ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

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Paper ID #17389

Optimization of Design of a Simple Composite Laminate: Project for Advanced Composites Undergraduate Course

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Introduction

With the widespread increase of use of composite materials in manufacturing it has become almost mandatory to teach courses related to these in engineering schools worldwide. Composite materials are manufactured with various matrix materials such as metals, ceramics and polymers. Out of these, polymers are being reinforced with fibers widely to manufacture composites. These composites are manufactured not only with specific mechanical and chemical properties for aviation and aerospace sectors but also for general use such as in sports goods, fluid containers and conduits, and vehicles for land and water transport. Thus, most of the courses[1,2,3,4,5] taught at the undergraduate level in material based programs focus on teaching about material constituents, material properties, manufacturing and design of fiber reinforced polymer composites (FRPCs).

The ABET-ETAC Engineering Technology programs at Western Washington University (WWU) have recently transitioned to ABET-EAC Engineering programs. Thus, many changes have been introduced to the already existing courses. This paper details one such introduction of project work involving hands-on manufacturing lab activities in an undergraduate course, Advanced Composites. The Advanced Composites course focuses mainly on teaching advanced methods of manufacturing as well as mechanics of fiber reinforced polymer composites. The objective of the project discussed in this report is to design simple composite laminates of certain strength so that they are able to sustain specific tensile and flexural loads. The loads are to be chosen based on the capacity of the load cells on the testing machines present in the Engineering Department. The design is then verified by manufacturing the laminates and comparing the targeted tensile and flexural strengths to those obtained through mechanical testing.

The fiber reinforced polymer composite laminates for testing are manufactured by curing pre-preg plies at elevated temperature by using one or more of the following: autoclave, compression molder, ovens, and heated mold. Undergraduate students work in two or three member teams to optimize and create the beams, test them, and write up a final report detailing the activities involved. Optimization is carried out using hand calculations, computational methods and finite element analysis through CATIA Composites Workbench. Along with the analysis and discussion of results, students are required to discuss and compare the optimization techniques that they used, in the lab report. This project may be used to evaluate student outcome (k) of ABET General Criterion 3.

Project Details

The course in which this project is carried out by the students is taught at the undergraduate level and focuses on design and processing of advanced composites. While taking this course, students gain knowledge about; how the constituent materials affect the chemical and mechanical properties of the composite; design and optimization of design of composites for advanced manufacturing; elevated temperature manufacturing of composites using pre-pregs; testing and interpretation of data from testing; and correlation between processing conditions and the outcome of the processing. The project is set up in such a way that concepts pertaining to most of the learning outcomes are involved in it. In the last quarter that the course was taught, students conducted the project in groups of two. This was the first time that this project was carried out in the changed form. From the time taken by the students to complete it and the scope of the project, it seems to be a good fit for teams of two.

Before the students actually manufacture the composite laminates they first design laminates of carbon or fiber glass reinforced pre-pregs with optimal properties based on the type and magnitude of loading and processing conditions. The design load is established by the student group by taking into account the load cells and the machines that are available in the Engineering Department. Currently, there are two universal testing frames with load cells with capacities of 10 kN, 22 kN, 25 kN and 100 kN. Students are required to design four laminates, two each for flexural and tensile loading types. Preliminary calculations using computational software and design using an FEA software helps them start with a simple design based on the loads for the first laminate. Then they have to incorporate changes into the design to suit usability and manufacturing conditions and make the second laminate. For example, for tensile loading they could begin with a unidirectional laminate with a certain number of plies, but find that a laminate with such a flat layup is difficult to manufacture at elevated pressure in compression molding due to spreading out (fraying) of fibers. Also such a laminate would have very less shear resistance and almost no strength in the transverse direction. Then they modify the design according to what they have learnt in class and design a better laminate for each of the two loading cases. Testing is then carried out to determine the loads or displacements and compare them to the values that they had chosen to target in their initial and optimized designs of laminates. A report is then written by each group to detail the design, optimization, manufacturing and testing steps carried out to complete the project. They also discuss the results they obtain from testing and compare them to the theoretical values they obtained from computation and/or FEA. Reasons for difference in the predicted values and the actual values obtained from testing are also required.

Preliminary computations and FEA analysis

Microsoft Excel is the computational software that is used by the students for the calculations as most of them do not take the Mathematics course in which MATLAB is taught. Advanced Composites is one of the few courses in the Plastics and Composites Engineering program in which a computational software is used. For preliminary calculations, students solve for expected strains and displacements during testing corresponding to the loads that they have designed their laminates for. The calculations are carried out using concepts of mechanics of composite materials that are learnt in the theory part of the course. By the end of this course students become proficient in using Excel for solving linear algebraic equations and equations required for calculating mechanical parameters of orthotropic materials. A few students do use MATLAB for the project and reinforce what they have learnt in the Mathematics course.

For carrying out the finite element analysis of composites, students have the option of using CATIA or ANSYS composite workbenches. The ANSYS composite workbench was not available for use last quarter but will be available for the students next time the course is taught. They also have the option of using a different software that they are comfortable with and have access to. One of the groups opted to use HyperMesh and OptiStruct as they were planning on using that software to design bridges for the SAMPE student bridge contest. Students get introduced to the composites workbench in the surfacing class with CATIA and strengthen their knowledge about how models are designed using orthotropic materials. Two lectures are set aside to instruct the students with the FEA laboratory. Examples of a model setup and the displacement results obtained by one of the student groups for flexural testing are given below (Figures 1 & 2.)

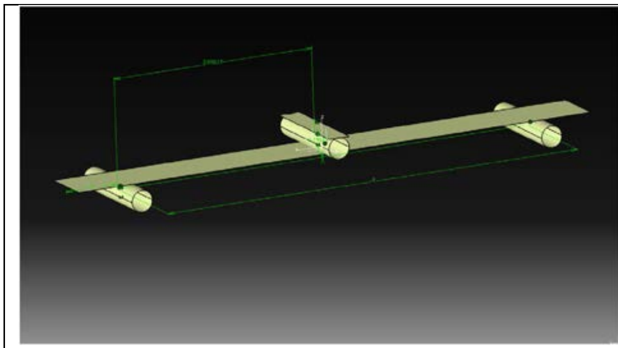

Figure 1. CATIA model of flexural test using surfaces

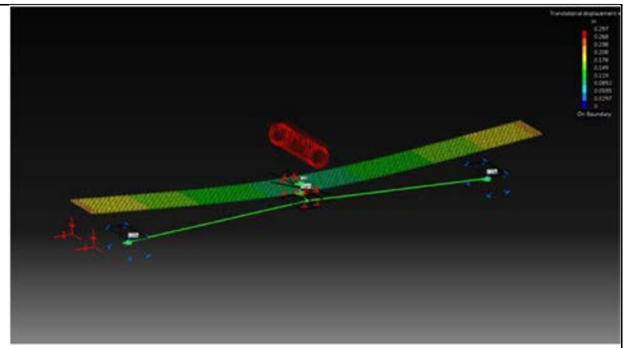

Figure 2. FEA result showing displacements in a composite specimen

Manufacturing of specimens

The Advanced Composites course is the third course in the series of courses related to composite materials in the program. Composite materials are first introduced in the Introduction to Materials Science course. The students in the program then learn about the constituent materials, room temperature processing and tooling of fiber reinforced polymer composites among other things in the Introduction to Composite Materials course. The Advanced Composites course includes instruction on manufacturing of fiber reinforced polymer composites at elevated temperatures. Thus, the students have the option of manufacturing their designed specimens by using one out of:

- a compression molding machine
- a heatable mold
- ovens or
- an autoclave.

Students are given demonstrations on how to work with the various processing methods available to them. The composite materials that they are allowed to use are fiber glass or carbon reinforced pre-pregs with various weaves and orientations. Unidirectional pre-pregs are preferred and then oriented according to the developed design. A demonstration is also given to show how to handle, cut and orient pre-preg materials on the molds and also about all the safety aspects involved. In all cases the students have to take care that the mold surfaces release parts without the mold release smoking or catching fire. They also learn about the various materials that go on heated molds along with the layup of the laminate. Thus, they learn about important differences between manufacturing composites at room temperature and at high temperatures.

Compression molding may be carried out using either of the available two compression molding machines, WABASH 30 tons (Figure 3) and WABASH 120 tons (Figure 4). Flat aluminum or steel plates are used for molds and the students have to figure out and set the machine parameters in accordance with the curing profile of the pre-preg being used. Molds with the pre-pregs under vacuum pressure may also be kept in ovens that have been set to the desired cure cycle. The heatable mold in the engineering laboratory has silicone tubing on the edges of the mold surface and is covered by a metallic frame that has a silicone sheet which can be made to seal by applying vacuum through it. So in this case too, the composite pre-pregs can be cured under heat and pressure.

Figure 3. WABASH (30 tons)

Figure 4. WABASH (120 tons)

The most common type of advanced composite processing used by the students is with the help of an autoclave. The Engineering Department has an autoclave (Figure 5) made by United McGill Corporation. The autoclave has a design pressure of 300 psi and design temperature of 700^{o} F and is thus suitable for processing most pre-pregs. Students use mold fixtures with envelope (Torr Technologies) bags within which the pre-pregs can be cured in the autoclave. The pre-pregs are first laid out on the flat mold surface of a fixture and then vacuum is drawn through a one way valve in the envelope bag to consolidate the plies. After this the fixture is locked in the autoclave and undergoes the pressure and temperature cycle pertaining to the pre-preg laid on it. Tooling for the autoclave is developed by students if composite parts with complicated shapes are to be manufactured. Sample plates prepared by any of these processing methods are cut using a water-jet machine or a water tile saw with a diamond blade.

Figure 5. United McGill Corporation Autoclave

Testing

As mentioned before, students conduct two kinds of testing to verify their design parameters. For the flexural testing they refer to ASTM D790[6] and also ASTM D7264[7]. This is the first course in the program in which they follow the testing standards rigorously to conduct testing. They are graded on this in their final report. This routine of following testing standards then is continued by them during execution of their senior project. For tensile testing they follow directions given in ASTM D3039[8]. Tensile testing of composites is a bit tricky as the specimens usually tend to slip out of grips and tabs have to be used[8] to grip the specimens correctly within the grip jaws. The department also has an MTS Landmark fatigue tester with hydraulic grips and that tester can be programmed to conduct static testing. The pressure being applied on the specimen by the grips can be set to a desired value. Most of the tensile testing of composites is carried out on this machine that has a maximum load cell capacity of 100 kN.

Students are advised to monitor the specimens during testing and record auditory and visual signs of failure and the corresponding loads. These can then be later compared with certain characteristics on the load displacement graphs (Figure 6) obtained. Types of failure (Figure 7) of the composite specimens as given in ASTM D3039 are also recorded by the students and are required to be stated in the project report.

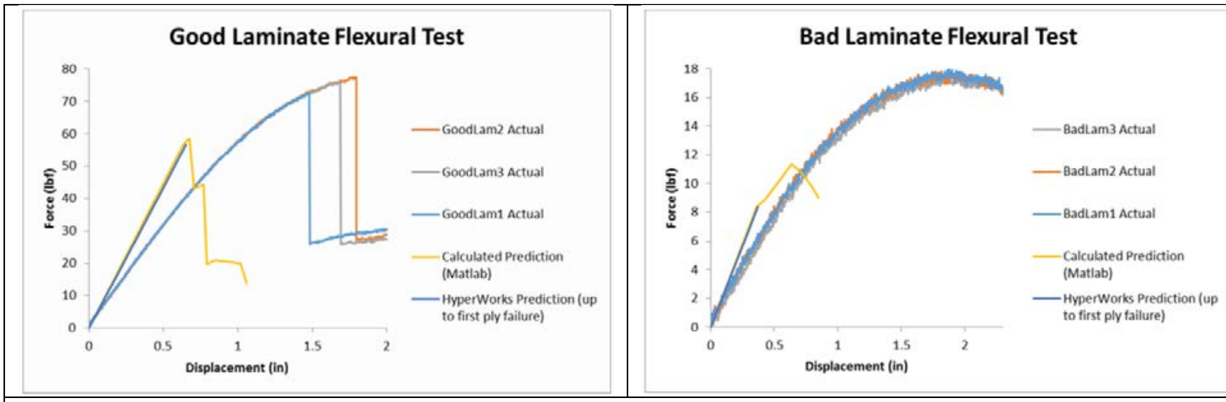

Figure 6. Examples of comparison of testing results with theoretical results

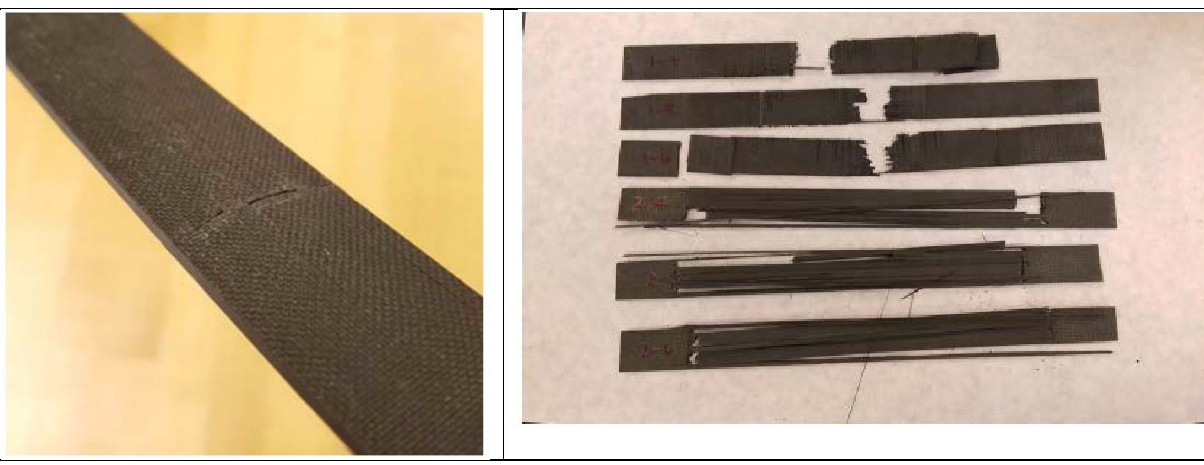

Figure 7. Examples of specimens depicting various failure modes

Project Report

The project report is the final part of the project and is submitted along with the tested specimens and the computational worksheets or code for evaluation. The report does not have a specific format and it is left to the students as this is taken by seniors. They are given a list of mandatory categories that they have to include in the report though. They are required to put extra focus on analysis, discussions and research in the report among other things.

Grading

The grading of the project is based on the cognition of the student of the various concepts that are taught in the Advanced Composites course. Salient concepts that students should show evidence of learning in the report for evaluation are:

- Calculations of loads and strains using classical laminate theory and a computational method
- Understanding and prediction of the effect of various orientations of the fibers on mechanical properties of the composite
- Development of the design of the laminates using computation and finite element analysis
- Ability to process composites at high pressures and/or temperatures using advanced processing techniques
- Discussion of the various processing parameters used and the noticeable effects on the quality of specimens produced
- Comprehension and use of ASTM standards during specimen preparation and testing
- Analysis and comparison of testing results to those obtained by computational methods and FEA of composites
- Discussion of reasons for differences in the above mentioned results
- Research carried out to compare results with data available in literature

The following performance indicators are used to evaluate whether the students have gained the required knowledge this project tends to impart:

- Ability to apply technology in design
- Ability to use technology for analysis or simulation
- Ability to use advanced manufacturing processes for composite materials
- Ability to use technology to effectively characterize properties of designed product, process or material

Results

This project was carried out by the students in Fall 2015 for the first time in its current form as the Advanced Composites course was taught in the Engineering format for the first time then. This course was taught to both Engineering Technology and Engineering students in the same class as some Engineering Technology students are still to graduate. The difference was that the Engineering students had to take the FEA part of the project as an extra credit and took this course for 4 credits. The Engineering Technology students enrolled for only 3 credits and did not take the FEA credit. Previously, in the Engineering Technology format, the major foci of the course and project used to be on processing of advanced composites. This time the course was taught with a bit more focus on the engineering design of composites relevant to the transition from Engineering Technology to Engineering. But, the manufacturing focus was still maintained by enforcing use of elevated temperature manufacturing for making composite laminates in the design project. From the grades obtained by the students on the project, it was found that on an average, the students enrolled in Engineering Technology performed almost the same as students enrolled in the Engineering portion of the course. Over 80% of the students in both categories were able to score more than 80% on the non FEA part of the project. But only 60% of the Engineering students were able to actually obtain results from the FEA analysis using CATIA and score more than 80% in that portion of the project.

Conclusion

The project discussed above was implemented successfully by most of the students from both Engineering and Engineering streams. It was found that the course requires some changes pertaining to the project and these will be implemented when it is taught again in Fall 2016 with only Engineering students. From the grades it is evident that the students require more instruction on the finite element analysis part of the project and thus it is proposed to have three lectures for the FEA lab instead of the two held currently. Also, the recommendation is that only the composites work bench in ANSYS be used to carry out the FEA analysis. This will make the project more uniform as the students will work with one FEA software rather than letting them choose the software of their choice. It will also make them familiar with a composites work bench other than that of CATIA.

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