ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education JUNE 22 - 26, 2020 #ASEEVC
Paper ID #30583

Simple Lab Exercises Using Composite Materials

Dr. William E Howard, East Carolina University

William E (Ed) Howard is an Associate Professor in the Department of Engineering at East Carolina University. He was previously a faculty member at Milwaukee School of Engineering, following industrial experience as a design and project engineer with Thiokol Corporation, Spaulding Composites Company, and Sta-Rite Industries.

Dr. Colleen Janeiro, East Carolina University

Dr. Colleen Janeiro teaches engineering fundamentals such as Introduction to Engineering, Materials and Processes, and Mechanics of Materials. Her teaching interests include development of solid communication skills and enhancing laboratory skills.

Simple Lab Exercises Using Composite Materials

Abstract

Many engineering programs include a course in composite materials, usually as an elective course at the advanced undergraduate or graduate level. These courses typically focus on the mechanics of fiber-reinforced composites. At East Carolina University, the elective composites course also contains some laboratory exercises that give the students a hands-on experience in the layup and testing of carbon-epoxy specimens. In this paper, the authors share lessons learned in making and testing these specimens for exercises that can be included either in a composite materials course or to supplement an introductory materials science or mechanics of materials course.

Fiber-reinforced composites can be made by wet layup, in which liquid resin is mixed and applied to dry fabric, or with materials that are preimpregnated with resin (prepreg). Wet layup is messy and controlling the amount of resin in the composite is difficult. The main drawbacks to using prepregs have been cost, availability of small quantities, and facilities, as aerospace-quality parts are cured in an autoclave or hot press. Over the past few years, lower-cost carbon-epoxy prepregs that can be cured without an autoclave have become available. The authors share details regarding material sources, low-cost tools, and cutting plans that minimize waste in the creation of the specimens.

For a composite material course, laboratory exercises include tensile tests for a variety of fiber orientations. Among the concepts reinforced with these exercises include strength and stiffness variations with orientation angle, progressive failure (resin cracking prior to fiber breaks), free edge stresses, and thermal property mismatches leading to residual stresses and/or specimen warping.

Composites Course Overview

At East Carolina University, MENG 4343 Composite Materials is an elective course taken mostly by senior-level students pursuing a mechanical engineering concentration. Most of course content is devoted to the mechanics of composites, based on classic texts by Jones, Tsai, and Hyer [1,2,3]. The course begins with principles from the theory of elasticity, including tensor transformations and general stress-strain equations. These principles are then applied to individual fiber-reinforced composite layers, with coordinate transformations for stresses, strains, and constitutive relation terms developed. These relations are then assembled into stress-strain equations for a symmetric laminate. Students create spreadsheets to analyze symmetric laminates under in-plane loading. Using these spreadsheets, students work through examples in which they calculate the laminate properties for various laminate configurations and attempt to optimize laminate designs for given loading conditions. Course topics then move to failure criteria, the analysis of symmetric laminates subjected to bending loads, thermally induced stresses, and finally to the analysis of general (non-symmetric) laminates, in which the in-plane and bending behaviors cannot be separated as they can for symmetric laminates.

Interspersed with the mechanics content are lectures covering manufacturing processes, including hand layup, filament winding, compression molding, resin transfer molding, pultrusion, and automated fiber placement. Mechanical property testing is covered by assigning students various ASTM standards to look up and report on to the rest of the class. The last several class periods are devoted to student presentations on applications of composite materials that are interest to them. The instructor also occasionally presents current events in the composites industry. The on-line newsletter from CompositesWorld [4] is an excellent source of news about recent developments in the industry.

One of the authors has taught a composite materials course for over 20 years, and during that time has attempted to add laboratory demonstrations and/or exercises to the course, even though the course has no formal lab component. At the beginning of that time period, it was difficult to find suppliers of small quantities of fibers preimpregnated with resin ("prepregs"). Since prepregs usually require an autoclave or hot press to cure, equipment availability was also a concern. Also, the shelf life of most prepregs was short, and storage in a freezer was recommended. An alternative is to use wet-resin layup, where the liquid resin and hardener are mixed just prior to use and added to the dry fibers with paint brushes and rollers. This process is quite messy and time-consuming. For several years, specimens for the class were made as large panels from prepreg materials and then cut into individual specimens with an abrasive saw. This method was also time-consuming and did not involve the students in the fabrication process.

The development of "out of autoclave" prepreg materials as a cost-saving measure in aerospace applications has been ongoing since the mid-1990's [5]. As a result of these efforts, reasonably priced small quantities of high-quality prepregs that can be oven-cured are now available from a number of sources. With these materials, the authors have incorporated both layup practice and mechanical property testing as supplements to the mechanics content of the composite materials course.

Specimen Fabrication

The materials that were used in the Fall 2019 semester were purchased from Rock West Composites [6]. These materials included unidirectional and woven carbon-epoxy prepregs. The unidirectional material (all fibers oriented in one direction) consisted of Grafil TRS-50 carbon fibers and Newport 301 epoxy resin. This material is one meter in width and is sold by the yard. (Composites engineers get used to working with mixed unit systems.) Each cured layer has a thickness of about 0.006 inches. As shown later, one yard is enough to make many small specimens suitable for mechanical property testing. The fibers have a published tensile strength of 710,000 psi [7]. The price for a yard of this material is approximately $50 for a single yard and drops to about $20 per yard if 10 are more yards are ordered. The cure temperature of the resin is 250-300 degrees F, and the material can be stored at room temperature for up to 30 days. The woven material is made with Toray T300 fibers and the same Newport 301 resin. Its price is higher – about $70 for a single meter-wide yard when one yard is ordered, and about $35 for 10 yards or more. Shipping does add significant cost, as the materials are recommended to be shipped next-day. Dry ice can also be added, but that has not been necessary in the experience of the authors (but might be considered if ordering in the summer months).

Before cutting the material, it is helpful to lay out a cutting plan based on the number and type of specimens desired. This is especially true if fiber orientations other than 0° and 90° layers are to be used, as there will necessarily be some scrap material created. The tensile testing machine at East Carolina University has 1-inch-wide grips, and ¾-inch-wide by 8-inch-long tensile specimens of different fiber orientations were planned. In Figure 1, a plan for a single yard of material is shown (the fibers run from left to right). Each of the squares is 8 inches per side. From this yard of material, the following specimens can be constructed:

- (2) 8-layer 0° (the angle is relative to the long dimension of the specimen)
- (2) 8-layer 90°
- (3) 8-layer 0°/90°/±45° (quasi-isotropic layup)
- (2) 8-layer 0°/90°
- (2) 8-layer ±45°
- (3) 8-layer ±30°
- (2) 8-layer ±60°
- (10) 3-layer 0°

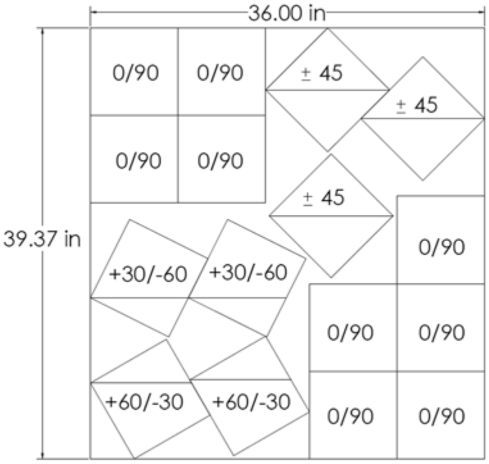

Figure 1 Cutting Plan Example

To help with fiber alignment, 3-D printed cutting guides were made. As shown in Figure 2, after drawing a line in the fiber direction on the material's backing paper, the guide is placed and the material square cut with a box cutter. In the background, a guide with 30° and 60° alignment features is shown.

Figure 2 Cutting Material Squares Using 3-D Printed Guide

When the squares have been cut, ¾-inch-wide strips are created using a simple paper cutter. The Fiskers-brand cutter shown in Figure 3 has a replaceable titanium blade that makes clean cuts, even when cutting across fibers. Ten strips can be cut from each eight-inch square. The cut strips are then grouped for students to assemble during a class period.

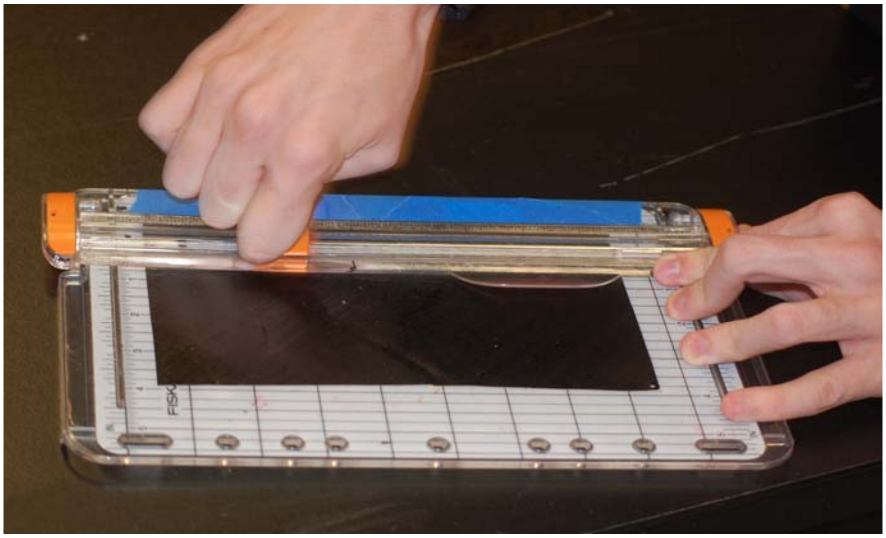

Figure 3 Cutting Strips with Paper Cutter

To assist with the specimen layup, 3-D printed guides were provided. The first layer of each specimen was placed in the guide with the backing paper facing down. Each following layer was then added with the backing paper facing up, as shown in Figure 4, and then the paper was carefully peeled away. The backing paper for the last layer was left on for easy handling until the specimen was ready for curing. Note that particular attention needed to be paid to the fiber orientations in order to maintain a symmetric laminate.

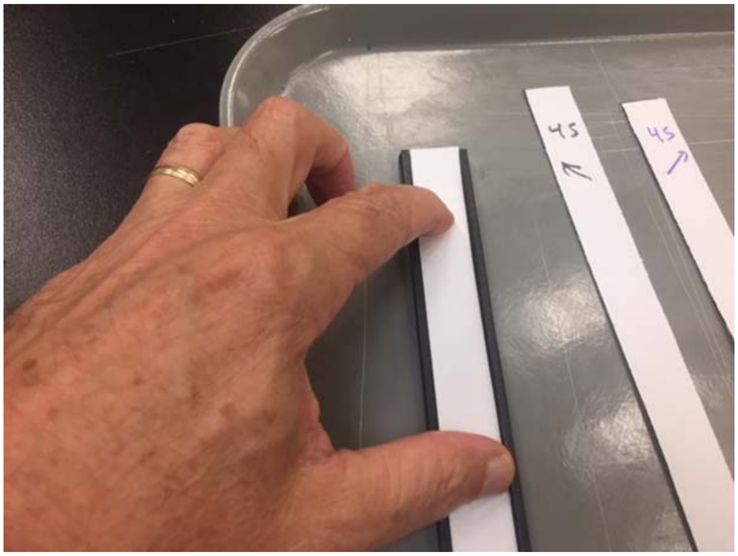

Figure 4 Placement of Strip into Guide

After all the specimens were made, the backing paper was removed from both sides. The specimens were then sandwiched between two layers of release fabric, which absorbs excess resin and creates a good surface finish, and two layers of plastic film, which prevents the resin from sticking to the aluminum plates used to hold the specimens flat. The aluminum plates can be stacked in order to allow more specimens to be cured at once, as shown in Figure 5. The plates were then wrapped with shrink tape, which applied some pressure during the cure. The oven was set to 250 degrees F and the left on for two hours to ensure at least one hour of elevated temperature after heating up. The oven was then turned off and the specimens allowed to cool within the oven for several hours.

Figure 5 Specimens Between Aluminum Plates in Curing Oven.

Specimens after curing are shown in Figure 6. The release fabric was then carefully peeled away.

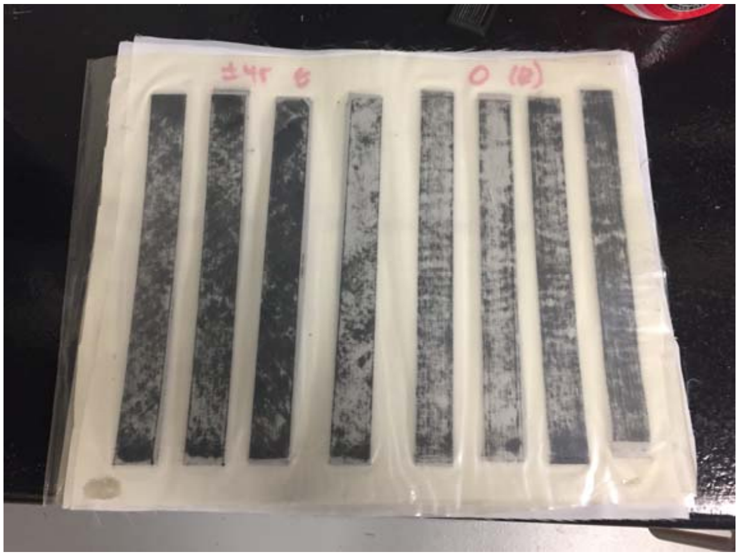

Figure 6 Specimens After Curing

Before tensile testing, reinforcing tabs were added to the ends of the specimens to allow better grip within the test machine and to prevent failures adjacent to the grips. Composite tensile specimens do not typically have the dog-bone shape of isotropic material specimens, as the cutting of fibers in creating a dog-bone shape would result in stress concentrations. ASTM-D3039 recommends the use of tapered end tabs [8], but experience has shown that simple end tabs made from a single layer of the woven material work well. The woven tabs were added to both sides of the ends of the cured specimen ends, and then cured in a second oven cure. As with the original cure, the specimens were sandwiched between release cloth, plastic film, and the aluminum plates. Completed tensile specimens are shown in Figure 7.

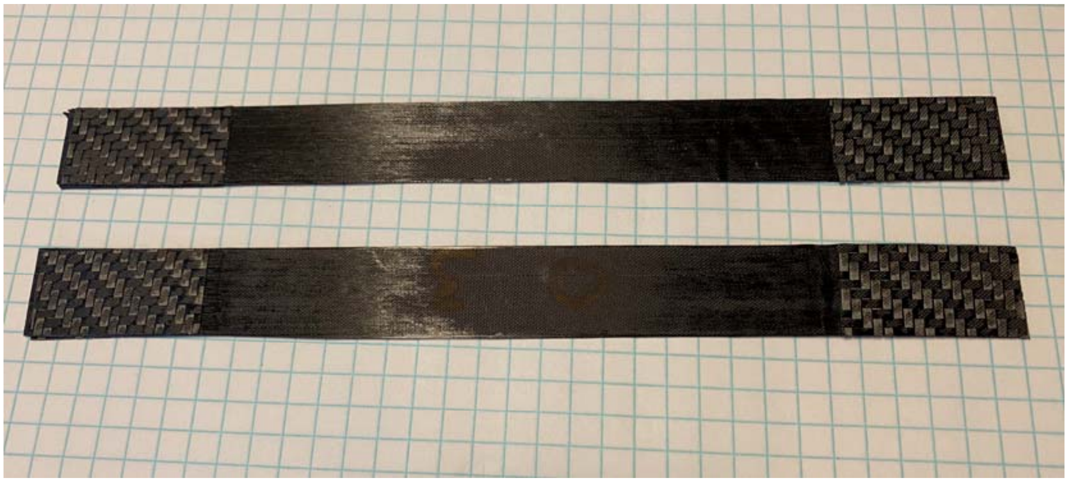

Figure 7 Completed Tensile Specimens with End Tabs

In addition to the tensile specimens, thin flat plates are often useful as hands-on demonstration items. Students can flex 0°/90° and ±45° plates and feel the relative stiffness differences in different directions. Also, plates that are laid up asymmetrically demonstrate the warping that can occur during elevated-temperature cure, as illustrated by the asymmetric 0°/90° plate shown in Figure 8.

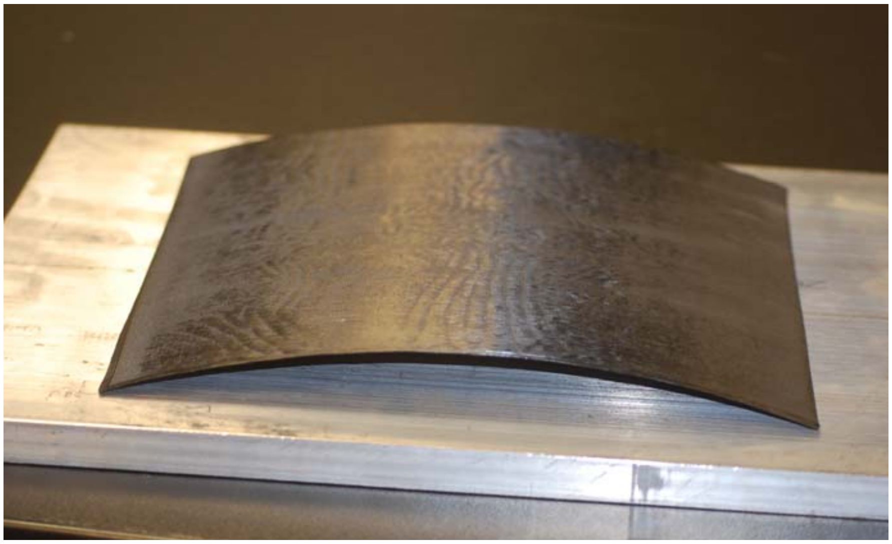

Figure 8 Asymmetric Plate Warped During Cure

Tensile Specimen Testing

The specimens were tested in an Instron tensile test machine. An extensometer was used to record strain data for the eight-layer specimens. Stress-strain data for a few of the specimens was provided to the students for them to curve-fit and determine the modulus of elasticity. Results are shown in Figure 9. The three-layer 0°specimens were tested to failure. The failure stresses ranged between 210,000 and 290,000 psi.

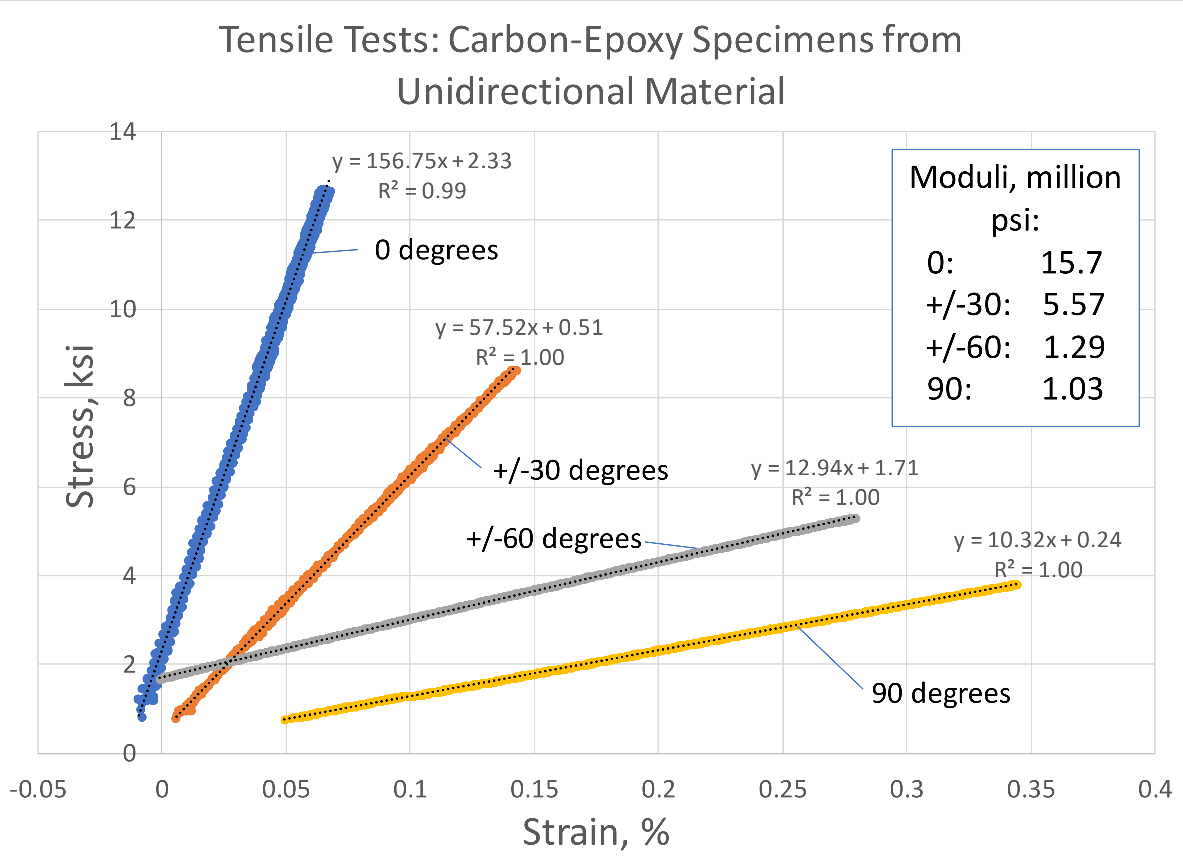

Figure 9 Stress-Strain Response of Laminates

Of course, the specimens were not fabricated with strict quality-control standards, and the test results reflect that fact. For example, the students' spreadsheet based on "typical" carbon-epoxy properties would predict a modulus of 18.5 million psi for the modulus of the 0° specimens, and the 700,000 psi published fiber strength would correlate to 420,000 psi tensile strength for a 0° specimen (assuming a 60% fiber content by volume). However, in the reflections from the students that are discussed in the next section, they recognized the importance of fiber alignment and the difficulty of maintaining good alignment when laying up the specimens manually.

Assessment

In an end-of-semester survey, students were asked to rate the following statements based on a 5-point scale, with 5 – Strongly Agree, 4 = Agree, 3 = Neutral, 2 – Disagree, and 1 = Strongly Disagree. Thirty-four students completed the survey:

- *Laying up the tensile specimens in class enhanced my understanding of the mechanics of composite materials concepts:* Average rating = 4.6. 94% rating of 4 or 5.
- *Observing the tensile tests and plotting the test data enhanced my understanding of mechanics of composite materials concepts:* Average rating = 4.5, 94% ratings of 4 or 5.

Qualitative assessment was conducted by including this assignment on a take-home exam:

> *Attach a brief (400-600 words) reflection on what you learned from the layup, testing, and data interpretation of the composite laminates. Did these activities help your understanding of the mechanics of composite materials?*

A few representative excerpts are shown here:

- Overall testing the different laminates was beneficial to my understanding of composite materials. It was nice to apply what was taught in class and to be able to picture what is happening, instead of just learning about the laminates abstractly.
- Making the layers ourselves was also a helpful experience … It goes to show why quality is so important when laying these laminates.
- Being able to layup these materials with the differing layer angles really gave me a better understanding of how exactly these laminates are made in real world applications.
- At the beginning of this class when you showed us the small piece of laminate, like the ones we tested in lab, and said that it could hold a pick-up truck I honestly did not believe you. I thought it was impossible, but now after learning the mathematics behind the calculations and witnessing it firsthand I was blown away and proved to be completely wrong. I really wish we could have performed more labs during this class and feel as if they would have been very beneficial, because I never I never knew how beneficial or interesting composite materials were until the completion of this course.
- One laminate we watched to failure had an explosive failure in the Instron machine. The explosive failure was preceded by resin cracking and the sound of multiple fibers snapping. The failures allowed me to understand that even though resin cracks and fibers break, intact fibers can sometimes allow a laminate to withstand even more loading before failure.
- During the layup portion of the composite laminate, I learned just how difficult it is to create a composite compound by hand… Ensuring that all layers were pressed neatly together really makes me appreciate the machinery that make these compounds on a much larger scale daily.
- By laying up the carbon fiber by hand, I learned why it is ideal for machines to lay up composites.
- All of us have done tensile test before, usually with steel and aluminum in mechanics of materials, but testing the carbon epoxy was completely different. The first sample tested was an all 0-degree laminate, at first, we heard some minor cracking, but the grips were slipping. After readjusting the grips and starting over, we started hearing twangs, almost like a guitar string breaking until all of the sudden, the entire laminate shattered (this was much cooler than what metals do when you do a tensile test). After this, we tested samples of 30, 60, and 90-degree laminates as well as 2 woven samples, none of which failed quite as cool as the all 0-degree laminate, but each failed in a different way than the others. It was interesting seeing how the different layup can affect the failure mode so drastically.

Other Possible Laminate Tests

The tensile tests described in the previous section were conducted during the Fall 2019 offering of the course. In past offerings, several other tensile tests have been conducted to demonstrate specific aspects of composite material behavior. These tests are described here:

- 0°/90° laminate: Testing this laminate illustrates the progressive failure of a laminate. When loaded in the axial (0°) direction, the resin between the fibers of the 90° layers begins to fail in tension at a relatively low load. These resin failures (sometimes referred to as "crazing") can be easily identified by a crackling sound. At a higher load, individual 0° fibers fail with a distinct pinging sound, followed by the failure of the entire laminate.
- Quasi-isotropic laminates: Aircraft structures typically use laminate configurations that have equal mechanical properties in every direction within the laminate's plane. These are referred to as quasi-isotropic, and can be made up of 0°/90°/±45°, 0°/±60°, or ±30°/90° layers (in each case, there are equal numbers of layers of each orientation, arranged symmetrically). With their spreadsheets, students can calculate that each laminate will have the same modulus in every direction.
- Edge-delamination specimens: A NASA-developed specimen configuration [9] is designed to delaminate at its edges when subjected to tensile loading. The design of this laminate is shown in Figure 10. An analysis of the design shows high through-the-thickness tensile stresses near the edge that lead to delamination. However, if the layers are distributed differently, so that 90° layers are moved to the top and bottom, then the edge stresses are compressive and delamination is not an issue.

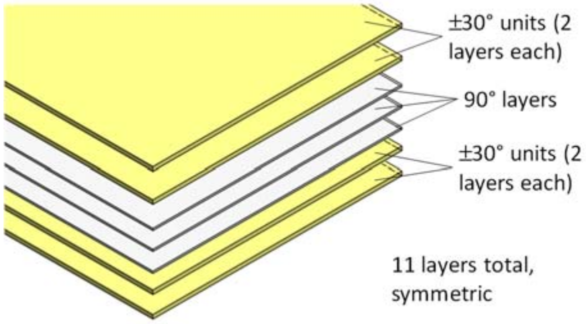

Figure 10 NASA Free-Edge Delamination Specimen

If strain gages and data-acquisition equipment are available, then adding axial and transverse gages to different laminate configurations can illustrate some interesting effects:

- A 0° laminate will have a Poisson's ratio ν_{xy} (defined as the ratio of the negative y-direction strain to the x-direction strain for loading in the x-direction) of about 0.25-0.30, similar to that of metals.
- A 0°/90° laminate will have a Poisson's ratio ν_{xy} of very close to zero, as the stiffness of the 90° fibers will resist the laminate's contraction in the transverse direction.
- A ±30° laminate will have a Poisson's ratio ν_{xy} of greater than one.

These tests demonstrate an important aspect of composites design: that all of the properties of a composite laminate can be varied by changing fiber orientations, opening design options that are not possible with metals or isotropic plastics.

Conclusions

Advancements in prepreg materials and the economical availability of these materials make including fabrication and testing experiences in a composite materials course more feasible than in the past. The value of these exercises is evident in the student comments. Student may be able to perform calculations, but do not always have a good feel for the magnitudes of the numbers. Adding a few tests such as these helps to put the numbers into context. Also, laying up specimens by hand gives more context to the lecture presentations about manufacturing methods. Students gain a better understanding of the importance of ensuring that fibers are oriented properly.

In the future, the authors plan to add composite testing to existing materials science and mechanics of materials classes. In particular, a tensile test with all fibers in the axial direction can be used to demonstrate the high specific strength of carbon-epoxy composites. These tests should stimulate interest in students to study composite materials further.

References

[1] R. Jones, *Mechanics of Composite Materials, 2nd Edition*, Philadelphia, PA: Taylor & Francis, Inc., 1999.

[2] S. Tsai, *Composites Design, 4th Edition*, Dayton, OH: Think Composites, 1988.

[3] M. Hyer, *Stress Analysis of Fiber-Reinforced Composite Materials*, Lancaster, PA: DEStech Publications, Inc., 2009.

[4] CompositesWorld.com, www.compositesworld.com.

[5] G. Gardiner, "Out-of-Autoclave Prepregs: Hype or Revolution?", CompositesWorld, Jan. 1, 2011, www.compositesworld.com/articles/out-of-autoclave-prepregs-hype-or-revolution [Accessed Jan. 31, 2020]

[6] Rock West Composites, www.rockwestcomposites.com.

[7]_Grafil, Inc. Pyrofil TR50S 12K Fiber Data Sheet, www.rockwestcomposites.com/media/wysiwyg/Product_Categories/Materials_Tools/TR50S_12K_-_14046_Fiber.pdf, 2008 [Accessed Jan. 31, 2020].

[8] *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, ASTM Standard D3039/D3039M-14, Oct. 15, 2017.

[9] T. O'Brien, "Characterization of Delamination Onset and Growth in a Composite Laminate," NASA Technical Memorandum 81940, Jan. 1981.