AC 2007-1005: MECHANICS, PROCESS, AND DESIGN SIMULATION OF FIBER-REINFORCED COMPOSITE MATERIALS – A NEW COURSE DEVELOPMENT

Yaomin Dong, Kettering University

Dr. Yaomin Dong is Assistant Professor of Mechanical Engineering at Kettering University. He received his Ph.D. in Mechanical Engineering at the University of Kentucky in 1998. Dr. Dong has extensive R&D experience in automotive industry and holds multiple patents. Dr. Dong's areas of expertise include metalforming processes, design with composite materials, and finite element analysis.

Jacqueline El-Sayed, Kettering University

Dr. Jacqueline El-Sayed is the Director of the Center for Excellence of Teaching and Learning and Associate Professor of Mechanical Engineering at Kettering University. Dr. El-Sayed's areas of expertise include manufacturing optimization and multi-disciplinary team teaching and course development. She currently serves as the leader of the Plastics Product Design Specialty within the Mechanical Engineering program. In 2004, she was appointed by Governor Jennifer Granholm to the Michigan Truck Safety Commission representing all four year colleges and universities, and in 2006 was elected chair. The MTSC provides education and compliance programs to increase truck safety in Michigan. She also serves as the Chair of the Driver's Education Advisory Committee and the Motorcycle Safety Advisory Committee to Michigan's Secretary of State Terri Lynn Land.

Mechanics, Process, and Design Simulation
of Fiber-Reinforced Composite Materials – a New Course Development

Abstract

Composite materials are widely used due to their advantages in high strength to weight ratios, high corrosion resistance, high fatigue life in cyclic loading, and great potential in styling design. This paper presents a new composite course development focusing on the properties, mechanics, manufacturing aspects, and design simulation of fiber-reinforced composite materials. Together with Properties of Polymers (MECH-580), Polymer Processing (IME-507), and Plastics Product Design (MECH-584), this new course will be an integral part of the course portfolio for the Plastic Product Design Specialty at Kettering University, which emphasizes both experimental labs and simulation techniques. Topics include Classical Laminate Theory (CLT), material characterization, failure and damage, manufacturing techniques, and composite structure and design. A course project is also developed to demonstrate the application of composite materials and design simulation. Kettering is a member of the Partners for the Advancement of CAE Education (PACE) program, and the term project will be performed using advanced workstations and CAE software suite.

1. Introduction

Composite materials are widely used in diverse applications due to their advantages in high strength to weight ratios, high corrosion resistance, high fatigue life in cyclic loading, and great potential in styling design. From aircrafts, spacecrafts, submarines, and surface ships to civil structures, automobiles, and sporting goods, advanced composite materials consisting of high strength fibers embedded in matrix materials are gaining increasing popularity. The Plastic Product Design Specialty (PPDS) is one of the six Mechanical Engineering's specialties at Kettering University. As a specialty, PPDS does not offer a course on composite materials in Kettering University today. Our students often ask for help in the field of composite materials used in their co-op jobs, senior thesis work, and other capstone course projects. A course focusing on the composite materials is much needed. In a recent Polymers Industrial Advisory Board Meeting at Kettering, the authors proposed a course outline to be developed on mechanics, processing, and design aspects of fiber-reinforced composite materials. The Board approved the proposal and gave input and a strong endorsement to the endeavor.

The topic of composite materials has a very broad spectrum. From a *material science and engineering* aspect, microstructures and properties are the main focus. The *mechanics* of composite materials includes equilibrium, stress, strain, deformation, linear and nonlinear behaviors and the relationships between them. The *manufacturing processes* of various composite structures deal with the tool design, process setup and quality control. The *design and analysis* of composite products must be based upon a foundation of understanding of all the areas above. Each of these topics can be a separate course, and is offered as such at various educational institutes. The need for a practical composite materials course for our students and the unique characteristics of Kettering University's 12-week terms determine the theme of the proposed course presented in this paper:

With the introduction of properties, mechanics, and manufacturing aspects of fiber-reinforced composite materials, design and simulation based upon CLT and FEA of typical composite structures are emphasized. Topics include: constituents and interfacial bonding, microstructure and micromechanics, theory of anisotropy, classical laminate theory, material characterization, failure and damage, manufacturing techniques, composite structure design, and introduction of nanocomposite.

The Mechanical Engineering Department of Kettering University has an enrollment of 1300 students, one of the largest in the country. For the past 75 years, Kettering University has strived to provide its students with top quality classroom instruction, state-of-the-art laboratory facilities and career oriented work-experience in industry. The *mission* of PPDS is to prepare the student as an entry-level product or process engineer with the appropriate plastic specialty knowledge for the first five years. Students gain the *basic skills* to

- Be able to converse with chemists and material supplier product specialists
- Understand the material's property changes with temperature and material selection
- Understand linear visco-elastic constituent equations and their inherent differences with linear elastic constituent equations
- Understand how mechanical engineering analysis and design changes with polymers
- Understand the primary manufacturing processing variables and their effect on part characteristics
- Understand how to interpret data from instrumented processes
- Understand process capability issues using statistical techniques
- Be able to compare process data to simulations in order to improve accuracy of simulation tools
- Be able to make engineering and project management decisions, and perform project cost analysis.

The specialty course composition consists of three mandatory courses and two electives. The mandatory courses include:

- MECH 580: Mechanical Properties of Polymers
- IME 507: Polymer Processing
- MECH 584: Plastics Product Design Capstone

The proposed course would serve as an elective for Kettering's senior-level students. Kettering University, formerly known as GMI Engineering & Management Institute, offers Bachelors Degree programs in Mechanical, Electrical, Industrial and Manufacturing Systems Engineering, Computer Science, Environmental Chemistry, Applied Mathematics, and Management. Kettering students begin a unique five year cooperative education program in their freshmen year by alternating 12-week period of classroom studies with related work experience in over 600 corporate affiliates. The corporate sponsors of Kettering University students include: U.S. Army, General Motors, Ford, Daimler-Chrysler, aircraft companies and their suppliers such as United Technology, Moog, Vickers-Airequip, computer manufacturer IBM, appliance manufacturer Whirlpool and over 600 other companies. It is seen that the companies that sponsor Kettering University students represent a diverse cross section of U.S. industries. The changes that have been taking place in these industries, their need and the challenges faced by them are immediately reflected in Kettering University's classrooms as the students bring valuable experience after 24 weeks of work experience per year with their corporate sponsor. This composite materials course will fill a gap between our current curriculum and the need from our corporate sponsors, and provide our students with hands-on design and application skills in composite materials.

2. Course Content

2.1 The course learning objectives (CLO)

The course learning objectives of proposed course "**Mechanics, Process, and Design Simulation of Fiber-Reinforced Composite Materials"** to be offered at Kettering University can be described as follows. Upon completion of the course students will be able to:

- Understand the fundamental properties of composite materials;
- Apply the fundamental principles mechanics of composite materials;
- Apply modern analytical techniques to mechanical systems with composite materials;
- Apply computational techniques to mechanical systems with composite materials;
- Understand the manufacturing processes and cost analysis in composite materials;
- Demonstrate effective communication and teamwork skills through technical presentations and reports in term projects.

2.2 Prerequisites

Based on input from Kettering University's Polymers Industrial Advisory Board and other faculty members of PPDS, three prerequisites are required for this senior undergraduate or postgraduate level course:

- Solid Mechanics (MECH-212),
- Computer Aided Engineering (MECH-300), and
- Engineering Materials (IME-310)

2.3 Tools

- UGS NX® (CAE software).
- Microsoft® Excel® (Spreadsheet solution based classic CLT)
- GENESIS® (FEA software for linear simulation of composite materials).
- LS-DYNA® (FEA software for nonlinear/failure simulation of composite materials).

2.4 Course Textbook

M. W. Hyer, *Stress Analysis of Fiber-Reinforced Composite Materials*, WCB/McGraw-Hill, 1998

2.5 Tentative Course Outline

1) Introduction of Fiber-Reinforced Composite Materials [1 Week]
   - Fibers – Carbon/Glass/Polymeric
   - Matrices – Thermoset/Thermoplastics
2) Elastic Stress-Strain Characteristics [1 Week]
   - Stress and Deformation
   - Relationships among Material Properties
   - Stress-Strain Relations
3) Engineering Properties Using Micromechanics [1 Week]
   - Material Properties of the Fibers and Matrix
   - Tension in Fiber Direction - Extensional Modulus and Poisson's Ratios
   - Transverse Tensile Loading - Extensional Modulus and Poisson's Ratios
   - Theory of Elasticity
4) Classical Laminate Theory [1 Week]
   - The Kirchhoff Hypothesis
   - Laminate Stiffness Matrix
5) Failure Theories [1 Week]
   - Maximum Stress Criterion
   - The Tsai-Wu Criterion
6) Manufacturing Techniques [2 Week]
   - Close-Mold Processes
   - Open-Mold Processes
   - Processes for Short-Fiber Composite Materials
   - Processes for Continuous-Fiber Composite Materials
7) Introduction of Nanocomposites [1 Week]
   - Nanotechnology – "Small is Big"
   - Nanomaterials – Nanoparticles, Nanotubes, Nanocomposites
   - Properties
   - Applications
8) Design Project [3 Week]

3. Course Project Development

One of the most important and challenging tasks in a practical application based course is the development of projects. Because this course focuses on application and design based on composite material's properties and mechanics, the course project needs to be practical, rigorous, interesting, and use state-of-the-art engineering tools in industry.

3.1 Objective

The objective of course project is to perform structural analysis to assist in the selection of reinforcement materials, bias angle, and wall thickness for a composite structure that must meet specific bending and torsional rigidity requirements in automotive windshield wiper systems.

TABLE 1 shows a particular set of technical specifications of a given platform. The part geometry and loads are shown in FIGURE 1.

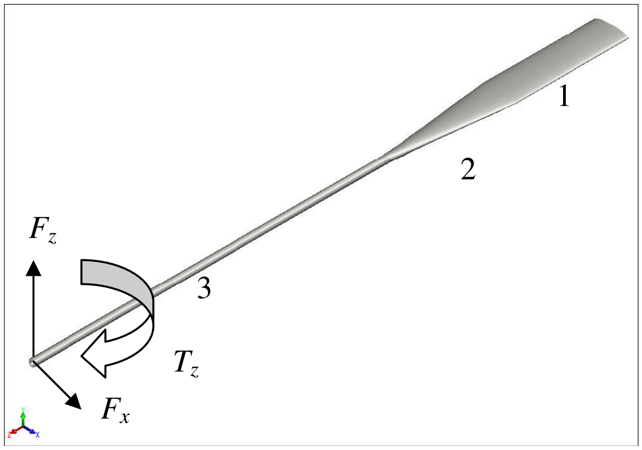

FIGURE 1 – A COMPOSITE STRUCTURE

TABLE 1 Technical Specification

Length (*mm*)	500
Width at Base (*mm*)	30.0
Depth at Base (*mm*)	6.00
Tip Load F_y (normal) at 0.5 ° Deflection (*N*)	8.11
Tip Load F_y (normal) at – 3° Deflection (*N*)	1.41
Tip Load F_x (lateral) at 0.6 ° Deflection (*N*)	2.90
Tip Load F_x (lateral) at 3.0 ° Deflection (*N*)	29.0
Torsional Load T_z (*Nm*)	0.42
Twist at the Tip (°)	1.00

3.2 Scope

This is a team project with 4 members per team. Each team will be given a set of technical requirements corresponding to a particular vehicle application. There are two phases in the design project. The first phase is Initial Design based on CLT and spreadsheet calculation. The second phase is FEA and Design Optimization based on the first phase. As an example, the following tasks are for a particular team:

- Perform spreadsheet solution on Microsoft® EXCEL based on CLT;
- The part needs to be straight and 500 mm long;
- The part will be divided into three smaller sections:
  1) 100 mm spring section #1 that is elliptical in shape, 30mm wide x 5 mm deep;
  2) 100 mm transition section #2 that transitions Section #1 to Section #3; and
  3) 300 mm cylindrical section #3.
- Assume wall thickness between 0.5mm and 0.75mm;

- Initial Design can be achieved based on the spreadsheet calculation (procedures will be given in the following sections);
- Starting with the initial design above, detailed structural analysis and design optimization using FEA will be performed to meet all the technical specifications.

3.3 Bending Analysis

The procedure to determine the bending deflections is based on linear elastic bending of laminated beams as described by Whitney [1]. The formulation is very similar to classical beam theory for isotropic materials, with the exception that the bending stiffness, EI, is replaced with a composite quantity that accounts for a variation in properties across the thickness of an elliptical or circular cross section. Referring to FIGURE 2, the composite EI for an elliptical section about the x-axis is given by:

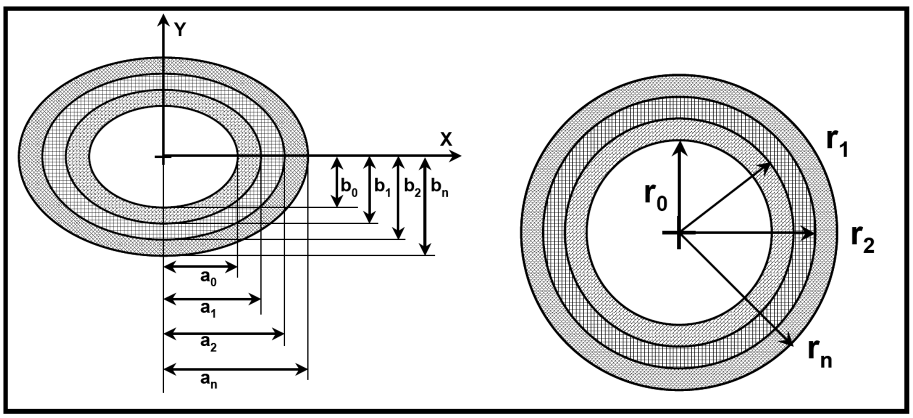

FIGURE 2 – ELLIPTICAL AND CIRCULAR CROSS-SECTION NOMENCLATURE

$$EI_{composite} = \frac{\pi}{4}\sum_{k=1}^{n} E_x^{(k)}\left(a_k b_k^3 - a_{k-1} b_{k-1}^3\right) \qquad (1)$$

in which

$EI_{composite}$ = bending stiffness of the layered cross-section

n = number of layers

$E_x^{(k)}$ = Young's modulus along the part axis for layer k

a_k = major axis of layer k

b_k = minor axis of layer k

a_{k-1} = major axis of layer $k-1$ (the layer immediately beneath layer k)

b_{k-1} = minor axis of layer $k-1$ (the layer immediately beneath layer k)

3.4 Torsion Analysis

Like the bending formulation, the equations for torsional behavior are similar to those of an isotropic material with modifications for a layered composite. The effective torsional inertia, *K*, for an elliptical section is given by Young [2]. As with the bending stiffness, a composite torsional rigidity is defined due to the layered construction of the arm:

$$GK_{composite} = \sum_{i=1}^{n} G_i K_i \tag{2}$$

in which G_i is the shear modulus of layer *i*.

3.5 Material Properties

The elastic properties (E_x and G) used in this analysis are based on typical composite properties achievable using two material forms: tubular glass and graphite braided reinforcement oriented at ±45°; and unidirectional "fabric," in which a small amount of tiny circumferential fibers hold fiber bundles along the axis in a tubular form. As the bias angle changes in a tubular braid, the elastic properties change in a predictable manner. The changes have been compiled [3] and are used to calculate bending and torsional response when the braid angle is changed from ±45°. Unidirectional fabric properties are not modified in this analysis, since it is assumed that this reinforcement form will be not be biased away from the part axis (bias reinforcement is accomplished with braid only.)

3.6 Analysis Tools

The equations are implemented in a Microsoft® Excel® workbook. The equations were solved numerically within the spreadsheet. The spreadsheet is created to handle changes in thickness and fiber orientation of up to four layers, and to accommodate linear tapering of radii, major axes, or minor axes. A brief description of the workbook and usage instructions is given below.

FIGURE 3 shows the worksheets comprising the Excel® workbook. "Deflection and Twist" is the primary worksheet into which material and geometry definitions are entered, calculations are performed, and results (deflection and twist) are displayed. "Materials" contains elastic property data tabulated for the range of possible bias angles. "Carbon Fibers" and "Glass Fibers" tabulate the changes to elastic properties and braid geometry that occur when a braid's bias angle is changed from the baseline ±45°. These data are taken directly from the "Braid Calculator" [3]. Data are tabulated based on changes to bias angle and based on percentage changes to the baseline diameter. The worksheet "A&P Data Sheets" contains data on standard braid products available from [3].

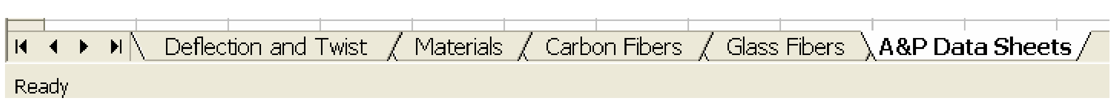

FIGURE 3 – WORKSHEETS STRUCTURE

3.7 Workbook Input and Output

FIGURE 4 shows the highlighted cells into which input data are entered. Cells C4 through K8 define the width and depth of the inside surface of the hollow part. The part has been divided into three sections along its length, labeled “spring,” “transition,” and “cylindrical.” “Start” and “end” refers to values at the beginning and termination of each section. Different values for “start” and “end” will result in a linear taper of that dimension along the length of the section. The length for each section is entered in cells I6 through I8. The running length of the arm is shown in column K and the total length of the arm is shown in cell K8.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Composite Structure Design Project												
2													
3	Part Geometry												
4			Width			Depth				Span	Running		
5	Section	Name	Start	End	ΔW/ΔL	Start	End	ΔD/ΔL	Length	Start	Length		
6	GS1	Spring	35	35	0	7	7	0	100	0	100		
7	GS2	Transition	35	7	-0.28	7	7	0	100	100	200		
8	GS3	Cylindrical	7	7	0	7	7	0	300	200	500	←	Total Length

FIGURE 4 – GEOMETRY INPUT

Users insert the applied load (in Newtons) and the applied torque (in N·mm) in Cells B18 and D18, respectively (FIGURE 5). It is assumed the load and torque are applied at the tip (small end) of the part. As the output, the deflection and tip angle due to the applied loads and the twist due to the applied torque are displayed in Cells B19, B20, C19, C20 and F19. The bookwork can recalculate these values for any change in the input data.

	A	B	C	D	E	F
16						
17	NORMAL		LATERAL		TWIST	
18	Load	1.41	Load	29	Torque (N·mm)	420
19	Dflxn (mm)	2.67	Dflxn (mm)	30.91	Twist (°)	0.49
20	Angle(°)	0.306	Angle(°)	3.537		

FIGURE 5 – INPUT AND OUTPUT

3.8 Structural Analysis Using FEA

GENESIS® is used to perform linear finite element analysis and optimization of composite materials for the course project. Based on the initial design obtained in the spreadsheet calculation, the FEA model is constructed (FIGURE 6). The bending and torsional rigidity requirements (FIGURE 1 and TABLE 1) are used in the FEA. Fiber angles, fiber thickness, and properties of fiber and resin materials are among the input data in the FEA. FIGURE 7 shows the deformation under the given loads.

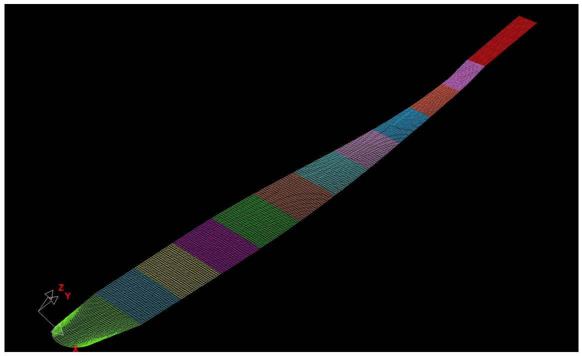

FIGURE 6 – FINITE ELEMENT MODEL

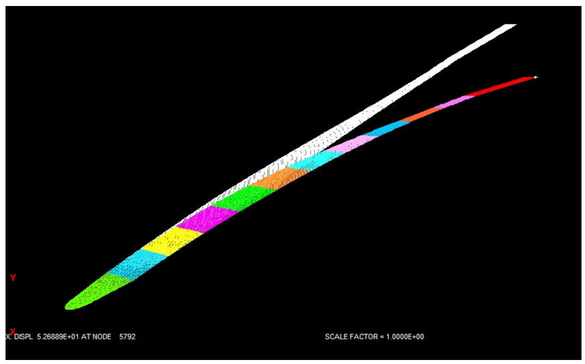

FIGURE 7 – FINITE ELEMENT ANALYSIS

4. Course Assessment Survey Questions

For continuity within the specialty, it is planned to add several lectures of composite materials at introductory level onto the existing course "Mechanical Properties of Polymers (MECH 580)". Systematic assessment will be carried out in order to obtain feedback from the students. These assessment results will help fine-tune the course before the official offering. The student survey will include specific questions regarding the content, tools, project, etc. and also general questions such as how and if composite materials are used at their co-op sponsor, and what they feel the scope of the course should be. We will also gather information such as what is their interest in the topic on a scale of 1-10, and the student's background.

Focus groups of students interested in composites will be gathered for informal discussions on the outline of the course and topics. This will help us understand the survey results in more depth. Once the course is offered, the students will be asked to list the course's strengths, potential improvements periodically. Student's insight about the course will be frequently tracked. In this way, continuous assessment and improvement will result.

4.1 Assessment Techniques and Tools

The Kettering University faculty has recently become acquainted with process education methodology through seminars facilitated by Pacific Crest. SII is a method of assessment articulated by Pacific Crest [4] which requires the assessor to focus on three main items: strengths, areas for improvement, and insights gained. *Strengths* identifies the ways in which a performance was commendable and of high quality. Each strength should include a statement as to why that particular strength was considered important and how the strength was produced. *Areas for improvement* identify the changes that can be made in the future to improve performance. Improvements should include the issues that caused any problems and mention how those changes can be implemented most effectively. *Insights* identify new and significant discoveries that were gained concerning the performance area.

4.2 Student Course Assessment Questions

When the course is actually taught, pre and post course surveys will be given electronically through Blackboard. Following are the questions for quantitative assessment (such as for ABET.)

1) Please rate your level of understanding of the fundamental properties of composite materials;
2) Please rate your ability to apply the fundamental principles mechanics of composite materials;
3) Please rate your ability to apply modern analytical techniques to mechanical systems with composite materials;
4) Please rate your ability to apply computational techniques to mechanical systems with composite materials;
5) How do you rate your ability to effectively communicate technical information in writing?
6) How do you rate your teamwork skills?
7) How do you rate your ability to make technical presentations?
8) How do you rate your ability to be a self-grower with regard to life long learning?

In addition to the above quantitative course assessment, an SII question will be asked in which the students will list their personal strengths, improvement areas and insights about their background knowledge of composite materials.

The following SII questions will be used for additional post course assessment to facilitate continuous improvement:

1) What are the three strengths of this course? Please explain.
2) What are the top three things that you have learned?
3) What are the three improvements for this course that would help you learn better?
4) How can these improvements be made?
5) What action plans can be put in place to help you learn more?
6) What have you learned about your own learning process?
7) Is there anything else you would like the instructor to know about the class?

5. Conclusions

A new course in composite materials has been proposed as a new elective of Kettering University's PPDS. This new course requires three prerequisites, namely, Solids, CAE, and Engineering Materials. It is four credits and meets three times a week for 120 minutes each meeting during the 11-week semester. The course covers constituents and interfacial bonding, microstructure and micromechanics, theory of anisotropy, classical laminate theory, material characterization, failure and damage, manufacturing techniques, composite structure design, and introduction of nanocomposite. A course project has also been developed to apply knowledge learned in the course to design an engineering structure using composite materials.

6. References

[1] Whitney, James M., *Structural Analysis of Laminated Anisotropic Plates*, Technomic Publishing, Lancaster, PA, 1987.

[2] Young, Warren C., *Roark's Formulas for Stress and Strain*, 6th edition, Table 20, Formula 13, pg. 351, McGraw-Hill, New York, 1989.

[3] "The Braid Calculator," A&P Technology, Inc., Cincinnati, OH (http://www.braider.com).

[4] Pacific Crest, *Teaching Institute Handbook*, Sponsored by Kettering University Center for Excellence in Teaching and Learning (CETL), May 4-6, 2006.