Modeling in a Composite Beam Design Lab

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Abstract

This research explores the use of computer modeling in an undergraduate materials course laboratory exercise. Modeling a beam can enhance learning beyond the traditional beam construction, hand analysis and test evaluation scenario. In our Composites courses MET382 (Plastics) and MET483 (Ceramics), there is a laboratory exercise in which wood core and fiberglass beams are designed and built. A traditional approach is followed; the beams are designed, their stiffness is predicted, and they are mechanically tested for stiffness. A number of parameters are discussed and used, such as geometry and volume fraction. However, the effect and importance of these parameters on mechanical behavior can be hard to grasp. Hand analysis is cumbersome, and may not be friendly to relational analysis.

Modeling can address these issues by allowing the student to readily change material and dimensional parameters to observe their consequences on mechanical behavior. This approach has been successfully used in other MET Program courses such Mechanics of Materials and Technical Dynamics. Examples include the effect of length on the moment of a cantilever beam and the effect of various beam shapes on mechanical behavior.

This study focuses on the use of spreadsheets and more capable modeling programs, such as MDSolids[TM], to support analyses in a specific laboratory exercise entitled: 'Composite Beam Design'.

Introduction

Modeling and applying design analysis is a high order learning activity. Simple structural models with hand analysis are commonly used[1], but computers have enhanced the accessibility of more complex analyses. In specific, analyses using spreadsheets have been used to enhance a composite beam design laboratory.

The Composite Beam Design laboratory exercise has been used for five years since the creation of the MET382 Plastics and Composites course. It is a popular laboratory done during the final weeks of the10-week quarter. Students coming into this elective course are required to have Chemistry, but not a materials course. This broadens the diversity of students in the course, and creates a tight schedule regarding inclusion of basic skills, processes and applications.

As an MET elective, the course involves both analysis and technology. The objective of the laboratory is to involve the students with hands-on experience in composite design. The students also test the beams for mechanical properties.

The laboratory exercise itself is implemented in four stages. First, students are given constraints on materials, sizes, and mechanical characterization. The students perform an analysis on an existing simple beam (usually a wood core material) to obtain its 'spring stiffness'. The spring stiffness is defined as the ratio of maximum load to maximum deflection in a three-point bend test. We then test this beam and compare the values. Second, the students build their own composite beams in the laboratory. This is usually done in pairs. Third, the students analyze their own beams and determine a spring constant. Since this is a composite beam, it involves more dimensional and volume fraction information. Forth, the students test their own beams and compare their experimental and predicted spring constant values.

This laboratory has worked well in many regards. The students interact with both theoretical and experimental aspects of composite beam design, and they have fun doing it. One complaint has been the amount of effort and complexity of the spring constant analysis. One way to ameliorate this situation is to create a spreadsheet for the analysis, like various texts use[2].

Method

Spreadsheets are commonly available. Unlike other specialty software, our university supports student computer labs with spreadsheet capability. A spreadsheet may not be as flexible as a other front-end programs like MatLab™, Mathematica™ and MathCAD™, but it does have usable capabilities. The spreadsheet allows clear definition of input parameters (usually by shaded regions) and output values. Comments can be inserted in the spreadsheet to guide the student through necessary steps in the analysis process. These spreadsheets can be linked through media packages like BlackBoard™ so the student can access them at their convenience. BlackBoard™ course statistical analysis shows that students spend substantial time on-line at late hours[3] when professors and classrooms are not available. This encourages non-linear education to occur, supporting learning objectives that depend on activities outside the classroom[4]. While not committing to the scope of a 'design project' that some engineering technology courses entail[5], this design laboratory does address some of the same objectives. These objectives include analytical, communication and continual learning.

From an analysis and modeling perspective, the spreadsheet is powerful. A sample data sheet for the spring constant analysis is shown below:

DESIGN OF A COMPOSITE BEAM & SPRING CONSTANT CALCULATION				
You must know(determine) the following parameters for your beam:				

1. **Enter data for the modulus of the wood core (Ew):**
2. **Enter data for the dimensions of the wood core (b,h):**
3. **Enter data for the composite matrix (resin) modulus (Em):**
4. **Enter data for the composite fiber/mat modulus (Ef):**
5. **Enter data for the volume fraction of fiber (Vf) and matrix (Vm) material:**
6. **Enter data for the thickness of each composite layer (t):**
7. **Enter data for the length of the beam (tested in 3-pt. Bend) (L):**

Enter values (in *italics* and shaded areas). These must be inserted for each problem.	**Problem Notes:**	*Simple beam only! Rectang. sandwich. Equiv. beam method*	
Input Data:			**Comments**
Wood Core Modulus =	Ew =	*1.0E+06* psi	Check by exp.
Base =	b =	*1.25* in	Use calipers.
Height =	h =	*0.6* in	Use calipers.
Composite Matrix (Resin) Modulus =	Em =	*1.00E+07* psi	Via database.
Volume Fraction of Matrix =	Vm =	*0.60*	Optical meas.
Composite Fiber (Cloth/Mat) Modulus:	Ef =	*3.00E+07* psi	Via database.
Volume Fraction of Fiber =	Vf =	*0.40*	Optical meas.
Thickness of composite layers =	t =	*0.1* in	Use calipers.
Length of the beam (in 3-pt. Bend) =	L =	*10* in	Use a ruler.
Computed Values:	Rule-of-mixtures	$E_c = E_m \cdot V_m + E_f \cdot V_f$	
Composite Layer Modulus =	Ec =	1.80E+07 psi	
Equivalent Beam Factor =	n =	1.80E+01	$'n' = E_c / E_w$
Equivalent Beam Base =	be =	22.5 in	$b_e = n \cdot b$
	Note: It's a really wide flange!		

Note the 'Equivalent' Beam Geometry:			
The real beam is a rectangular sandwich: ‖‖	Base = b		
But the equivalent beam has wide flanges: ‖‖	Flange base= be		
(and uses the modulus of wood alone)			
Computed Values:	Simple beam $I = 1/12\ bh^3$ but:		
Composite Beam Moment of Inertia = Ic =	0.629 in^4		$I_c = 1/12\ bh^3 + 2[1/12\ b_e \cdot t^3 + (b_e \cdot t)(h/2 + t/2)^2]$
Composite Beam Spring Constant = Kcalc =	3.0E+04 lbs/in		
('K' is the slope of load vs. displacement)	where $K_{calc} = 48 \cdot I_c \cdot E_w / L^3$		
Experimental Determination of K:			
First, test the beam in 3-pt. bend.			Now,
Second, plot Load vs. Displacement.			compare
Third, determine the slope of P/S: Kexp =		lbs/in	them!

This approach allows the students to concentrate on getting the necessary parameters to determine a spring constant. It also allows the student to change these parameters and see their effect on the spring constant. This aspect of the spreadsheet can be advantageous in weighting the parameters regarding their importance in the analysis. Though some parameter limits are discussed (e.g. volume fraction), determining the 'design drivers' is an aspect of the laboratory that has eluded our attention.

Results and Discussion

Using spreadsheets is a new compliment to the Composite Beam Design laboratory exercise. In itself, it alleviates problems in analysis computational errors. However, it allows other analyses to occur such as parameter weighting. The modified laboratory exercise includes a number of comparisons that the students can model. These topics for comparison include:

- Compare the weight increase vs. attaining a 10% increase in stiffness via increasing the core height vs. increasing the amount of composite.
- Compare various beam geometries using the same amount of core and composite material to attain a maximum stiffness.

These comparisons are incorporated into the first stage of the laboratory. Not only will the simple beam be analyzed and compared with experimental data, the various student groups can work a comparison study as homework. Increasing the time-on-task of the students is an important goal, and with the spreadsheet as an analysis tool it is possible to assign this type and level of homework.

An example spreadsheet for the first comparison study is show below:

TRADE STUDY OF WEIGHT AND STIFFNESS VS. CORE & COMPOSITE DIM.					
Assume: 1. The base dimension is constant					
2. No stability analysis is applied					
3. Manual data generation is required					
1. Enter data for the density of the wood core (Rw):					
2. Enter data for the 'base' beam dimension (b):					
3. Enter data for the height of the wood core (h):					
4. Enter data for the density of the matrix (Rm):					
5. Enter data for the density of the fiber (Rf):					
6. Enter data for the volume fraction of fiber (Vf):					
7. Enter data for the thickness of composite layer (t):					

Enter values (in _italics_ and shaded areas).		**Problem**	_Simple beam only!_		
These must be inserted for each problem.		**Notes:**	_Rectangular sandwich._		
Input Data:					**Comments**
Wood Core Density =	Rw =	_5.0E-01_	g/cc		Search database.
Base Dimension of Beam =	b =	_1.25_	in		Link from Sheet 1
Height of the Core =	h =	_0.63_	in		Link from Sheet 1
Composite Matrix (Resin) Density =	Rm =	_0.40_	g/cc		Search database.
Composite Fiber (Cloth/Mat) Density =	Rf =	_0.1_	g/cc		Search database.
Volume Fraction of Fiber =	Vf =	_0.40_			DesignValue
Thickness of composite layers =	t =	_0.1_	in		Link from Sheet 1
Computed Values:					Convert g/cc
Weight of wood core =	Ww =	1.42E-02	lbs/in		to #/cu.in.
Weight of composite =	Wc =	2.52E-03	lbs/in		use .03605 multiplier
Weight of composite beam =	Wb =	3.58E-05	lbs/in		

Trade Study Analysis:

	Height	Thickness	K (lb/in)	Wt.(lb/in)	
Ex. Improve K by 50%					
Note: 1.5 x 20245 = 30367.5	0.5	0.1	20245	2.84E-05	Original Dim.
Now calculate the effect of changes in	0.5	0.2	54985	5.69E-05	
core height and composite thickness	0.5	0.15	3.5E+04	4.26E-05	
on weight and stiffness. Type in values of	0.5	0.13	28882.8	3.7E-05	
h and t on the first spreadsheet to get K.	0.5	0.135	30463	3.84E-05	
Copy this K to the appropriate cell at right.					
Copy the weight (Wb) to the cell at right.					
	0.5	0.1	20245	2.84E-05	Original Dim.
Note: Changes in K and W must be sought!	0.6	0.1	27720	3.41E-05	
Repeat this process and build up data.	0.7	0.1	36455	3.98E-05	
	0.65	0.1	31928.1	3.7E-05	
Results: Increasing height for stiffness	0.63	0.1	30206.8	3.58E-05	
creates a lighter beam than adding comp.					

Comparison: (100*(3.8E-5/3.8E-5)/2.8E-5)=35.7% wt inc. for thickness change

(100*(3.8E-5/3.6E-5)/2.8E-5)=28.6 % wt inc. for height change

This data indicates that core height increase will provide the necessary stiffness increase with the smallest weight gain. This may be contrary to what the students might guess, and is certainly an important insight. Also, it points out important aspects of design constraints regarding size and dimensional aspects.

The laboratory exercise also includes experimental testing of the student's beams. In the past, accuracy of predictions has been of interest. Now, a variety of beam designs allow discussion of other issues, such as stored energy management. Also, various failure mechanisms can be addressed, assuming the designs are sufficiently diverse.

MDSolids™

Another analysis tool available to our students is MD Solids™ [6]. This software package allows the student to input complex beam geometries and determine basic responses like shear and moment diagrams, and deflections. This also allows another level of analysis to be explored. In this program you can define odd beam shapes and sizes. Therefore asymmetric beams can be explored. Examples of comparison studies are listed below:

- Using the same core and composite materials, redistribute them to achieve a maximum stiffness.
- Compare three different beam shapes (rectangular, I-beam, and T-beam), using the same amount of core and composite material, with regard to spring stiffness values.

An example, comparing a layered composite rectangular beam with an I-beam of the same material, is shown below. The program models the rectangular beam 1" wide by 0.5" high via standard graphic-user-interface (not shown here). Modulus information is selected, and then cross-section calculations are displayed. For comparison, it is easy to change the geometry to an I-beam, keeping the same area (flange and core), and displaying new cross-section information. Results from both geometries are shown in Table 1, below:

Table 1 MDSolids™ example data

Layered Composite Rectangular Beam	I-beam (of equal area)
Modulus of Flange = 10 msi, Area = 0.1 sq.in.	Modulus of Flange = 10 msi, Area = 0.1 sq.in.
Modulus of Core= 1.8 msi, Area = 0.3 sq.in.	Modulus of Core= 1.8 msi, Area = 0.3 sq.in.
Moment of Inertia (z-axis) = 0.0476 in4	Moment of Inertia (z-axis) = 0.3620 in4

The quick, illustrative output has great visual impact. This analysis tool has been adopted by our students, and is as a primary resource for beam analysis. The data above clearly shows the superior increase in performance of an I-beam over a rectangular beam, with regard to the increased moment of inertia. Since the analysis is quick and thorough, other aspects of beam performance may be investigated, such as weight and stability.

Summary and Future Plans

Improving an educational activity is part of the 'continuous quality improvement' of a healthy program. The Composite Beam Design laboratory exercise was previously successful, and the current modified version is even more so. Modeling analysis tools were incorporated into the laboratory, allowing greater depth of technical coverage and higher level learning to occur. Future modifications include expanding the laboratory fabrication facilities, so that more geometric beam shapes can be made.

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