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INTRODUCTION TO LOW COST MANUFACTURING OF COMPOSITE LAMINATES

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INTRODUCTION:

This new laboratory experiment in MEEN 300 Experimental Methods in Engineering in undergraduate mechanical engineering curriculum, presents new low cost fabrication process known as Vacuum Assisted resin Transfer Molding (VARTM) to manufacture composite laminates. This experiment emphasizes mechanical engineering concepts such as ability to apply knowledge of science; ability to design a process to meet desired needs; knowledge of contemporary issues; ability to solve engineering problems which are listed in course content evaluation form of ABET (American Board of Engineering and Technology). The experiment is divided into three laboratory sessions. Each session runs approximately one hour and fifty minutes.

LABORATORY SESSION 1:

In this session students are introduced to composite materials and different manufacturing techniques. The VARTM process is discussed in detail.

Overview of Composites

A composite material is made of two or more chemically different materials with a distinct interface between them. The individual constituents maintain their own properties. However, the combination of materials develops a material that has properties and characteristics different than those of the original constituents. The properties of the composite material depend on the properties and geometry of the constituent materials and the distribution of the phases.

The composites are becoming popular in industry due to their high specific strength and high specific modulus. They have improved corrosion and wear resistance, low thermal conductivity, and increased fatigue life. The endurance limit of toughened composites can be much higher than for steel and aluminum. Composites have certain disadvantages: they are expensive; there is lack of high productivity manufacturing methods and clear-cut design rules. Composites have enormous number of applications in the aerospace, automotive, construction, sports and medical industry.

Constituent materials in the composite are fibers and matrix. Fibers are major load carrying components. Matrix transfers stresses between the fibers, provides barrier against adverse environments, protects the surface from abrasion and provides lateral support. The different fibers used are glass, carbon, aramid, boron and alumina.

There are mainly four different types of composite materials depending upon the matrix used. They are Polymer Matrix Composite (PMC), Metal Matrix Composite (MMC) and Ceramic Matrix Composite (CMC) and Carbon/Carbon composites. PMC's are suitable for relatively low temperature applications. Polymer matrix is called resin. The popular resins are polyester, vinyl ester, cyanate ester and epoxy [1].

There are various forms of fiber reinforcements in the composites like unidirectional, multidirectional, woven, knitted, braided and stitched. Each of these forms has certain advantages. There are various methods used in manufacturing of composites.

METHODS USED IN MANUFACTURING OF COMPOSITES:

There are various methods that are used to manufacture the composite laminates [2]. These methods include wet lay-up, prepreg method, autoclave processing, filament winding, pultrusion, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM). The brief description of these methods is given in the following section. This section also presents merits and demerits of these methods. In addition this section also explains VARTM process in detail.

Wet lay-up method

This is one of the oldest methods that involve laying the dry reinforcement (most often a fabric or a mat) into the mold and applying the resin. The wet composite is rolled by hand to evenly distribute the resin and thereby removing the air pockets. Another layer of reinforcement is laid on top, after which more catalyzed resin is poured, brushed, or sprayed over the reinforcement. This sequence is repeated until the desired thickness is reached. The layered structure is then allowed to harden (cure). This method is conceptually simple, does not require special handling of wet fabrics, and allows the resin to be applied only in the mold, thus helping to maintain a neat surrounding area. But it is very difficult to maintain product uniformity. Voids are common problem. Mechanical properties are low compared to other composite manufacturing methods.

Prepreg method

It can be viewed as an extension of the wet lay-up method. The fabrics are usually a unidirectional tape or a woven fabric, impregnated with initiated resin, partially cured and then rolled up for shipment. But the prepreg method requires a vacuum bagging and is often autoclaved. The resin distribution in the prepreg method is usually very even and is controlled during tape manufacture. But this method is slow and labor intensive compared to the automated methods and has a potential high rejection rate because of faulty bagging procedures.

Autoclave processing

The autoclave consists of a vessel that can be pressurized internally up to 5 bar (~ 75 psi) and then the contents are heated. The vessel must be sufficiently large to accommodate large components. They are pressurized with gas, usually nitrogen that is circulated through the heaters to maintain a uniform temperature throughout the vessel. The basic feedstock for the process is preimpregnated warp sheets or prepreg. A raw laminate along with a bleeder pack is placed under a nonstick gas permeable film and then that is followed by a breather pack. This whole unit is kept in a vacuum bag to maintain vacuum pressure on the laminate. The outer membrane is pressed against the laminate by atmospheric pressure. The whole unit is then placed in the autoclave where the bagged molding may be reconnected with the evacuation system to maintain the vacuum. The autoclave is pressurized which augments the consolidated pressure.

The temperature of the autoclave is reduced when the resin is adequately cured. The main aim of this process is to manufacture the laminate with uniform thickness and to ensure minimum porosity. The major difficulty in the autoclave process is the high capitalization cost and the stringent pressure code regulations.

Filament winding

A continuous tape of fibers impregnated with resin is wrapped over a mandrel to form a part. Successive layers are added at the same or different winding angles until the required thickness is attained. The mandrel or the application head can rotate to give the fiber coverage over the mandrel. Cylindrical parts can be manufactured with filament winding procedure. The pressure vessels, fuel and water tanks for storage and transportation and pipes can be manufactured by this method. Use of pressure during the cure is another method of making non-cylindrical parts. The process can be used to make parts with strength in several directions. This process can easily manufacture parts with high-pressure ratings. The difficulty of this process is programming the winding.

Pultrusion

Continuous reinforcement fibers are impregnated with resin and passed through a die. Then the part is cured and available for use. As this is a continuous process the production rate is very high. The cross section of the part has to be constant for using this process. But the thickness of the part produced can be varied by having a movable dies. The part usually gels in the die itself and is then fully cured when the part travels through a curing oven. The main advantage of this process is the high usage of fabrication material. But the problem can come when the resin or fibers accumulate and build up at the die opening and the equipment can jam. Voids can also result if the dies are run with too much opening for the fiber volume.

Resin transfer molding (RTM)

In this process a mold is loaded with the reinforcement material and then it is closed. The resin is injected into it. The mold with the preform is often put under vacuum so that the vacuum removes all the entrapped air in the preform and speeds up the RTM process. Typically, the resin is injected at the center of the top surface of the mold and the flow of resin occurs radially outwards till it reaches the vent lines. In this process the flow of the resin occurs in the plane as well as in the transverse direction of the preform. The fiber architecture, permeability of the preform and the fabric crimps has an influence on the wetting of the fabric.

Vacuum assisted resin transfer molding (VARTM)

VARTM is a single sided tooling process where the dry preform is placed into the tool and vacuum bagged in conjunction with resin distribution and vacuum distribution lines. A low viscosity resin is drawn into the preform through the aid of vacuum. In VARTM process, the flow of resin occurs in plane as well as in the transverse directions to the preform. The permeability of the preform, fiber architecture and fabric crimp has an influence on the wetting of the fabric.

This process has certain advantages as listed below.

- Relatively low cost for high volume production
- Simple low cost tooling
- Very large and complex parts are practical
- High fiber volume fraction than hand lay-up
- On site manufacturing and repairing is possible
- Reduced environmental concerns than hand lay-up as it is closed system

This process is being currently used in many of the applications in the general aviation industry, defense sector and in the transport industry. The schematic for the fabrication is shown in the Figure 1 and is discussed in detail in the following section.

VACUUM ASSISTED RESIN TRANSFER MOLDING

Material system

In the present study plain-woven carbon fabric in conjunction with the epoxy vinyl ester is used to fabricate the composite panels. This plain-woven fabric (3K-70-P) is supplied by BGF Industries, Inc. [3]. The carbon fiber used in the fabric is AS4™ manufactured by Hexcel Corporation [4]. The resin used is Derakane™ Momentum™ 411-350 epoxy vinyl ester supplied by The Dow Chemical Company, Inc. [5]. The viscosity of the resin is 350 cps at 77^0F temperature. This is suitable to do VARTM at room temperature.

Material Cost:

1. Glass fabric plain weave $300.00 per roll (approximately $0.2 per sq. ft.). Each roll is 300 ft. long and 5 ft. in width.
2. Vinyl ester resin 5 gallon for $50.00 (approximately $2.3 per Kg.) 5 gallon ~ 21.5 Kg
3. Other related fabrics for VATRM approximately $10.00 per panel of size 2' x 2'
   Eight layers 2' x 2' glass composite panel consumes approximately 1 Kg resin. Thus the total cost will be $6.4 for glass fabric + $2.30 for resin + $10.00 for other fabrics = $18.70 per panel.

The VARTM process involves the following steps [6]:

1. Mold preparation and fabric lay up.
2. Sealing off the mold and running vacuum.
3. Resin preparation and degassing.
4. Resin impregnation.
5. Post cure of fabricated panels.

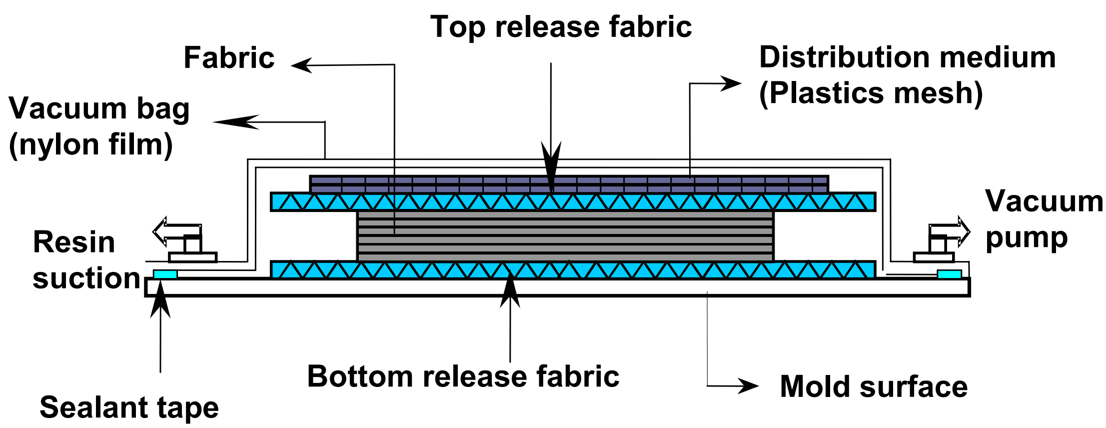

Figure 1. Schematic for the Fabrication of the Composite Panel

Mold preparation and fabric lay up:

1. Mold Surface: The mold used for the fabrication is a metal plate. The metal plate (usually aluminum) has a provision of heating while the fabrication is in progress. The heating is not required for 411-350 resin as its viscosity is 350 cps at 77^0F.

2. Mold Surface Protection: The 2 mil (25micron) polyester film is used to protect the mold surface. This film facilitates the easy removal of the panel from the mold surface after the fabrication process is over.

3. Bottom Release Fabric: This is a porous release material which leaves an impression on the part suitable for secondary adhesive bonding (like tabbing) without further surface preparation.

4. Fabric Lay-up: The size of the composite panel is 2’ x 2’. There are 8 layers or plies of plain-woven fabric stacked one above the other. Such layered composite is also called laminate.

5. Top Release Fabric: This is a porous release material which facilitates the resin flow through and leaves an impression on the part suitable for secondary bonding without further surface preparation.

6. Distribution Medium: The distribution medium is a mesh, laid on top of the top release fabric. This helps to maintain an even distribution of resin on the top of the panel and also facilitates the flow of resin through the thickness of the panel

7. Resin and Vacuum Distribution Line: Spirally cut HDPE tubes are used for this purpose. These lines are laid above the distribution media at two sides of the fabric lay-up and go along the length. The resin line is closed at one end and connected to resin supply through the peristaltic pump at other end. The vacuum line is closed at one end and connected to vacuum pump through the vacuum gage. It is standard practice to place the closed ends of these lines opposite to each other.

8. Breather: The breather material acts as a distributor medium for the air and escaping volatiles and gasses. It is placed over the resin distribution media and resin and vacuum lines. It also acts as a buffer between the vacuum bag wrinkles and part surface. It is a highly porous material and mostly made of fiberglass, polyester felt and cotton. The use of breather is dependent on the fabric-resin system and the thickness of the panel.

9. Vacuum Bag: 2mil (25micron) Nylon film is used as vacuum bag. This film is placed all over the mold area and is sealed firmly using special sealant tape. The sealant seals off the vacuum bag and helps to maintain a uniform vacuum throughout the molding process.

10. Peristaltic Pump: This pump delivers fixed amount of resin in the mold in particular time duration. It assures the in-plane and through-the- thickness soaking of the fabric in the resin. The quantity of resin (say cc/min) is dependent on the pump speed. The pump speed again is function of fabric-resin system and thickness of the panel. The speed is decided according to the previous experience. Additionally, ON-OFF timer is connected to pump. It keeps pump running for certain period and shuts it off for certain period. In the present study, equal cycle of 30 seconds

for ON-OFF timer is used based on the previous experience with the resin and woven carbon fabric.

11. Vacuum Gage: This gage monitors the vacuum in the entire vacuum bagging and resin impregnation process. It also detects any leaks in the bagging. The vacuum less than 0.5 torr was maintained while bagging. Figures 2 and 3 shows vacuum bagging process.

Sealing off the mold and running vacuum

Once all the fabrics and other relevant materials are laid over in particular sequence, the entire mold is sealed with sealant and vacuum bag. Then the vacuum pump is used to maintain lowest possible vacuum throughout the process.

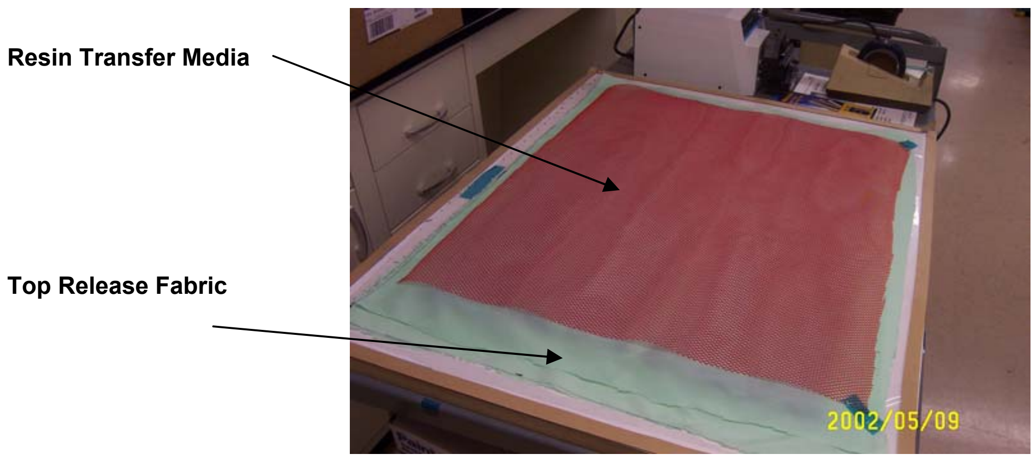

Figure 2. Vacuum Bagging

Bag leaks are the most common problems observed during the fabrication process. This may be due to damage of the nylon film before cure. Nylon film is hygroscopic and subjected to moisture changes due to changes in the moisture level in the surrounding environment. Dry and brittle film can cause cracking when it is handled too much. There is also a possibility of leaks at the nylon material and sealant interface. Once the leaks have been removed and the vacuum bag completely sealed, the vacuum pump is kept running for at least for 12 hrs to achieve a good vacuum in the bag.

Pleating is an important step involved in the fabrication of the panel. The pleats help to avoid air pockets in the panel. The pleats go along the edges of the fabric lay-up. The pleats help the mold to direct the air, if entering the mold through any of the leaks, to go through them and then subsequently through the vacuum line. At the end of the first laboratory session, the composite panel is vacuum bagged and lowest possible vacuum is maintained in the bag.

LABORATORY SESSION 2:

In the second laboratory session, students perform resin preparation and degassing, resin impregnation operations. Details of these operations are provided below:

Resin preparation and degassing

The resin is mixed with catalyst, promoter and gel time retarder in the precalculated percentage suggested by the resin manufacturer. The following are the proportions of resin and the ingredients [5]:

- Resin – Derakane Momentum 411-350 Epoxy Vinyl Ester
- Cobalt Napthenate-6% - 0.02 to 0.13% by weight
- CoNap6% is <u>promoter</u> in chemical reaction
- 2,4-Pentanedione – 0.015 to 0.0175% by weight
  2, 4-P is gel time <u>extender </u>(retarder)
- Methylethylketone Peroxide – 1.0 to 1.5% by weight
  MEKP is <u>catalyst </u>in chemical process

Catalyst is the substance that promotes or controls curing of the resin without being consumed in the reaction. Promoter is chemical additive that accelerates the curing process. Curing of theroset resin is exothermic reaction. It dissipates the heat to the surroundings. Gel time retarder is chemical additive, which absorbs free radicals once exothermic reaction has started. It retards curing process, so that molding will be complete before resin gels.

Before adding the resin to the mold, it has to be free of all the air pockets that may cause voids if they enter the mold. For this purpose, the resin is kept in a cylinder that maintains a vacuum of approximately 5 torr. This enables the suction of all the gases that have been trapped into the resin.

Resin impregnation

Once the resin is ready it is injected into the mold at a very slow rate. The flow of resin is controlled with the help of peristaltic pump in such a way that it is allowed to flow in the distribution medium for some distance and then the resin inlet is shut off to enable the resin go through the thickness. This cycle is repeated until the whole panel is soaked in resin. Figure 3 shows the resin impregnation setup. It took approximately 50 minutes of flow time for complete soaking of the panel. The panel was kept in the mold for 24 hours at the room temperature for curing which is called green cure.

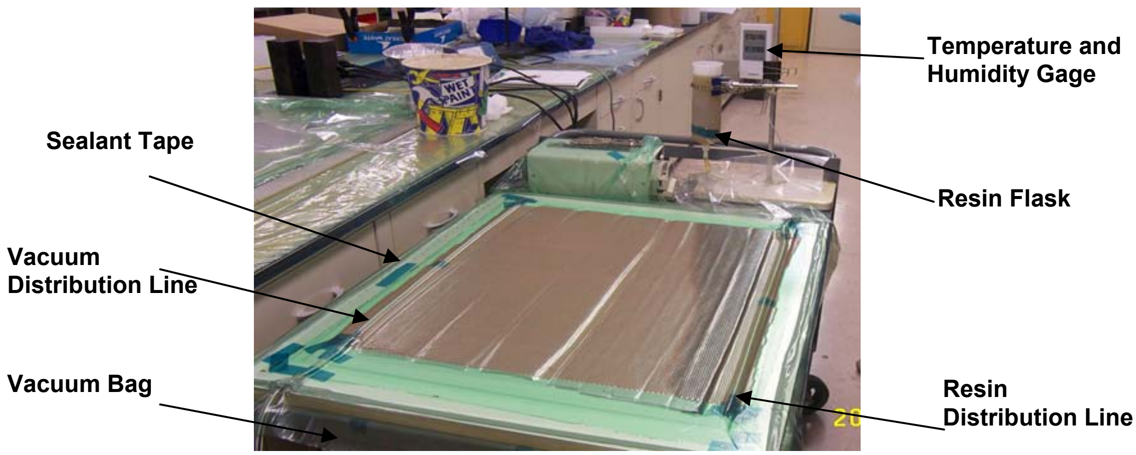

Figure 3. Resin Impregnation

LABORATORY SESSION 3:

Before students come for the third laboratory session, at the end of second laboratory session (after green cure), the panel is removed from the mold and kept in the oven at 180^0 F for 8 hours for post cure.

In the third laboratory session, student use density method to calculate the fiber volume fraction of the cured panel [1]. Details of the density method are given below.

The density of composite panel, post cured resin and carbon fibers were found by using the techniques explained by ASTM D792-86. The Figure 4 shows the experimental set-up. The expression for fiber volume fraction based on the density of the composite is:

$$V_f = \frac{\rho_c - \rho_m}{\rho_f - \rho_m}$$ where,

ρ_f, ρ_m and ρ_c = densities of fiber, matrix and composite.

Figure 4. Density Measurement

These fabricated panels later can be cut into the tension test coupons as suggested by ASTM 3039. These tensile coupons can be tested by same group of students in the Strength of Materials Laboratory.

Deliverables

At the end of three laboratory sessions, following deliverables are expected from the students:

1. Good quality composite panel free from any defects such as random air pockets at the surface, dry fibers, large variation in thickness.
2. The batch of student will write laboratory report, which will have following details.

- Process parameters during manufacturing which are temperature of mold, temperature of resin before and after mixing, temperature after degassing, vacuum in the bag before and during impregnation, vacuum during degassing, time for degassing, time for impregnation, time for green cure and time for post cure. Students are also encouraged to note unusual things occurring during composite panel manufacturing.

- Overall fiber volume fraction in the composite panel.

This new experiment generated lot of interest in undergraduate students to perform the research in the general area of manufacturing of composites. This laboratory experiment has yet to be assessed. It is planned to assess this laboratory experiment upon class completion this year.

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Biography

DR. AJIT D.KELKAR is a Professor of Mechanical Engineering at North Carolina A&T State University. His research interests include manufacturing of composite materials, finite element modeling, fracture mechanics, high temperature materials, ceramics and composites. Specifically, his work has included the low cost manufacturing of composite materials, damage characterization of thin and thick composite laminates subjected to low velocity impact loadings, three dimensional finite element micro mechanics modeling of composites, modeling of textile composites, geometrically nonlinear plate and membrane problems, modeling of ceramic composites, fracture toughness studies of high strength materials, finite element modeling of offset car crash simulations. He is the member of several professional societies including ASME, AIAA, and ASEE.

JITENDRA S. TATE is a doctoral student at North Carolina A&T State University. Currently, he is researching on Federal Aviation Administration's project "Performance Evaluation and Modeling of Braided Composites". His research interests include low cost manufacturing of composites, fatigue behavior of composites, finite element modeling, CADD, mechanical event simulations, and statistical analysis. He is the student member of ASME.

RONNIE BOLICK is Research Projects Manager of the Mechanical Engineering Laboratory, a Researcher and PhD candidate at North Carolina A&T State University. His research areas have been in embedded fiber optic sensors, fatigue and durability studies for the automotive industry for replacement of mechanical fasteners, manufacturing of composite materials, high temperature materials, both ceramics and composites and low cost manufacturing process development for composite laminates. He has extensive experience in testing and data acquisition ranging from: low velocity impact studies, stress and strain measurement using laser displacement sensors, strain gauges and load cells, and component life/endurance limit prediction. He is a member of several professional societies including ASEE, ISA and SAE.