Session 3464

Composite Materials Instruction at the United States Naval Academy

Oscar Barton, Jr., Paul H. Miller
United States Naval Academy
Annapolis MD
21402

Abstract

Composite materials are widely becoming the material of choice for many structural and nonstructural applications. The aircraft industry for example, has used composites for wing skins and other control surfaces that provide savings in fuel consumption and weight. The marine industry incorporates thick single skin and sandwich composites for hulls, decks, risers and other primary structure, and the automotive industry uses composites to fabricate body panels, springs and drive shafts. The civil engineering community uses glass and carbon reinforced plastics in the repair of aging bridges, piers, columns and other structures vital to the nation's infrastructure and economy.

Exposure to the mechanics of composite materials and structures is usually reserved for the graduate student. However, many undergraduate institutions find the need to provide their students with experience with these advanced materials and have crafted courses to do so. This describes the motivation at the United States Naval Academy (USNA). For the same reasons as other industries, the U. S. Navy is incorporating more composite material systems into its ships, aircraft and land vehicles.

The paper describes a dual effort to expose midshipmen to composite materials and structures. Theory of composite materials is presented in a senior-elective course in the Mechanical Engineering Department. Here the midshipmen, using computational tools such as IDEAS, are taught the mechanics of composite materials including classical lamination theory(CLT). An elective course in the Naval Architecture and Ocean Engineering Department focuses on experimentation and fabrication. This senior-level course combines both theory and practice in the selection and planning of methods, materials, and equipment to fabricate, upgrade, and repair marine structures (ships and offshore structures) made of composites and traditional materials.

Introduction

The U. S. Navy is increasing its use of advanced composite materials to satisfy many program design requirements. Defining the Navy of 2020 and beyond requires the development of new classes of fighting vehicles which are more lethal, less expensive and yet do not sacrifice innocent lives or property. One example is the rapidly reconfigurable, survivable surface ship. This vehicle is envisioned to incorporate robotic and intelligent machines, a distributed power generation system and a distributed energy storage system. In addition, its mission-flexible architecture provides a vehicle to suit many combat environments. All these capabilities provide the Navy with versatility and power. Yet this vision is possible only if the enabling technologies required for production have reached a sufficient level of maturity. Among other technologies, such as expert systems and artificial intelligence, the development and use of advanced composite materials is a crucial enabling technology if the vessels are to come into being. Other concept vehicles include the stealthy modular submarine and the unmanned aerial vehicle, each requiring the use of advanced composites for development.

With the increasing presence of composite materials in military vehicles, aircrafts, and structures, it seems reasonable that the operators should these have an understanding of the behavior of these materials. The USNA supplies the Navy with a major portion of its officer corps and has provided the future officers majoring in engineering an opportunity to study the fundamentals of composite materials and mechanics.

The USNA was established in 1845 and is the premier institution producing officers for the Navy and Marine Corps. Its mission is "to develop midshipmen morally, mentally and physically and to imbue them with the highest ideals of duty, honor and loyalty in order to provide graduates who are dedicated to a career of naval service and have potential for future development in mind and character to assume the highest responsibilities of command, citizenship and government". The Academy's 4100 midshipmen are provided the opportunity to pursue studies in one of several broad areas including engineering, math, science or the social sciences. The Engineering and Weapons Division includes aerospace, electrical, mechanical, ocean, systems and weapons engineering and naval architecture, with each maintaining ABET accreditation.

The Mechanical Engineering (ME) Department provides a broad exposure in engineering. The department provides five tracks in which midshipmen can focus their selection of major elective courses to provide a theme to their undergraduate education. These tracks are energy systems, engineering mechanics, marine propulsion, materials engineering and nuclear engineering. Composite mechanics exposure is provided to those selecting the mechanics or materials track. The Naval Architecture and Ocean Engineering (NAOE) Department provides concentration in an engineering discipline with tracks in environmental, civil and underwater engineering and naval architecture. Exposure to composite materials comes through either the civil engineering or naval architecture track and addresses applications of composite materials to both shipboard and offshore structures. Students from either department can take the courses offered by another department.

Facilities

Through the Division of Engineering and Weapons Technical Services Department, both departments have use of a wide range of equipment to support its research and academic endeavors. Material testing is supported with several tensile testing fixtures including a MTS combined loading test fixture. This servo driven axial-torsion fixture can apply a maximum axial load of 55 kips with a torsional capacity of 20,000 in-lbs. Unique at the Academy is the ship structure panel tester with can apply uniaxial load along with transverse pressure to panels up to 4 by 9ft. The in-plane capacity is 480 kips and lateral pressure is limited to 40 psi. A

124-channel data acquisition panel completes the system, Figure 1. Environmental effects on composites materials are explored using the environmental test chamber, Figure 2, which includes temperature and moisture conditioning. The system meets ASTM specifications as prescribed in B117, D2247, D1757 and G85. The chamber can vary its temperature from ambient to 130^{o} F and vary relative humidity from ambient to 95% during salt/fog cycles.

Figure 1. Panel test fixture

Figure 2. Environmental chamber

Shown below is the Department's autoclave capable of maximum pressures of 250 psi and maximum temperatures of 850^{o}F. The 12ft x 4ft section is sufficient for large-scale projects such as rotor blades, wings, rudders or large panels. Students can be involved in composite material research projects including structures for naval and recreational craft.

Figure 3. End view of Autoclave

Curriculum Offerings

A brief description of two courses offered in the NAOE and ME departments is presented in this section and is further detailed later in the paper. Each course provides a complete, yet different, presentation of the utility of composite materials, and students in either department may take one or both courses. EN445, Marine Fabrication Methods presents the basic techniques used to fabricate offshore structures and structural components aboard ships. The organization of this course is a 2-2-3 format providing two lecture hours supported with two hours of lab experience each week, giving a total of three credits. Every other week the lab focus is on a different hands-on fabrication method, such as welding, riveting, bolting, machining or laminating. Lectures provide analytical background providing design methods for the specific fabrication method. The intervening labs are for quality control non-destructive and destructive testing of the components built by the students. The course begins with fabrication and forming methods for metals and other isotropic materials and progresses to reinforced concrete and composites. The students' major assignments are group projects on the fabrication of a real component in each of the three material groups. The assignments are drawn from current naval projects such as floating docks, utility boats, foundation piles and aids-to-navigation markers.

In the composites section, topics such as resin and fiber properties provide the midshipmen a method of discerning the difference in the behavior of isotropic materials and those used to construct orthotropic structures and laminates. CLT programs combined with the Tsai-Wu failure criterion are provided to the students, who also develop spreadsheets with specific criteria for bolted and bonded joints and modify them as design tools for their projects. Likewise, hand lamination is taught in lab and demonstrations of automated composite manufacturing methods provide important comparisons of manufacturing efficiency.

EM436, Introduction to Composite Mechanics, presents the theory behind composites materials and structures. Also using the 2-2-3 format, this course relies heavily upon computational tools to support the two hours of lecture. Lecture topics include generalized Hooke's Law, micro-mechanics relationships, macro-mechanics relationships, failure theories, hygro-thermal analysis and classical lamination theory. Each topic is reinforced with a computational lab project requiring a written report.

Course Discussion and Assessment

One drawback to presenting a computationally intense course is how best to perform the numerical work. For EM436, several approaches have been explored to obtain computational results required for every lab submission including basic hand computation, computational software and computational tools. Results determined using hand calculations remain a requirement for all projects to ensure the midshipmen understand the basic theory supporting the analysis. This approach however, proved to be extremely laborious and taxing when parametric analysis and design-oriented projects were assigned. Computational software was used to gain the benefit of computational efficiency. MATHEMATICA was the first to be used followed by MATLAB in later years. Although no formal course in programming is taught in our curriculum, many midshipmen have been exposed to algorithmic thinking while in high school, at other colleges and universities, and other courses here at the academy. To capitalize on this and to minimize frustration for those less prepared, several introductory lectures were prepared and delivered during lab hours detailing programming methods and language syntax. Developed programs were probed to resolve questions of how and why. To further aid midshipmen, skeleton programs were provided requiring only a few lines of codes to complete.

Many midshipmen benefited from the use of these programs. Barton and Wallace[1] published an article exploring the use of MATLAB as the support program for the composite mechanics course. Further improvement on computational efficiency came when IDEAS was adopted as the computational workhorse for the department. First shown in the introduction to engineering course and later in the machine design course, midshipmen were quite familiar with its platform. Adoption to the composite mechanics course only required learning a new task.

IDEAS, developed by Structural Dynamics Research Corporation (SDRC), provides a host of computational tools for use in engineering. One such tool is its laminate task contained within the simulation application. With this tool one can perform all the required analysis for a composite material including creating composite laminas and laminates, plotting stress and strain distributions for a given laminate and loading, as well as plotting failure envelopes. Figure 4 presents results from IDEAS that allow midshipmen to efficiently compute the elements of the extensional stiffness, coupling stiffness, and bending stiffness matrices.

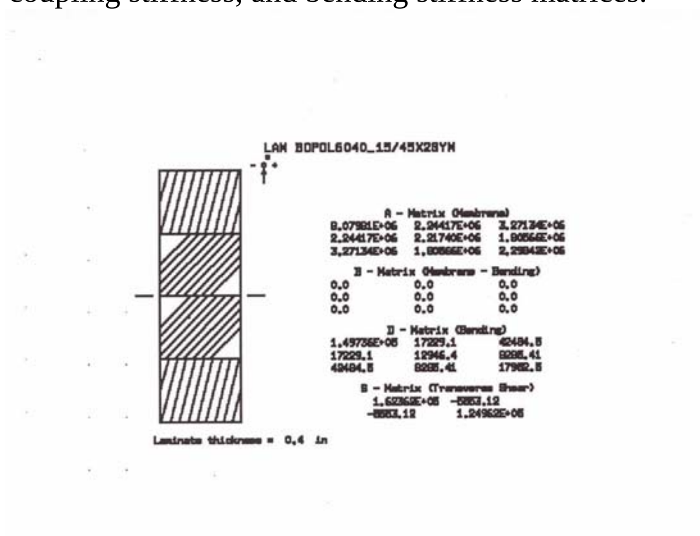

Figure 4. Elastic stiffness constants

The laminate is a four-ply symmetric laminate $[15^o/45^o]_s$ whose 0.1 inch thick plies are composed of 60% Boron fibers and 40% Polymide matrix. Another useful capability is graphing of stress and strain variation for given input force and moment resultant. Figures 5 and 6 show the in-plane stress and strain variation (respectively) for the four-ply symmetric laminate defined above when exposed to the following force and moment resultants: N_{xx}=1000 lb/in, N_{yy}=N_{xy}=0, M_{xx}=1000 in-lb/in, M_{yy}=M_{xy}=0.

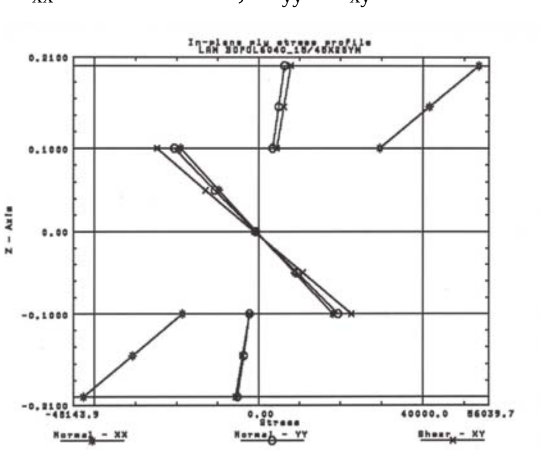

Figure 5: Stress distribution for symmetric laminate

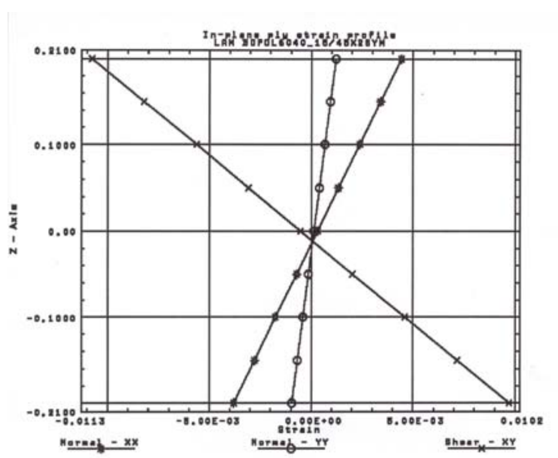

Figure 6: Strain distribution for symmetric laminate

Table 1 presents a breakdown of the computational tools used during the history of EM436 and Table 2 shows the number of midshipmen enrolled. Reviewing the midshipmen course evaluations provides qualitative assessment of the usefulness of the computational tool. The format of the evaluation forms changed during this course history which prevents a more quantitative assessment. Without a doubt MATHEMATICA seemed to be less well received despite any additional effort to overcome programming difficulties. Midshipmen views on the overall course objectives appeared to be less definitive and many indicated the course required additional effort and time. Comparatively, comments summarized during the period in which MATLAB was used did not speak of extra effort to complete lab projects. No programming was required for IDEAS.

Table 1. Computational tools used in EM436

1994	MATHEMATICA
1995-1998	MATLAB
1999	MATLAB/IDEAS
2000	IDEAS
2001	IDEAS

Table 2. Midshipmen enrollment for years 1995-2001

	1995	1996	1997	1998	1999	2000	2001
Number of Midshipmen	16	22	10	19	18	8	14

EN445, Marine Fabrication Methods, presents the basic fabrication methods used to fabricate offshore structures and structural components aboard ships. A typical ship or offshore engineering project follows the phases of design, analysis, fabrication, installation, maintenance, and decommissioning, and most undergraduate engineering courses focus on design and analysis. EN445 introduces the students to the fabrication, installation and maintenance phases, and was a direct result of feedback from officers in the fleet. Comments included observations that although the junior engineers were capable of adequate analysis, their designs often could not be efficiently built or maintained[2].

The course covers fabrication methods for metals, reinforced concrete and composites, generally following a path of increasing analytical and fabrication complexity. An important part of each project is a “reality check” calculation of the preliminary design. As mentioned above, the students are given three group projects drawn from current naval fabrication projects. The groups of three to four students interact with the project sponsors and develop a 15-20 page report presenting a preliminary design and fabrication process. The sponsor along with the naval design agent and the instructor grade the projects. Each project is selected so that the primary design calculations can be easily handled by a senior undergraduate, freeing the student to concentrate on the fabrication. The goal is to give the students the feel for fabrication issues and to learn simple "reality check" calculations to ensure that the final part will be in the ballpark for its intended use. For composites the CLT presented in lecture is compared to simple rule-of-mixtures[3], carpet plots and finite element analysis, illustrating potential pitfalls.

Figure 7 is a sketch of the group project given to the students in the fall of 2002. The design was for an 18-foot fiberglass garvey to be used as a utility and coaching boat at the USNA. The specified service life was 25 years and the midshipmen were given a primer on fiberglass fatigue[4]. The conceptual design was completed by the professor using the American Bureau of Shipping (ABS) Rules for Building and Classing Reinforced Plastic Vessels (1978)[5] and "Fiberglass Boat Design and Construction" by Robert Scott, 1996[6]. The students were tasked with developing the preliminary design and process for fabricating 20 vessels at the Annapolis Naval Station facility. Four of the six groups chose female molded, resin-infusion, vinyl ester/E-glass laminates based on a series of tests performed at the Naval Academy[7]. One group chose low temperature epoxy prepregs and one chose a wet layup epoxy laminate. Three groups increased the laminate thickness due to a belief the vessels would see greater impact loads then those anticipated by the ABS Rule. Each group submitted proposed shop layouts of the Hangar Building at the Naval Station to most efficiently produce the vessels, and quality control and material specifications were included in their reports. While not quite sufficient for actual production, the 15-20 page documents were sufficient for bid purposes and indicated the students learned the fundamentals of a marine composite fabrication project.

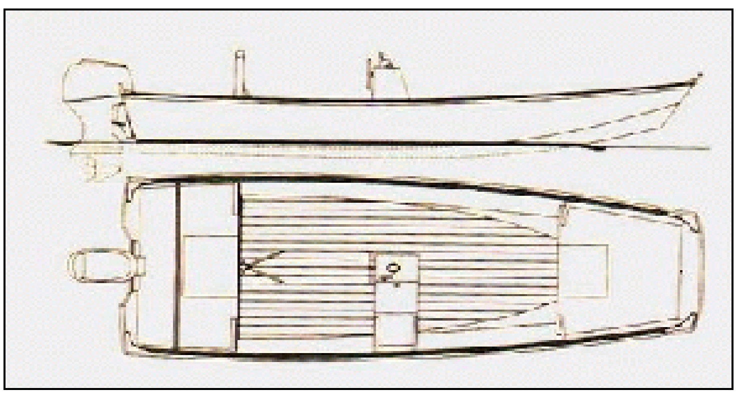

Figure 7. Eighteen foot garvey design used for composite group project.

Feedback from the students on the teaching evaluation forms has been universally positive. The combination of hands-on fabrication and quality assurance testing combined with the application of their learned design skills has been extremely popular. Limited by shop space to 21 students, the course has been oversubscribed each time it was offered. Changes over the four years include more emphasis on spreadsheets for the calculations rather than specialized programs (allowing the students to bring their spreadsheet files with them to the fleet), more emphasis on non-destructive evaluation testing to reflect government practice, and providing specific examples of the report coverage and format desired.

Conclusion

A cursory view of the importance of composite material to the Navy, if new and emerging designs are to become reality, has been considered. Those that are to operate these vehicles must have an understanding of the importance and difference new materials have on the performance and operation of the vehicles. Through the two courses described above, the Naval Academy provides midshipmen exposure to the analysis, design, and fabrication of composite materials which they will encounter in aircraft, ships, and fixed structures. Experience in the analysis and design of composite materials comes through EM436 presented in the Mechanical Engineering Department and experience in fabrication, testing, and design comes through EN445 presented in the Naval Architecture and Ocean Engineering Department. Each course has been successful, based upon midshipmen feedback and course enrollment, and satisfies a need for both each department and the U. S. Navy.

Bibliography

1. Barton, O., Jr., Wallace, J.B., "Composite Structural Mechanics Using MATLAB", Computers in Education Journal, Vol, 10, NO. 2, April 2000, pg. 36 – 43.

2. Comments from the "Faculty Operational Command" workshop, Norfolk, VA, June 2000

3. Greene, Eric., Marine Composites, 2nd Edition, Eric Greene Associates, Annapolis, MD, 1999

4. Miller, P. H., "Fatigue Prediction Verification of Fiberglass Hulls", Marine Technology, Volume 38, Number 4, October 2001, pg 278-292.

5. American Bureau of Shipping, "Rules for Building and Classing Reinforced Plastic Vessels", Houston, Texas, 1978

6. Scott, Robert, Fiberglass Boat Design and Construction, Society of Naval Architects and Marine Engineers, Pavonia, New Jersey, 1996

7. Arvidson, M. A., Miller, P. H., "Hull Material Evaluation for Navy 44 Sail Training Craft", Naval Engineers Journal, Spring 2001, pg 71-78.

Biographical Information

OSCAR BARTON JR. is an Associate Professor in the Mechanical Engineering Department at the USNA. He received his Ph.D. from Howard University. His research focus is on structural mechanics of composite materials.

PAUL H. MILLER is an Assistant Professor in the Naval Architecture Program at the USNA and received a B. S. in Mechanical Engineering from Tufts University and a M. E. in Ocean Engineering from Stevens Institute of Technology. He also completed a M. E. in Naval Architecture and a D. Eng. in Civil Engineering from the University of California at Berkeley. His research focus is on marine composites.