensions of the hand lay-up parts in mind. However, this caused a problem when RTM parts were injected using the same amount of fabric as the hand lay-up beams. Since the RTM process requires a certain amount of fabric in the mold to keep the fabric from moving around while it is injected, additional fabric needed to be added in order to keep the fabric from being pushed into waves or to one side of the mold. These beams represent a more optimized structure, due to their higher fiber volume.

Case 3 (C Beams)

In the third case the flanges and web were fabricated separately by RTM and adhesively bonded together. The parts, although having the same geometry as those in the Case 1, have smoother and more uniform dimensions, and therefore a more uniform bondline. This represents an intermediate case that would potentially allow a blade manufacturer to use existing patterns to make molds. All of the RTM bonded beams were created with additional fabric as in Case 2.

The finished specimens underwent mass property and free-free modal tests at Sandia National Laboratories, performed by the modal testing group. Test results were used in verification of the design tool NuMAD.

Testing

Mass property and modal testing were conducted at SNL. Before testing, the beams were prepared by cutting them so that they would have clean, sharp ends and be ninety inches in length(± 0.1 in.). Modal testing was done by using a POI3500 test machine. The beams were also tested in four point bending to failure at Wichita State University, however the results are not available at this time.

Results

In the following tables the "A" beams refer to the hand lay-up beams (Case 1), the "B" beams refer to the all RTM beams (Case 2), and the "C" beams refer to the RTM/bonded beams (Case 3).

Table 1 Weight, Moment of Inertia (MOI), and Center of Gravity measurements (Part 1)

Unit Designation	Weight (± 0.05 lbs.)	Z axis CG inches (± 0.1)	Ixx lb-in ² (± 0.1 in.)	Iyy lb-in ² (± 0.1 in.)	Radius of Gyration (Ixx) (± 0.1 in.)
A1	56.05	45.3	38970	38450	26.4
A2	53.15	45.1	37110	36560	26.4
A3	61.10	44.8	42490	41540	26.4
B1	61.60	45.1	42700	41970	26.3
B2	61.30	45.0	42420	41780	26.3
B3	61.55	45.0	42700	42050	26.3
C1	64.30	44.8	44540	43560	26.3
C2	63.45	44.9	43620	43130	26.2
C3	64.20	44.8	44440	43510	26.3

Table 1 Weight, Moment of Inertia (MOI), and Center of Gravity measurements (Part 2)

Unit Designation	Radius of Gyration (Iyy) (± 0.1 in.)	X axis CG inches (± 0.1)	Y axis CG inches (± 0.1)	Ixx/Iyy (± 0.002)	Δ Weight=Unit Wt.-Ave. Wt. (± 0.1 lb.)
A1	56.05	45.3	38970	38450	26.4
A2	53.15	45.1	37110	36560	26.4
A3	61.10	44.8	42490	41540	26.4
B1	61.60	45.1	42700	41970	26.3
B2	61.30	45.0	42420	41780	26.3
B3	61.55	45.0	42700	42050	26.3
C1	64.30	44.8	44540	43560	26.3
C2	63.45	44.9	43620	43130	26.2
C3	64.20	44.8	44440	43510	26.3

Table 2 Comparison of the Modal Frequencies for the Three Fabrication Methods

Mode Shape Description	Average Frequencies "A" beams	Average Frequencies "B" beams	Average Frequencies "C" beams
Fundamental Twisting	24.0	24.2	24.3
Web Bending	52.2	31.8	33.6
Fund. H-Beam Bending	133.	157.	154.
Fund. I-Beam Bending	166.	180.	178.

Table 3 Comparison of the Average Measured Modal Frequencies with the Initial NuMAD Analysis

Mode Shape Description	NuMAD Analysis	A Beam Ave.		B Beam Ave.		C Beam Ave.	
	Freq. (Hz.)	Freq. (Hz.)	Diff.* %	Freq. (Hz.)	Diff. %	Freq. (Hz.)	Diff. %
Fundamental Twisting	17.3	24.0	28	24.2	29	24.3	29
Web Bending	36.7	52.2	30	31.8	-15	33.6	-9
Fundamental H-Beam Bending	134	133	-1	157	15	154	13
Fundamental I-Beam Bending	155	166	7	180	14	178	13

*Diff=(test frequency-analysis frequency)/test frequency

Discussion

Mass Properties

Table 1 shows the results of the mass properties tests. Examining Table 1, the weights, CG's, and mass moment of inertia have been listed for the nine beams, breaking them into the groups of

three fabrication techniques (A, B, & C). The uncertainty of the measurements have been included in the table so that one can determine significant differences between the beams. The second column reveals the weight of the beams, and they are fairly consistent except for A-type beams which vary significantly. Note there are significant differences between the average weight of the A, B, and C beam types. The sixth and seventh columns show the radii of gyration, which removes the effects of mass differences. Here we see tremendous consistency. Note that the radius of gyration for I_{xx} is always greater than that for I_{yy} , as it should be due to the I-beam cross-section. The eighth and ninth columns show the CG's for the x and y axes. Generally they are very close to zero, except for beam C2 which has a significant offset. This beam was checked twice, and the results were repeatable. The last columns show the ratio of I_{xx} to I_{yy} and the difference in the weight of the particular beam as compared to the average for its beam type. If all the beams were identical in construction, then (I_{xx}/I_{yy}) would all be the same. This ratio tends to reflect the amount of material that is in the flanges as compared to the web, because it's the web and flanges that causes I_{xx} and I_{yy} to be different. Note that for beam A3 the ratio is significantly higher than that for A1 or A2; also A3 weighed 4.3 pounds more than the average A beam. This additional 4.3 pounds of material somehow reflects a difference in the beam fabrication. Note also beam C2 has a lower ratio than C1 or C3, and its mass is lower as well.

The larger variations for the A beams is not a surprise since the hand lay-up process does not have a means to uniformly control fiber volume. The laminator applies the resin and works it into the fabric with

Figure 3 Schematic of the noodle region.

Figure 4 Web bending.

Figure 5 Fundamental twisting.

various tools and thus consolidation is dependent on his/her technique and skill. Furthermore, there are typically no finished edges making trimming a necessity; offering one more source of variation. The C beams are approximately 4% heavier than the B beams, probably due to the adhesive used for bonding.

All of the beams were intended to have the same dimensions and laminate schedule. A laminate schedule was agreed on prior to the start of the project and it was to be used to produce the A beams. The parts of one of these beams (i.e. flanges and web) were used to size the patterns to make the RTM mold. Hand lay-up cannot attain a very high fiber volume, resulting in thicker parts for a given laminate. In theory the resulting RTM mold should produce beams with the same fiber volume as the A beams. However, at this lower fiber volume the flow aspect of the RTM process caused "fiberwash" (fiber displacement). As seen in the table, the weights vary between each of the groups which is attributable to changes in the beam reinforcement schedules that became necessary to combat the "fiberwash". Attempts to RTM beams using the hand lay-up schedule resulted in poorly distributed and significantly misaligned fibers. In the B and C beams, additional plies were added to the flanges, as well as adding more glass to the noodle region to help direct the flow of resin. The noodles are conduits created when the plies of fabric are folded to form the "c-channels" of the web. This allows the resin to flow unimpeded, the length of the beam resulting in uneven and multiple flow fronts which in turn can trap air and produce dry spots. It is these additions that explain the differences in weight between the groups. See the appendix for construction details.

As stated earlier, the radii of gyration and the centers of gravity are very consistent for all three groups of beams. These properties are essentially geometric. This consistency is only significant in that it shows that all three manufacturing methods produced very similar beams after accounting for mass differences.

Modal Test Results

Sandia National Laboratories conducted modal tests on all nine beams to determine several of the

lowest natural frequencies. For the test set-up the beams were hung from a structure by bungy chords in a free-free fashion.

Accelerometers were attached along the beams and connected to a data acquisition system. When the beams were excited by a

hammer blow, the accelerations were recorded. Subsequent data analysis resulted in natural frequencies, mode shapes and damping levels (which are not reported here). The modal shapes (see figures) of primary interest were fundamental twisting, web bending, fundamental H-beam bending (edgewise), and fundamental I-beam bending (flapwise). The H-beam and I-beam modes are of special interest because they represent the edgewise and lead-lag modes that are of significant importance in wind turbine blade performance. Table 3 shows the average

Figure 6 Fundamental H-beam bending (edgewise).

frequencies for each mode for each beam group. Beams B and C have almost identical frequencies for these four modes. Beams A are lower in frequency for the H-beam and I-beam bending- this is due to the lower fiber content. The web bending is substantially higher for the A beams. This is due to the increased thickness of the web for the hand laid-up beams.

In fundamental twisting the frequencies were consistent between the three groups of beams.

NuMAD Results

In addition to the comparisons of different manufacturing methods, a primary objective of the program was to verify SNL's NuMAD design tool. A model using the hand lay-up design dimensions was developed with NuMAD and the results compared to the data collected from each of the beam types. These results in Table 4 indicate that the model closely predicted the H and I-beam bending for the case of the hand lay-up beams. It underpredicted the web bending and fundamental twisting mode for the A beams. This indicates that the web was modeled too softly. A follow-on effort of updating the model with as-built properties and creating a separate model for each beam set will likely result in even better comparisons..

Conclusions

The results of this study show that there is very high consistency among structural properties for the RTM'd beams. There is more scatter for the hand-laid-up beams; this is due to the dependence upon the fabricator. The higher fiber content of the B and C beams produced higher I_{xx} and I_{yy} values as well as higher edgewise and flapwise natural frequencies. The difference, however, may not be enough to justify the higher cost of the RTM process. This suggests that even though less sophisticated, hand lay-up is capable of producing structurally sound parts. However, the advantage of the RTM process is seen in the uniformity of the B and C beams.

The choice of process really boils down to a matter of economics. The typical argument that arises when discussing open molding and RTM centers around tooling costs and labor costs. Clearly hand lay-up has the advantage when it comes to the cost of tooling. Even though more molds may be required to make a given part, the complexity and the structural requirements compared to RTM tooling is much lower and therefore less expensive. However, as can be seen from the physical properties of the beams made by each of the processes, there is a much more uniform result from the RTM processes. It is easily seen that in any structure that requires uniformity or balance (i.e. wind turbine blades) it would be necessary to spend some considerable effort to match the hand lay-up blades to each other. For low production rates this may be acceptable, but the time and effort necessary to rework large structures or higher numbers of parts could easily offset the money saved on molds.

Figure 7 Fundamental I-beam bending (flapwise).

In reality, RTM is probably not the best process to use for the production of utility grade wind turbines since the tooling would be quite complex and expensive. However, closed molding for the production of large parts is going to become very important when the MACT (Maximum Achievable Control Technologies) takes effect. This will put stiff limitations on the amount of styrene that can be emitted, which will cause open molders to develop costly mitigation programs or adapt to other processes such as infusion methods and vacuum bagging. These intermediate processes offer closed molding to the open molders without necessitating all new tooling. In addition, higher fiber volumes and more uniform laminates are added bonuses with these processes versus hand lay-up. However, converting equipment, training a work force in new methods, and increased consumables will all come at a cost.

The use of NuMAD looks quite promising as a blade design tool. In this initial outing it was able to closely predict the key modal frequencies for a hand laid-up I-beam. Even though it proved to be somewhat insensitive to the absence of construction details, it is expected that with the inclusion of bondlines and reinforcement schedules that the accuracy of the model would improve.

The beam configuration used in this study was readily produced by both RTM and hand lay-up. However, in producing more complex shapes certain processes might not be suitable, requiring the designer to understand the capabilities and limitations of the different processes. This is where modeling tools like NuMAD will prove invaluable. Designers will be able to readily analyze geometric options that can be readily produced by a given process.

Appendix

The following section describes the dimensions and materials used in each of the test cases.

General Construction Notes

Fabric is defined as either zero degree fabric or ± 45 degree fabric. The zero degree fabric is Knytex A130, a unidirectional fiberglass fabric. The phrase "zero degree" means that all of the fibers run the length of the I-beam. The ± 45 degree fabric is Knytex DB120, a bi-axial fabric made from two separate plies stitched together. The phrase " ± 45 degree" means that in one ply of the fabric half of the fibers form a positive 45 degree angle with the zero degree fabric and half of the fibers form a negative 45 degree angle with the zero degree fabric. For all parts the resin system was Interplastic Cor-63-AX-051 unsaturated polyester resin. In the cases where bonding was employed ITW Plexus® M-325 methacrylate adhesive was used.

Specimen Dimensions and Lay-up Schedules

All dimensions in inches.

Average dimensions for the hand lay-up beams. See figure 9 for references.

- A. Beam depth averages 8.00.
- B. Flange width averages 9.00.
- C. Flange thickness averages 0.42.
- D. Web thickness averages 0.20.
- E. Subflange width averages 4.50.
- F. Subflange thickness averages 0.13 (composite averages 0.07, bondline averages 0.06. Detail shown in page 7) at the edge and then tapers thicker towards the center at an angle of 2 degrees. The edge has a 45 degree chamfer.
- G. Web fillet radius averages 0.25
- H. I-beam length for all parts equals 92.00.

Figure 8 Beam parts.

Figure 9 Beam dimension references.

Average dimensions for the RTM beams.

- A. Beam depth averages 8.19.
- B. Flange width averages 9.00.
- C. Flange thickness averages 0.50 at the edges and then tapers thicker towards the web at 1 degree.
- D. Web thickness averages 0.20.
- E. Sub flange width averages 4.50.
- F. Sub flange thickness averages 0.13 at the edge and tapers thicker towards the center at 2 degrees. The edges have a 45 degree chamfer.
- G. Web fillet radius averages 0.25.

I-beam length averages 92.

Hand lay-up lamnate schedule

Each preform of the low fiber volume parts can be thought of in the four pieces (figure 10), two flanges and two half webs. The hand lay-up beams were made by adhesively joining these four parts with bondlines approximately 0.06 thick. The lay-up schedule for each flange is $[\pm 45/0_4/\pm 45/0_4/\pm 45]_s$ (the s indicates that this schedule is symmetric about the s, in other words the entire lay-up is $[\pm 45/0_4/\pm 45/0_4/\pm 45/\pm 45/0_4/\pm 45/0_4/\pm 45]$). In each of the flanges the center 6 inches was cut out on the 5th and 18th plies. This ply drop is shown in drawing 2.5. For each of the half webs the lay-up was $[\pm 45/0]_s$. The dimensions for the hand lay-up beams are different from the RTM beams due to bondlines and method of manufacture.

Laminate schedule for the RTM and the RTM/bonded beams

Each preform of the high fiber volume parts (RTM and RTM/bonded beams) can be thought of in the six pieces (figure 12), two flanges, two noodles and two half webs. The lay-up schedule for the flanges is $[\pm 45/0_6/\pm 45/0_6/\pm 45]_s$. In each of the flanges the center 6 inches was dropped on the 7th and 24th plies. This is shown in figure 11. For each of the half webs the lay-up was

Figure 10 Bondline locations for the hand lay-up beams.

Figure 11 Ply drop.

$[\pm 45/0]_s$. For each of the noodles the lay-up was $[0_5]$.

RTM /bonded beam manufacture

In order to create the RTM bonded beams the entire lay-up was placed in the mold with pieces of plastic between the web/subflange lay-up (web and noodle lay-ups) and the flange lay-up. This kept the flanges from bonding to the web/subflange during processing. The finished web/subflange part was then bonded to the two flanges. The thickness of the adhesive bondlines between the parts is approximately 0.06. RTM bonded parts and adhesive layers are shown in figure 13. To account for the additional thickness of the adhesive the dimensions of the other parts must decrease slightly.

Figure 12 Parts of the RTM and RTM/ bonded beams.

Figure 13 Bondlines for RTM/bonded beams.

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