AC 2008-803: COMPOSITE COLUMN DESIGN/TEST LAB

Craig Johnson, Central Washington University

Craig Johnson is a Professor and Coordinator of the Mech. Eng. Tech. Program (ABET) in the Ind. & Eng. Tech. Dept. at Central Wash. Univ. (www.cwu.edu/~cjohnson). He is also Coordinator and FEF Key Professor of the Industrial Technology Cast Metals Program. He has a P.E. in Metallurgical Engineering, but also has a B.S. in Phys. Sci. and previously taught high school. His BSME is from U WY, an MSMSE from UCLA, & a Ph.D. in Eng. Sci. from WSU. Dr. J. is a past ASEE Materials Division Chair. He specializes in test design, interface characterization/joining. & process optimization (forming & casting). CWU, 400 E. University Way, Ellensburg, WA 98926-7584 509-963-1118 cjohnson@cwu.edu

Composite Column Design/Test Lab

Abstract:

Effective engineered composite design activities require predictive and quantitative methodology. This research incorporates engineering design, using smart spreadsheets, into a laboratory activity focusing on columns made of composite materials.

In a previous work[1], a laboratory activity was developed supporting composite design of polymer matrix composite beams. The present work applies a similar approach expanded to ceramic composites in the form of columns.

In the lab, students simulate composite columns and use a smart spreadsheet to help optimize their design for engineering performance, including 'specific' properties. Parameters are discussed and evaluated before the column is made. The composite is then fabricated. Finally, the composite is tested and the experimental data ('critical load' for columns) is compared to predictions.

Introduction:

The National Educator's Workshop requires certain information be provided in the manuscript. This information includes 'Key Words', 'Target Grade Level(s)', 'Prerequisite Knowledge', 'Objectives', and 'Equipment and Supplies Needed' are shown below. A traditional 'Introduction' appears subsequently.

Key Words: Composites, Column Design, Spreadsheet Optimization

Target Grade Level(s): This activity is oriented to Grades 13-16 (undergraduate college).

Mode of Presentation (lab, demo, in-class activity, etc.): This activity includes in-class, demo and lab aspects.

Prerequisite Knowledge: Students should be able to

1. use spreadsheets,
2. have basic knowledge of both structures (beam bending and columns) composites and composites structures, and
3. have the logic and math skills necessary to plan and quantify the composite design and optimization process.

Objectives:

- Students should be able to design an appropriate composite column structure, model the composite structure, optimize the composite structure design, and subsequently predict its performance.

- Students should be able to fabricate the composite using an appropriate method and test the composite for critical parameters.
- Students should be able to critically evaluate the composite's performance with reference to the predictions, testing methods, and appropriate literature data.
- Time Required: 2-3 weeks duration with 3-5 class interactions depending on curricula, and infrastructure for fabrication & testing.

Equipment and supplies needed:

- Modeling: spreadsheet and platform, access to composite properties, knowledge of composite design/mechanics, knowledge of column design and failure (buckling)
- Fabrication: ceramic composite matrix and reinforcement (continuous/discontinuous), processing facilities (press, vacuum, etc.)
- Evaluation: compression testing (size dependent), dimensional measurement (modal description)

In a traditional composite lab approach, composite structures (beams and columns) are designed, their properties (e.g. stiffness) predicted. Then they are mechanically tested. Tensile testing (three-point) beams is more suited to polymer matrix composites than ceramics (with a pardon to all the bridge decks vs. columns out there). So at Central Washington University, the MET382 Plastics and Composites course utilizes beams while the MET483 Ceramics and Composites uses columns as target structures. In a previous effort[1], a smart spreadsheet was created specifically to solve for three-point bend stiffness of a layered polymer composite in support of MET382 Plastics and Composites. The current effort focuses on column design for the MET483 Ceramics and Composites course, but also endeavors to include an optimization routine targeting 'specific' properties (e.g. stiffness per unit weight).

In the ceramics class, compression testing allows a brittle material to survive longer than tensile tests. Bend tests are conventional for many bridge applications, but they are done in the MET382 course. For diversity, and other attributes, compression testing is the primary focus for the ceramics course. Most students do not engage often in structural design regarding compression, but may be introduced to 'column design' as an example. Introductions usually occur in a 'Strength of Materials' course[2]. Thereafter, information may be found in some 'Machine Design' courses[3]. Typical engineering handbooks[4] also summarize column design, and relate the variety of analytical approaches. There are numerous 'critical load' equations for different materials (e.g. steel vs. aluminum) and different lengths (e.g. 'short'-Euler vs. 'long'-Johnston). In practice, the predominant method for design of any sort is numerical. On a recent peruse of the Internet, a site was found that listed many numerical analysis programs that are available[5]. Because of the education level of interest in this lab, all design analysis was constrained to analytical. This both reduces costs (for the numerical programs) and emphasizes the parametric nature of what affects the performance of these column structures. For this paper, two critical load calculations have been included (long and short). Euler is used for a 'long' column, and a Graphite/Epoxy (Gr/Ep) relation from Jones[6] is used for a 'short' column. This illustrates the extreme variability of predictions.

A number of parameters, key to the success of this type of structural design, are implemented in this lab. These parameters include geometry, volume fraction and loading. The effect and importance of various composite parameters on mechanical behavior can be hard to grasp. Since traditional hand analyses are cumbersome and prone to error, the use of 'smart' spreadsheets is appropriate. Hand analyses are also not very friendly to relational analyses and optimization. This lab uses smart spreadsheets to alleviate these issues. An excerpt of the lab is shown below:

Instructions: Note: Please observe lab safety policies during this activity.
The plan: Everyone should make two columns: one homogenous and one composite (though a two person team can make two sets). Our immediate objective is to design the column. We will spend a class session on this part of the lab. Start by writing design requirements and constraints. For example, we will test the columns on the Tinius Olsen. The plattens will be vertically oriented, and the columns should not exceed a foot tall. Available materials include concrete, wood core, fiberglass, epoxy, graphite, honeycomb, etc. (in HT212), one of which must be a ceramic).

The next step will be to predict the properties for each individual column. Custom Excel™ spreadsheets have been created to assist your analysis. The geometry is limited to traditional column analysis (see Hibbeler or Beer & Johnson or Mott). Create a design and input the appropriate geometry and material properties. The spreadsheet will calculate the resulting radius of gyration, slenderness ratio and critical load (mode one deflection caused by free-end loading).

Each student (or team) will have to research and decide on a design, material, and forming method for their columns. Specify a column-geometry (suggested length of about 12", width and thickness less than 1"). You must select a composite material and lay-up design, and then construct the column. We have a hot press, vacuum bags, and even an RTM (resin transfer molding) system.

We will then test the columns and compare their experimentally measured properties (critical load) to the calculated load. The Tinius Olsen is a tensile/compression tester on which can you measure both the load and the resulting deflection (to detect mode one initiation).

You will have to plan your activity due to time constraints. Check your schedule and plan for the testing needed. We will do a preliminary compressive test on a column of simple wood core, so that you'll have a clue of what to expect during the testing of your column. We don't have to break the column, only initiate 'mode one' deflection. We're trying to predict the critical load on the column. A requirement is that you predict the structures' behavior before you test it.

After you have tested the column, compare your prediction with your test data, and also what is in the literature (if possible). Comment on how close your values are (in percent), as well as reasons that explain your results. For example, your predictions may have assumed a more favorable fiber volume or material property than actually existed in your structure.

The lab (both from lecture and handout) also describes the spreadsheet and its use. The spreadsheet itself has areas of ‘input’ (gray shaded) and areas of ‘calculated values’. It generally flows from top-to-bottom, and data is entered sequentially. The front page is shown below:

DESIGN OF A COMPOSITE COLUMN & CRITICAL LOAD CALCULATION by Craig Johnson
You must know (or determine) the following parameters for your column:

1. Enter data for the modulus of the core (Ew) below:
2. Enter data for the dimensions of the wood core (b,h) below:
3. Enter data for the composite matrix (ceramic) modulus (Em) below:
4. Enter data for the composite fiber/mat/other modulus (Ef) below:
5. Enter data for the volume fraction of fiber (Vf) and matrix (Vm) material below:
6. Enter data for the thickness of each composite layer (t) below:
7. Enter data for the length of the column (L)
below:

Enter values (in *italics* and shaded areas). These must be inserted for each problem.	**Design Notes:**	*Analysis for a simple column only! Assume a rectangular sandwich. Use an equivalent column method Critical Load (Pcr) shown below:*

Input Data:				**Comments**
Core Modulus =	Ew =	*1.0E+06*	psi	Check by experimental testing.
Base =	b =	*1.00*	in	Use calipers.
Height =	h =	*0.70*	in	Use calipers.
Composite Matrix Modulus =	Em =	*1.00E+06*	psi	Search a database.
Volume Fraction of Matrix =	Vm =	*0.60*		Vf+Vm=1 with 30<Vf<70
Composite Fiber Modulus =	Ef =	*3.00E+07*	psi	Search a database.
Volume Fraction of Fiber =	Vf =	*0.40*		Measure optically
Thickness of composite layers =	t =	*0.1*	in	Use calipers.
Length of the Column =	L =	*10*	in	Use a ruler.
End Fixicity, K (Free=1, Fixed=.65) =	K =	1		Fix/Free=2.1, Fix/Pin=0.8
Composite Strength =	Sc =	50	psi	Tables or other source.
Column Constant =	Cc =	223.0309534		Cc=(.02*pi^2E/Sy)^.5
Computed Values:				Uses 'Rule-of-mixtures'
Composite (Layered) Modulus =	Ec =	1.26E+07	psi	Ec=Em*Vm+Ef*Vf
Equivalent Column' Factor =	n =	1.26E+01		'n' = Ec/Ew
Equivalent Column Base =	be =	12.6	in	be = n * b
Area of contact =	A =	0.900	in2	
Effective Length of the column =	Le =	10.000	in	Effective Length is K times L
Use 'Equivalent Beam/Column' Theory for Moment of Inertia:				
The real column is a rectangular sandwich:	||||	Base = b (width)		
(the flange is the top or bottom)				
But the equivalent column has wide flanges:	___||||___	The new		NOTE: Moment of Inertia = I
(and uses the modulus of wood alone)		Flange base= be		
Both I and Slenderness Ratio are used to calculate Pcr:				Simple column I=1/12 bh^3 but:
Composite Column Moment of Inertia =	Ic,x =	0.434	in^4	Ic,x = 1/12 bh^3 + 2[1/12

Trans Composite Column Moment of Inertia =	Ic,y =	33.398		be*t3+ + (be*t)(h/2+t/2)^2] Ic,y = 1/12 hb3 + 2[1/12 t*be3]	
Radius of Gyration, rx =	(I/A)0.5=	0.69			
ry =		6.09			
Slenderness Ratio, SRx =	KL/rx =	14.40239676		The column is:	Short
SRy =		1.641577754			
SRmin =		1.641577754			
Determination of Pcr:					
If a short column (SRmin<Cc):	Pcr,s =	12600	lbs	Pcr,s=Ec*t^3/(b^2) GrEp Jones	
If a long column (SRmin>Cc):	Pcr,l =	41532673.12	lbs	Pcr,l=π^2EA/(KL/r)2	
	Pcr =	12600.000	short		
Experimental Determination of Pcr:					
First, test the column in compression.					
Second, record the load at n=1 deflection:	Pexp =	10000	lbs		
Third, compare experiment with calculation:	Error =	0.26	%	% off =Pexp-Pcalc/Pexpx100	

Comments:

An integral part of the lab is the use of the spreadsheet to optimize the column design and predict properties, while alleviating problems with computational errors. This assumes that the students have the basic knowledge of structural design. Students should be aware of various types of loading, moments of inertia, and important design criteria. In the case of a column, this means that they are cognizant of short vs. long column criteria, and can understand critical loads (Pcr).

An introduction to the spreadsheet and some of its features is typically needed (depending on the class response). The spreadsheet has multiple ‘sheets’. Some input cells have limits that reflect real bounds on the value. Comments are written in the right column. So in-class demos of various input and resulting outputs are used to show the design and optimization process.

The spreadsheet is used during class to promote discussion, and is also available on BlackBoard™ for off-line reflection. There is a requirement that a spreadsheet (with predictions) is to be submitted before testing can occur. The goal here is to avoid the trap of students wanting to build the ‘strongest’ column, but to keep their interest in building a most ‘predictable’ column.

The composite structure fabrication aspect of the lab depends on the resources of the institution. Simple pressure (gravity) is appropriate, though various bag technologies are nice. This is the reason that the Pcr equations are tailored to a composite sandwich structure.

Testing is also dependent on available resources. A tensile/compression tester is a common tool for evaluating structures. A simple dial-gage is typically used to measure lateral displacement, though a light profile has also been employed. Only the critical load is recorded for comparison to the predicted value.

Evaluation of the Activity:

During the 2-3 weeks that the activity occurs, student work is handed in regularly. Initially, effort is directed at model creation and performance prediction. This culminates in the student handing in the necessary documents for each. The model is drawn, with relevant composition and fabrication information. The prediction requires the student hands in a spreadsheet (evidence) with its relevant information.

The second phase of work evaluated is the composite structure itself. Previously the students have been in the lab applying their knowledge of ceramics and composites with regard to both manufacture and characterization. By this experiment, they demonstrate their abilities to fabricate a structural column that matches their proposed model. The instructor can compare geometry and other composite parametric information.

The final phase of effort involves the testing and comparison of composite column performance. Students hand in a lab report that includes evaluation of the design process, including statements directed at sources of error and remediation techniques.

The completeness and sequential aspect of this laboratory allows for multiple assessments. As the students interact with both theoretical and experimental aspects of composite design, the instructor can track progress and remediate concerns. Multi-step labs are easier to grade (in parts).

The lab can also address objectives pertaining to communication and continual learning, with specific metrics. For example, the preliminary design work can be graded individually, but the columns could be fabricated in teams and assessed for that objective. An example of lab deliverables is shown below:

Student work categories:	Metric used:	Ex. of student performance:
Column design (geometry)	4 Design Para's (1pt each)	70% scored '4'
Pcr prediction	Spreadsheet completeness	90% completed
Column fabrication	Integrity, geometry, fiber dir.	70% scored '3'
Experimental vs. Prediction of Pcr	1 pt for each std deviation off	50% scored < '5'

Four student work categories were used to assess the lab. While most of the students completed the 'design' phase of the lab (70%), predicted a buckling load (90%) and fabricated a column (70%), they were not as successful correlating their prediction well with their experimental results (50%). This reflects both the predictive relation used, and the experimental methods employed. There are multiple critical load relations, and future work is devoted to developing validity. Also, the critical load is sensed by lateral motion in Mode 1 with a dial indicator. The deflection that correlates with Mode 1 is small (a few thousandths of an inch) and it does not appear abruptly. A larger lateral displacement would allow students to more easily see the buckling behavior. A longer column might allow both the larger lateral displacement and lower the overall buckling load. There is a vertical constraint of about two feet on the available tensile tester, but there is room for modifications. These issues will be addressed in future labs.

Student comments were sought from a recent class, and some feedback is shown below:

How much do you agree with the following statements:	1 (disagree) to 5 (agree)	Standard Deviation
The Column Design laboratory made me think of *predicting* a design property	4.04	0.84
The spreadsheet made it *easier to calculate* a critical buckling load	4.00	0.96
Fabricating and testing the composite column was an important part of the lab	4.48	0.92
The spreadsheet made it easier to use important composite design parameters	3.88	0.93
The Column Design laboratory was worthwhile.	4.12	0.83

Students in MET483 are of mixed background such as Industrial Technology and Electronics Engineering Technology. Many are unfamiliar with the use of spreadsheets and the design process, but most appreciated their use for 'calculating', 'predicting' and 'using' design properties and critical buckling loads. Since the course uses BlackBoard™, many students download the spreadsheet and work off-line and off-hours[7]. This is also a plus for engaging students in the process.

Most of all, students find fabricating structures and subsequent testing is very 'important' (4.48/5), and the lab in general was 'worthwhile' (4.12). Standard deviations were below one, but no other statistical analyses were done.

Conclusion:

The Composite Column Design/Test Lab combines an educational environment that promotes the design and optimization of a composite structure, with the fabrication, test and comparison of experimental results and predictions. Metrics were used to support outcomes of order learning (e.g. Bloom's taxonomy and 'design'). This was useful in meeting the needs of ABET requirements. Student feedback indicated strong support for continued use of this lab.

Acknowledgements:

Fiberglass used in this laboratory were provided by The Boeing Company and Battelle (PNNL).

Bibliography:

1. Johnson, C.H., "Modeling in a Composite Beam Lab", ASEE Annual Conference, 2002.
2. Hibbeler, R.C., "Mechanics of Materials", Prentice-Hall.
3. Mott, R.L., "Machine Elements in Mechanical Design", Prentice-Hall.
4. Avallone, E.A., Baumeister III, T., "Marks' Standard Handbook for Mechanical Engineers", McGraw-Hill.
5. http://www.structural-engineering.fsnet.co.uk/free.htm Last updated: 21 May 2006.
6. Jones, R.M., "Mechanics of Composite Materials", Scripta Book Company and McGraw-Hill.
7. Johnson, Craig, "BlackBoard™ MET382 Course Statistics", Central Washington University, 2006.