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Design and Manufacture of Composite Prototypes*

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This paper details the development and implementation of a course on the design and manufacture of composite prototypes. The course is taught as a design elective resulting in student groups designing and demonstrating a manufacturing process to fabricate an actual composite prototype. The students are responsible for determining their own metrics in evaluating their manufacturing process. The paper identifies key learning points, and the course syllabus demonstrates the implementation of the learning kernels. Projects from the past seven years are itemized, and lessons learned are drawn from the cumulative experience. The course was developed at the University of Maryland to instruct undergraduate students about the manufacturing of composite structures by providing a hands-on design experience of a real-life composite prototype. The students are formed into teams and are responsible for developing a manufacturing process to produce a composite component. The students demonstrate the feasibility of their process by producing a prototype. The students conduct a preliminary marketing analysis and must conclude whether or not further pursuit of their manufacturing process is warranted. The course enhances the undergraduate design experience while training students in the science of composite manufacturing.

INTRODUCTION

THE USE OF composite materials provides the designer with great flexibility with which to meet part performance requirements. Even after a composite material has been selected, the design must still address the microstructure of the component. The type of reinforcement—continuous fiber, short fiber, whiskers, chopped roving, woven or braided fabrics and preforms—and its orientation greatly affect the performance of the component. Indeed, the ability to tailor a component increases its range of functionality as well as the complexity of the design. For example, the skin of an aircraft wing near its root may involve a hundred plies. Although the plies may all be the same material in the same format, it is the collective orientation of the plies that yields the desired extensional, flexural, and torsional stiffnesses. The design at the microscale is more important than simply the orientation of the reinforcement. Failure mechanisms such as delamination, fiber microbuckling, fiber kinking, transverse cracking all occur on the microscale and are sensitive to manufacturing variations.

Just as the design must address the microstructure, the design must also address the macroscale. Composite materials can be formed into near-net shapes. Construction of components that often require many individual parts can be made in one step. Stiffeners can be staged, cocured, precured and integrated, or bonded. Sandwich construction with honeycomb or foam results in lightweight alternatives to discretely stiffened panels. As the part count is reduced, the complexity of the components is increased. The structural design may be as extensive as the aft fuselage of the V-22 Osprey (built by Boeing) or as simple as composite dimensional lumber made from recycled plastics.

Designing composites for structural performance initially involves meeting a set of desired performance specifications (typically weight in aerospace applications) at a minimum cost. When one introduces manufacturing costs as a constraint in addition to structural performance, the cost optimization process becomes more complicated. Designing composites for manufacturing is more involved than designing the part to be fabricated within specified dimensional tolerances. Indeed, the desired orientations of the reinforcement must be met with special attention paid to the presence and effects of anomalies or defects. Moreover, the prospect of large, integrated structures necessitates designing the manufacturing process concurrently with the component.

The material devoted in textbooks that specialize in composite structures demonstrates an indication of the difficulty in addressing this rather important issue. Since the 1975 release of *Mechanics of Composite Materials* by R. M. Jones, there have been many texts dealing with the mechanics of composite materials. A small number of these texts address manufacturing aspects along with the mechanics. A limited few texts are available with manufacturing or integrated design of composite structures as their focal point.

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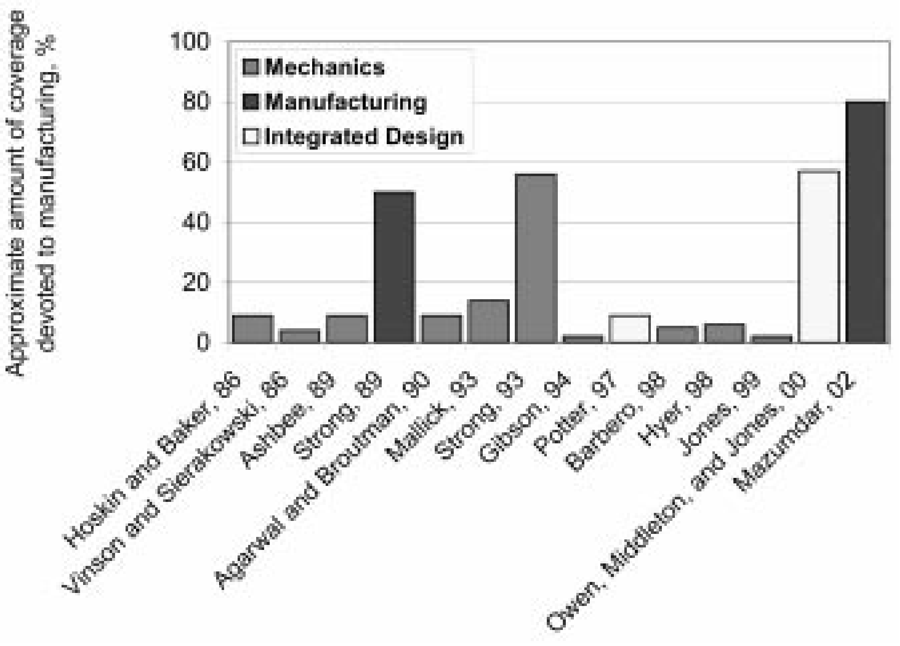

Fig. 1. Composite manufacturing in textbooks.

Those texts were surveyed to determine the amount of content devoted to manufacturing and are placed in chronological order in Fig. 1.

Traditionally, those texts dealing with mechanics typically devote no more than 10% to manufacturing. Strong's 1993 text is the exception in that it updates much of his earlier text in manufacturing for a mechanics-based audience. In recent years integrated manufacturing texts (Potter and Owens, et al.) have been published, providing new sources. Thus, integrated manufacturing and structural design within academia is probably lagging behind structural design of composites by nearly twenty years. Although mechanics of composites is taught with regularity at most universities, manufacturing of composites is less common. Often such offerings are the result of an active research program that relies on the manufacture and testing of composite specimens (e.g., Syracuse University, MAE415 Design and Test of a Composite Hat Stiffener). The availability of manufacturing equipment is essential as well as a commitment to the science of manufacturing. Even in processing-rich academic environments such as Brigham Young University and the University of Delaware, composite manufacturing science courses focus on processing mechanics rather than a design experience in manufacturing and processing.

The course developed at the University of Maryland approaches the science of composite manufacturing by providing a design experience in prototype fabrication. This course differs from offerings at other universities through its hands-on approach to real-life articles. Based on fundamentals of design, student teams demonstrate the validity of their manufacturing process through market research and fabrication of a functional prototype.

LEARNING KERNELS

The course was originally introduced in 1990 as a course on the manufacturing of composites. The goals of the course were to train students in the composite manufacturing practice as it pertained to a research program. Although the skill set provided in the course would be of significant value to the student both externally in the composite community and within a research program, the presentation of the material would only appeal to students already involved in composites.

In 1994, the University of Maryland received a grant to include more manufacturing in its curriculum. The course, originally titled 'Manufacturing with Composites,' was renamed 'Design and Manufacture of Composite Prototypes'. Most of the material in the original course remained; however, the goals of the course were changed and the method that the material was presented was radically altered.

The objective of the current course is to have the students design a manufacturing process for a composite *widget*. The students are formed into teams and are responsible for producing a composite prototype. The students need to determine the market for the component, perform cost analyses, and work within the scheduling requirements of the laboratory. Structural tests are determined and performed to assure reasonable performance of the prototype. The restrictions in choosing the prototype is that it must be nominally no larger than 1 cubic foot and have no single obvious manufacturing method. The structure should already exist in the market place and preferentially being made out of composite materials. This allows the focus of the class to be on the manufacturing process rather than on the structural performance of the component. The students are expected at the end of the semester to provide a conclusion of whether or not the production of the component is justified based on the fabrication of the prototype.

The 3-credit-hour course is implemented by two hours of lecture and one 3-hour laboratory session each week. A weekly syllabus is provided in Table 1. Many of the lectures are devoted to covering materials and processing aspects of composite structures. For the most part, Strong's 1989 text is followed although not in the same order. Because the initial choices made by the students will be which manufacturing method to use, these are covered first (Chapter 5). Ideally the project is chosen after the first two weeks of lecture. At this point post-cure fabrication methods are covered (Chapter 6). As the semester progresses, matrix and fibers are covered (Chapters 2 and 3). The bulk of the lectures conclude with testing methods. Both destructive mechanical testing and non-destructive inspection techniques are covered (Chapter 7). Additional lectures are provided that apply to the design process (cost estimation and technical writing). Towards the end of the class, the lectures explore additional concerns of composite structures but do not necessarily apply to manufacturing aspects such as fatigue, damage tolerance, and repair. Weekly problem sets are assigned based on the lectures and the associated reading assignments.

Table 1. Abbreviated course syllabus

Week		Material	Reading
1	Lec 1	Intro, design overview	Ch 1, 9
2	Lec 1	Manufacturing I	Ch 5
	Lab	***Laboratory tour***	
3	Lec 1	Manufacturing II	Lab Guide
	Lec 2	Manufacturing III	
	Lab	***Cut & lay up demo***	
4	Lec 1	***Machining demo***	Ch 6
	Lec 2	Fabrication I	
	Lab	**Winder activity**	
5	Lec 1	***Bonding demo***	Notes on
	Lec 2	***Computer tools demo***	Mechanics of
	Lab	***Project Groups Meeting***	Composites
6	Lec 1	Fabrication II	Ch 2
	Lec 2	Matrix Materials I	
	Lab	Project Groups Meeting	
7	Lec 1	Matrix Materials II	
	Lec 2	*PDR*	
	Lab	Design Reports	
8	Lec 1	Reinforcement I	Ch 3
	Lec 2	*Quiz #1*	
	Lab	Project Groups Meeting	
9	Lec 1	Reinforcement II	Ch 7
	Lec 2	Testing I	ASTM
	Lab	**Hot press activity**	Standards
10	Lec 1	***Gaging demo***	
	Lec 2	Testing II	
	Lab	**Computer tools activity**	
11	Lec 1	Technical Writing I	
	Lec 2	Cost Estimation	
	Lab	Open Laboratory	
12	Lec 1	Technical Writing II	
	Lec 2	*Open discussion*	
	Lab	Open Laboratory	
13	Lec 1	*IDR*	
	Lec 2	*IDR Feedback*	
	Lab	Open Laboratory	
14	Lec 1	Fatigue and Service Life	
	Lec 2	*Quiz #2*	
	Lab	Open Laboratory	
15	Lec 1	Damage and Repair	Ch 8
	Lec 2	*Open Discussion*	
	Lab	Report Generation	
16	Lec 1	*Open Discussion*	
17		CDR	

Laboratory demonstrations (***bold italics*** in Table 1) reinforce hands-on learning skills. An initial laboratory is dedicated to touring the laboratory and acquainting the students with standard laboratory procedures and safety requirements. Demonstrations are conducted on key segments including hand lay up and vacuum bagging techniques, strain gauging, and computer tools. The bulk of the demonstrations provide a fundamental training of the student for the work force at large or, more importantly, a graduate research program. Two quizzes based on the material in the lectures and the demonstrations are administered.

Team building is encouraged through laboratory projects that make use of specific laboratory and analytical skills (**bold** in Table 1). The last portion is dedicated to written and oral communication skills (*italics* in Table 1). The student groups provide oral preliminary, intermediate, and critical design reviews. The preliminary and critical reviews are accompanied by a written document.

Ideally, the curriculum must be adjusted to meet the available resources. The availability of autoclaves, hot presses, filament winders clearly provide manufacturing alternatives. However, a suitable course could be developed around molding methods and oven curing. Resin transfer molding (RTM), vacuum-assisted RTM, and press-claves can be developed at relatively low cost to provide manufacturing alternatives. In addition, local industrial resources are often available at least for demonstration purposes.

The goal of the lectures is to provide the teams with the ability to choose among the many manufacturing techniques available for their project. The course material thus stresses the manufacturing process first and the material selection second. Often students may be forced to use a material based on its availability in the laboratory or on what materials can be obtained within a two to four week window.

Because the class is organized about the design

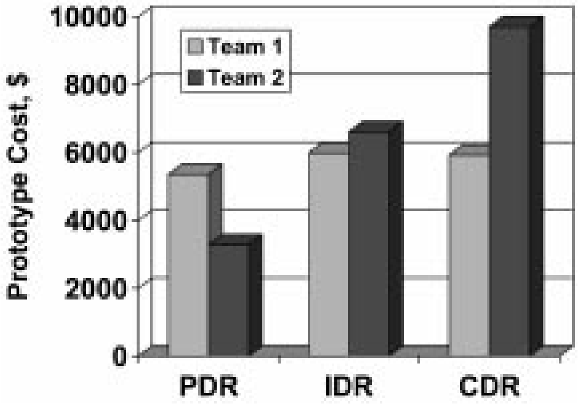

Fig. 2. Estimated prototype costs.

of a manufacturing process, the students also receive a design experience. Most graduate students have already completed such a course, seniors are concurrently taking a two-semester sequence in design, and juniors have had no design experience except for an introductory course when they were freshmen. Principles of design are not taught directly in this course, yet students are exposed to the group dynamics common to such design processes.

Several other learning kernels are contained in the course, although not part of the formal curriculum. The students begin their project often by locating competing components. They search for other manufacturers and the market price of the component. Because they are operating in a multi-user laboratory environment, the students also learn about scheduling. No equipment or facilities are set aside for their exclusive use.

The last major learning kernel is cost. So often students have no feel of what their designs cost. By performing the process they design, students get an appreciation of the amount of labor required to manufacture composite structures. Because the course is offered in a laboratory that acts as a cost center for research and local industry, equipment, labor, and material rates are well established. Students are required to forecast the cost of the prototype and production units in each of the three reviews. Often cost is the least understood aspect as is shown in Fig. 2. Competing teams provided prototype costs at each of their three reviews. Although prompted as to what costs to include, one team underestimated their total cost by a factor of three while the other team was significantly more accurate.

Table 2. Enrollment and projects

Semester	Students/Groups	Project
Spring '94	17/4 (20%)[1]	Roller blade
Spring '95	8/2 (10%)	Bicycle wheel
Spring '96	8/2 (12%)	Avionics box
Spring '97	12/3 (17%)	Helmet
Spring '98	6/2 (10%)	Connecting rod
Fall '99	9/2 (13%)	Paddle
Fall '00	6/1 (10%)	Low-cost airfoil

[1] Percentage of senior class

PROJECTS

Typically at the end of the first two or three weeks of the 15-week semester the project is chosen. Not having an assigned project at the onset allows the instructor to field suggestions from the students themselves as well as to determine any specific areas of significant interest. Although it is wise to have a default project chosen prior to the start of class, projects suggested by the student body often result in greater interest, and thus a better overall outcome.

Since 1994, seven projects have been conducted. During this time the composition of the class has varied from all undergraduates to a 50–50 mix of graduate and undergraduate students. The projects have varied greatly from sporting goods to automotive applications to aerospace components as outlined in Table 2. The number of students in the class and the number of individual groups are detailed. Because the course is in the curriculum as a senior aerospace elective, the size of the class relative to the total size of the senior class is also provided.

It is hard to sense what aspects of a given project will provide the most difficulty to the students. It is also difficult to assess the specific talents necessary to be successful in designing the manufacturing process. The first project was a roller blade. The performance requirement was that it had to be sufficiently strong to be used by a weekend athlete weighing approximately 200 lbs. The groups uniformly converted this to a 600 lb load capacity. Three of the four groups opted for molding while the group with the least background in composites and machining opted for a simple open C-channel mold and a secondary operation to cut the cured C-channel into two corresponding L-sections (middle roller blade in Fig. 3).

In the following year, a scaled bicycle wheel was chosen. The students made use of local bicycle shops and located the then two competing makers of graphite/epoxy bicycle wheels. Conveniently, each team chose a different structural configuration and overall manufacturing approach.

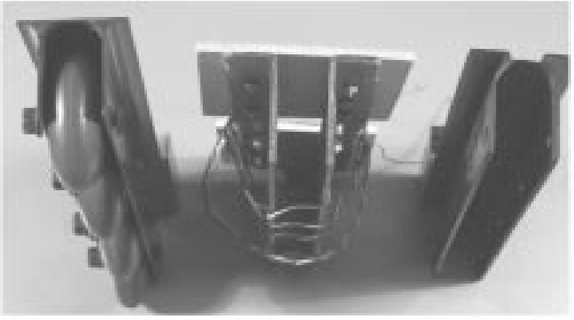

Fig. 3. Roller blade profiles.

Fig. 4. Wheel with open spokes.

Fig. 5. Wheel with solid spokes.

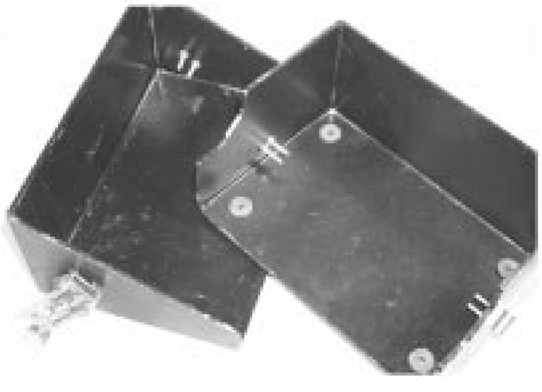

Fig. 6. Nesting avionics box.

One team manufactured an open mold and used high-density foam as additional mold pieces to manufacture the spokes (Fig. 4). The other team chose a closed mold with an elastomeric tool that expanded significantly with heat resulting in graphite/epoxy spokes wrapped around a foam core as shown in Fig. 5.

Fig. 7. Compression-molded avionics box.

Fig. 8. Motorcycle helmet.

The next year, with input from a former student working at NAVAIR, the avionics box for the Hawkeye E-2C aircraft was chosen. The box had to be easily stored and assembled in the field for logistics requirements. One team used wood molds and hand lay-up techniques resulting in two halves that nest into each other (Fig. 6). The other team chose a more aggressive path and decided to use a pelletized reinforced thermoplastic and a compression molding process. Their box offered easy access from the rear but would not pack well (Fig. 7). The team had to redesign their mold several times to account for the high pressures and had to determine the appropriate amount of material to be placed in the mold and the processing cycle.

The following year, helmets were chosen as the component, and the groups could choose to develop a helmet for any application. Two groups opted for motorcycle helmets (Fig. 8), whereas the third group opted for a ballistic military helmet (Fig. 9). The groups that opted for a motorcycle helmet found the current test

Fig. 9. Ballistic helmet.

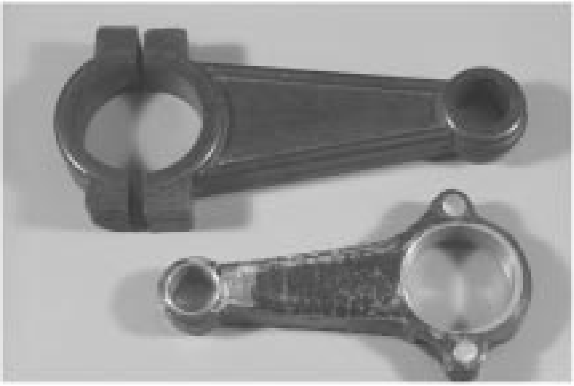

Fig. 10. Connecting rods.

standards for such helmets and chose one of the tests. The other group tested monolithic cured Kevlar/epoxy and laminates that sandwiched unimpregnated Kevlar fabric to demonstrate that their proposed laminate of a hard Kevlar/epoxy shell around multiple layers of fabric could resist a 9-mm round at a 7-m range. The double curvature of this object posed a significant challenge to all of the groups. Machining a mold was impractical due to time and cost limitations. One group used a glass bowl to form most of their mold, while the ballistic helmet group used a surplus helmet.

The component chosen the next year was a connecting rod for an internal combustion engine. Again the teams diverged with one team choosing to manufacture a low-cost, high-volume connecting rod for commercial engines and the other team choosing the high-end application of racecars (Fig. 10). The low-cost team machined a simple mold and chose to use a bulk-molding compound. They made several attempts to determine the right amount of material to be placed in the mold. The other team used a combination of foam and elastomeric tooling and pre-impregnated material.

The next year, the component chosen was a

Fig. 11. Close-mold paddles.

Fig. 12. Open-mold paddle.

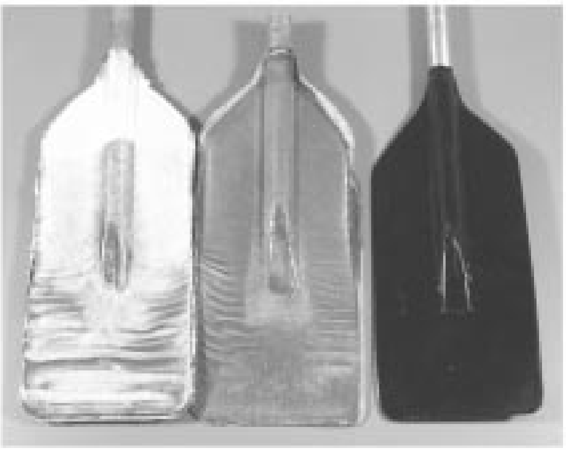

Fig. 13. Paddle evolution.

Fig. 14. Low-cost airfoil with mold.

paddle. Both teams chose a simple flat paddle common for kayak or canoe use. One team chose a closed-mold process with elastomeric tooling (Fig. 11). They had to manufacture a ½-scale version to reduce the overall cost of the aluminum mold. The other team chose an open mold process (Fig. 12). As such they were allowed to violate the 1 cubic foot requirement. Both teams opted for prefabricated shafts. The group using the closed mold process found that excessive wrinkling occurred (Fig. 13) due to the amount of material placed into the mold. The second group found how critical the applied pressure was in the success of the process.

The final project was to fabricate low-cost wings for unattended air vehicles (UAVs). The manufacturing process had to be able to produce annually 1000 to 2000 8-ft wings. No other specifications were given. Because of the aggressiveness of this task and previous experience with three-member teams, the entire class was organized as a single team with a group of NASA Goddard Space Flight Center employees acting as competition. The team concentrated on a molding process again using elastomeric tooling to provide an internal pressure inside of a closed mold (Fig. 14). To maintain some uniformity in consolidation, the team located a low-pressure sheet-molding compound and determined the appropriate method to lay up the material in the mold and then to extract the inner elastomeric tool.

After several projects, a specific skill set becomes apparent. The necessary skills within each group include machining capability, graphic representation, which includes technical drawing, dexterity when working with composite materials, and group leadership. Often a group lacks one of these necessary aspects. However, members frequently gain a level of expertise during the semester. When dividing the class into groups, a random process is used. The results of the process; however, are reviewed prior to formally dividing the class. If a group is overly filled with a specific talent it will usually be deficient in another skill.

LESSONS LEARNED

Several lessons have been learned through teaching this course. The overall restrictions of a 1 cubic foot volume and no one obvious manufacturing method are valid. It is imperative that an existing application is chosen, preferably one already being manufactured out of composite materials. This will allow the students to concentrate on manufacturing and less on the functionality of the component. Whenever the specifications of the project are reduced, the students tend to be more creative. Typically, this results in student groups opting for a version of the component that is of great interest to them and, hopefully, is the easiest to manufacture.

Teams should be on the order of three to five students. Beyond five students there is a tendency for some individual members not to contribute. This is due to either duplicity of their skill set in other members or group dynamics that tends towards smaller groups. Small groups run the risk of being unsuccessful if any one member fails to perform adequately. Often in such small groups, students will learn new skills. Never underestimate the ability of a team to complete the task at hand. In the weeks prior to the end of the semester, several teams have asked either for an extension or inquired as to the consequences of not completing the prototype. In all cases they were informed that no extensions were allowed and failure to complete the project would result in their collective failure of the class. All 16 teams to date have completed the project at the scheduled end of the class.

All designs should incorporate some element of testing. The test requirement can either be specified (e.g. to be used by a 200-lb adult) or a result of team choices and manufacturing process (e.g. impact or ballistic resistance). Testing is essential in any assessment of the prototype although one can make adjustments in performance from the prototype to final production. Changing dimensions to increase performance often does not warrant a change in the manufacturing process. An additional benefit of having testing is that it provides quantitative material (besides cost) to be included in the reviews.

Because fewer specifications often lead to greater creativity, do not limit projects to those that conceivably can be manufactured with available equipment and on-hand materials. The resourcefulness of students is surprising. They can often locate material vendors willing to donate small quantities of material and innovate a manufacturing process without high-tech equipment.

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