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Virtual Hands-on: Taking a Design Lab Online

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Virtual Hands-On: Taking a Design Lab Online

Impetus: COVID as a design constraint

As with the rest of industrialized society, the reliance of design education on digital tools and virtual platforms is on the rise. There are ample examples in the literature dealing with transitioning specific learning outcomes from hands-on to online.[1] However, what if the transition to the virtual space was total, immediate, and involuntary? Of course, this scenario is exactly what the COVID-19 pandemic engendered for a number of professions. For many of us involved in teaching engineering design, this manifested an interesting and urgent challenge. How do we run normally hands-on, data-driven labs online that emulate the experience of a turnkey design project that produces a physical prototype?

This paper covers our process for modifying an existing undergraduate structural performance and failure design lab. We used the constraints of having to go online as an opportunity to improve the course through tightening the correlation between theory and data and solidifying the underlying design methodology fundamental to the course's pedagogical goals. Outlined are steps to developing a virtual engineering design project that requires an iterative design process informed by the application of specific theory contextualized by data and communicated through a detailed graphic spreadsheet modeler.

It should be noted that we offer no quantitative assessment comparing the online course to the hands-on version. The design intervention described here was by necessity accomplished quickly and without access to typical curriculum adjustment protocols. In fact it started mid-semester of Spring 2020 when we were suddenly forced to go online. In addition our university responded to the unique challenges posed by the pandemic by allowing professors to opt out of course evaluations for that semester if they so chose. In short, we simply do not have reliable data to conduct a meaningful comparison of student response between the two course modalities. Be that as it may, we believe that the process, specific adjustments, and lessons learned are valuable and worth sharing.

Starting point: the original hands-on design lab

"Structural Performance and Failure" is a required team-based sophomore design class at our university. It is taught on average to about 600 students in 25 individual sections. The project topic is the design, fabrication, testing, and analysis of trusses. The pedagogical context is the application of theory informed by data to solve a defined problem through an iterative design process. Tension, compression, and shear are introduced in the context of truss theory. Theoretical calculations and published specifications are juxtaposed to data collected from testing brass profile and assembly samples toward the understanding of how geometry and loads interact. Truss geometries are then analyzed mathematically to calculate theoretical failure loads and modes. The final design project involves creating truss geometries that have high strength and strength to weight ratios. Groups choose one truss design to fabricate and test, allowing a comparison of theoretical and empirical failure results. This all leads to a final competition where fabricated trusses are tested to failure with results compared both to one another and to theoretical projections for each truss (see Figure 1).

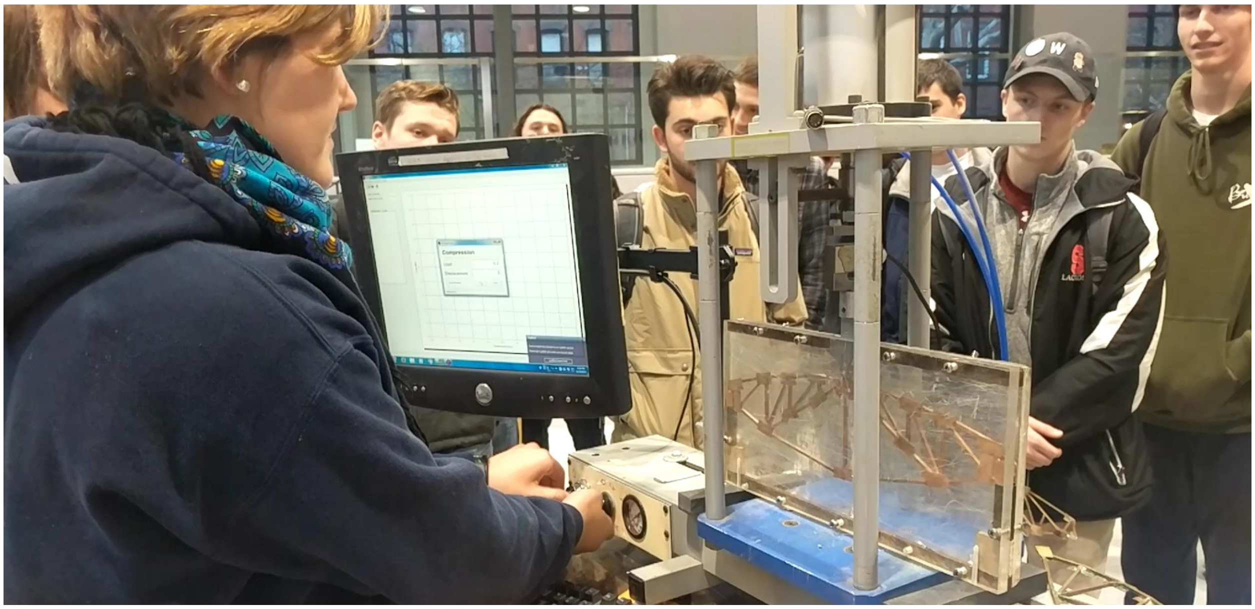


Figure1. Hands-on design lab culminates in the fabrication and testing of a soldered brass truss.

Course redesign strategy: improve correlation between theory and collected data in service to a re-focused iterative design process

WWDPTTSTD? What would a design professor tell their students to do? In our courses, we are always preaching to students that constraints are what design pushes against to take shape [2]. Going online is just another constraint on course design, so we asked ourselves what advantages could be found. First off, what is being constrained? When analyzing this course, we realized that students do two things hands-on in the lab: data collection and prototype fabrication. How could we turn the online forfeiture of these activities into course improvements?

Elementary truss design is an interplay between geometry and material. As such, it can be accomplished with the application of fairly basic engineering theory using standard theoretical equations and published material specs. At the same time, specimens can be tested to failure using inexpensive equipment to generate data that can be used in comparison to the theoretical calcs and published specs. The more accurate the data collected, the more instructive this comparison for students. Since currently students could not collect data online, it would have to be provided. We resolved to use this constraint as an opportunity to examine closely and clean-up our data collection methodologies to improve this data to theory linkage. In the process, we would generate a series of datasets that would serve as the "gold standard" for student collected data in future semesters.

But what about prototype fabrication and testing? Bringing something imagined into the physical world is a complex, difficult transition. Anyone with design/build experience knows that intimately. There is no substitute for that experience, so that is a loss plain and simple. However, we realized that the prototyping process in this course takes up about 1/3 of class time and only generates two useful datapoints in testing: truss failure load and weight. Some would argue this is a poor return on investment. Practically speaking, not being able to fabricate opened up a lot of class time.

Upon a bit of reflection, the answer to what could fill this void was obvious. Undergraduate engineering design has by definition a strong theoretical and technical foundation, but design is fundamentally creative in that it starts with a problem (nothing) and generates a solution (something). In our experience, beginning engineering designers often resist the creative process. They want to be given the answer upfront and be taught how to work toward it. Ironically, design professors can suffer from the same affliction. The question of how to teach the creative application of theory toward an unknown solution to a defined problem is itself a design problem. We resolved to take advantage of freed-up class-time to focus on refining and teaching an iterative design methodology that would be applicable to the design tasks in the course and hopefully beyond.

Tightening the correlation between theory and collected data

In the hands-on lab, students design, fabricate and test trusses using brass HSS tube stock soldered to brass strips. Simple planar truss theory posits physical constraints that result in two force members that experience either compression or tension normal to the cross-section of the member. Joints are not considered in the theory, so in practice they need to be "infinitely strong", i.e. if joints fail, the theory cannot be applied to truss performance. For class purposes, we present the joints as experiencing shear stress, and so they need to be designed to take a worse case scenario load that is below a computed shear stress for the joint assembly. Therefore, experiments are designed to test brass specimens to failure in tension, compressive buckling, and shear. We were aware that in previous semesters data collected by students in these experiments did not align well with published specifications for the material specimens we were using. We had some theories, but the current situation gave us a mandate to conduct a careful study.

In our first experiment for the hands-on semester, students use testing equipment and specimens manufactured by the same company and designed to be used together in measuring stress/strain of specimens under an axial tensile stress. We discovered that the statistical noise of outlier data from a percentage of students attributable to beginner's error had obscured important information. Upon closer study, generalized student results in previous semesters were that consistent ultimate tensile stress (UTS) values closely aligned with specifications provided by the company [3]; however, Young's modulus (stress/strain) numbers from the same tests were about 1/4 of specified values. Analyzing this result, it seemed that the load cell was functioning well, but inaccurate displacement data was collected. This can be deduced since UTS (stress) is a function of load and cross-sectional area, while strain is a change in specimen length which is measured by the displacement sensor.

Armed with this clue, we discovered that part of the reason for poor strain measurements was that students were not carefully enough following protocols related to accurate displacement measurements. After careful adherence to manufacturer protocols including displacement calibration of the tensile testing equipment prior to testing according to provided specifications and pre-loading of the specimen to remove slack from the load string, our dataset correlation to published values improved considerably. Upon further investigation, we realized part of the fault was ours, as we had not been following the methods outlined in ASTM standard E111[4] to determine the Young's modulus from the collected data. Incorporating this tweak into our analysis brought our measured modulus values in line with published specs. Specifically, the dataset of nine specimen had a coefficient of variation of 2.3% and a mean Young's modulus of 80.7MPa with a manufacturer supplied spec of 80MPa, almost certainly a rounded value.

The second course experiment collects buckling data. Our testing equipment system includes brass samples designed for use in tension experiments, but not buckling. As a result, we have been manufacturing our own chucks to hold specimens in place for an axial buckling test of brass HSS profiles. These custom chucks provide connections with indeterminate end conditions values, a fact that we use to our advantage in the buckling assignment (see below), but that makes evaluation of testing accuracy harder to undertake.

Still, we knew student datasets were faulty due to the large range of values encountered in a controlled experiment. We thought one reason might be our chuck design and another was most likely novice mistakes. The sensitive nature of the buckling load on minor deviations in end conditions, asymmetric loading, or initial lateral deformation of the specimen [5] emphasizes the importance of a closely controlled testing environment. After a complete redesign of the chucks (see Figure 2) and carefully controlled collection protocols designed and implemented by experienced users, our datasets became very consistent and had good correlation with theoretical calculations (see Figure3).

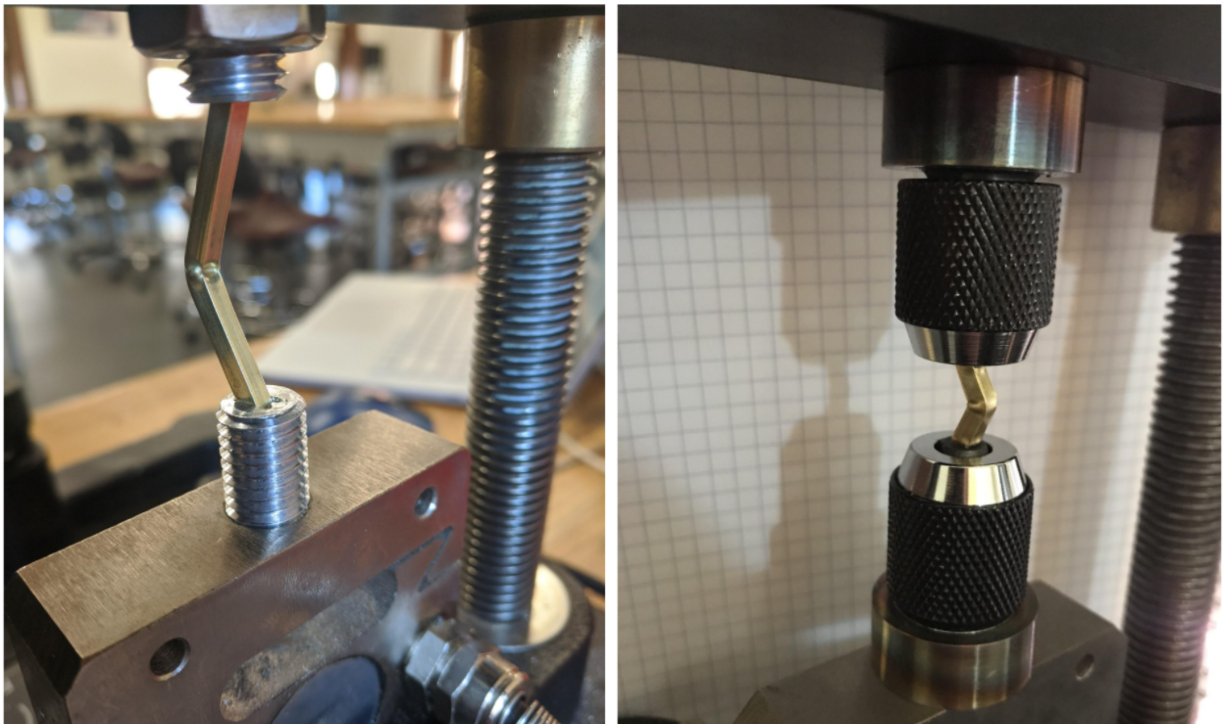


Figure 2. Custom chucks redesigned as part of a move to calibrate collected data to theoretically derived and published values: (a) old design allows for movement within the connection; (b) new design utilizes keyless, self-adjusting drill-type chucks for more consistent connections.

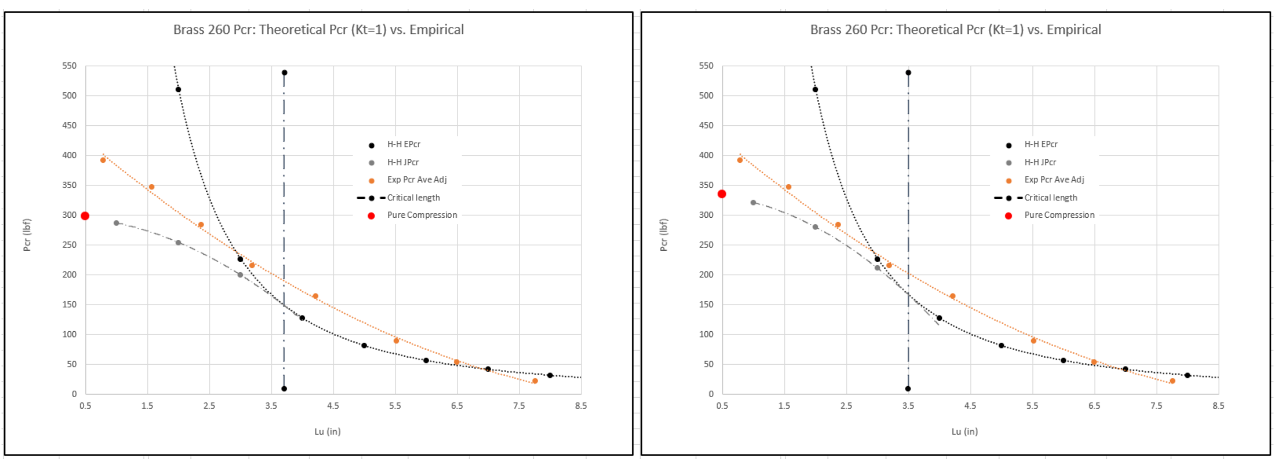


Figure 3. Euler's and Johnson's theoretical critical buckling load equations (black and grey) and measured dataset (orange) show a close correlation. (a) Yield = 48Kpsi; (b) Yield = 54Kpsi.

The situation with our joint testing data was harder to solve. Since our truss fabrication method has been soldered joints, students had been building and testing soldered brass overlap joints to failure. As with the other experiments, data has typically been inconsistent with two explanations proffered. First, solder connections are a site made material whose strength is dependant on a number of local variables including fabricator's skill. Time constraints in the hands-on studio essentially meant that we were testing joints fabricated on the same day the student fabricators started to learn to solder. In this scenario, there can be little hope of consistent or meaningful results through a cross-section of students. More fundamental than the question of data accuracy was whether soldered joints were appropriate at all in this context. We had inherited the practice of soldered trusses in the course curriculum. The concept was to find a testing and fabrication method that would allow the same material to be used in individual variable testing (tension, compression, shear) and in fabrication, all at a small scale workable in a crowded lab. Soldered brass was chosen and did hit most of the marks.

But there were also problems. First, solder is an adhesive and as such has a complex, nonlinear relationship between overlap area and failure load [6] that actually cannot be approximated with a simple shear analysis. This meant that even data from well fabricated and tested soldered joints would not reflect shear theory. Secondly, simple planar truss theory requires that all truss joints be hinged. Soldering creates a fixed joint, therefore simple truss theory is not strictly applicable due to bending moments in the members. A symmetrical geometry of soldered triangles is a moment frame, not a truss. This distinction is perhaps trivial for large span trusses in bridges or other assemblies of large scale, but our lab equipment limits us to very small (15" x 4") assemblies were moment will have a much larger effect on loaded member strength. The result were large differences between theoretical projected and actual tested performance in final student projects. Clearly we needed a new fabrication methodology to allow for hinged joints. The online semesters gave us time to begin development of one for when we return to our labs (see Figure 4). In the meantime, we were able to fabricate and test brass pins in shear and generated a dataset that correlated well with shear theory (see Figure 5). This would be used with a revamped joint design assignment (see below).

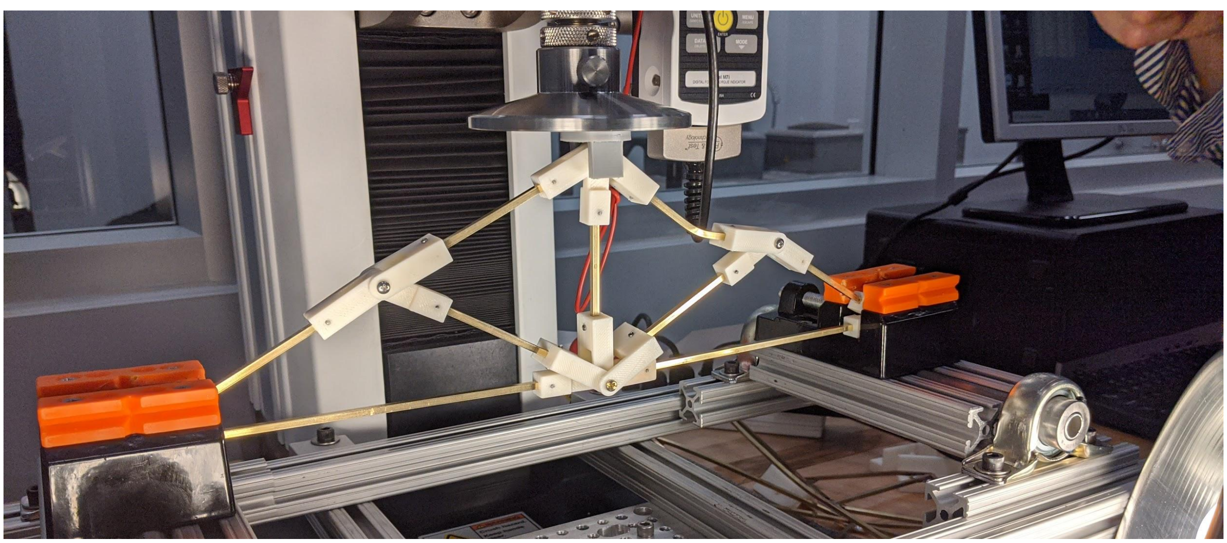


Figure 4. 3D printed pinned joints under development as replacement for soldering fabrication.

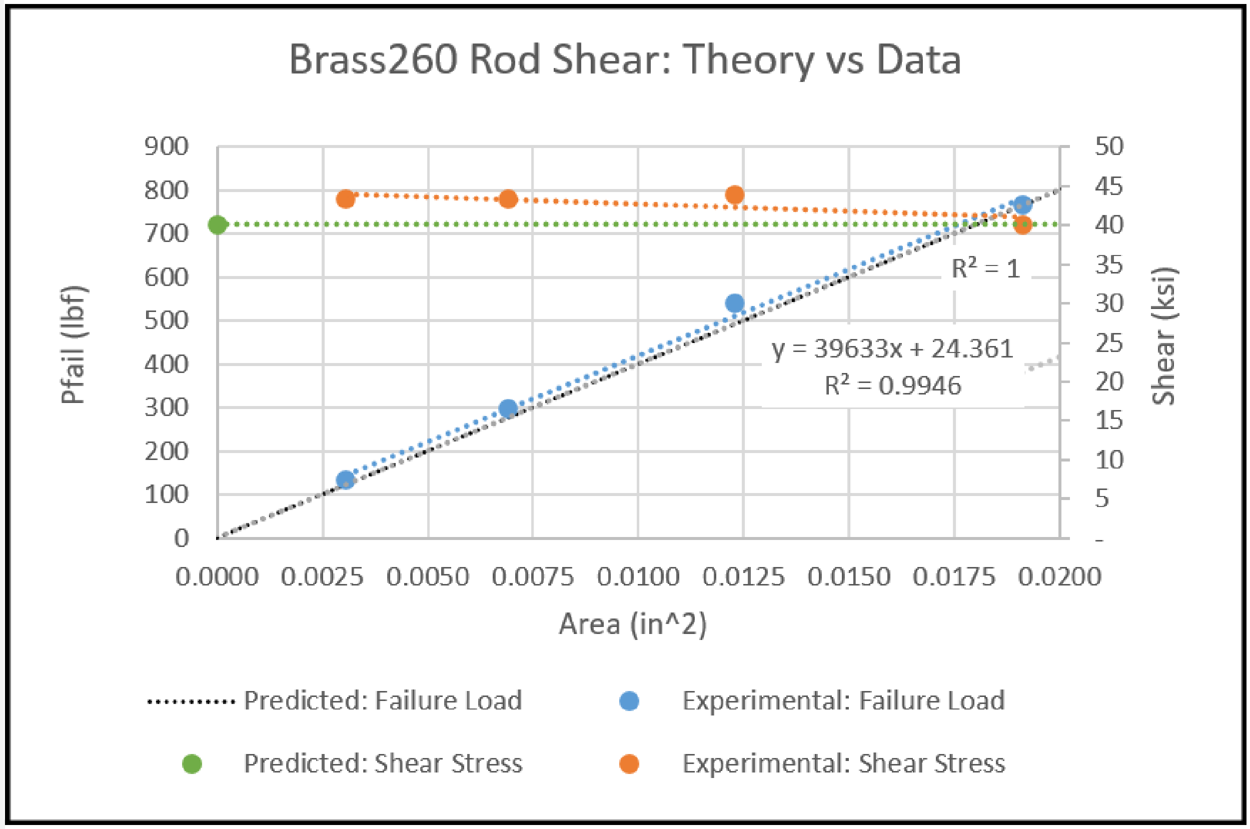


Figure 5. Data from brass rod tested in shear correlated well with shear theory.

The takeaway is that the COVID induced investigation of our data collection procedures bore real infrastructural fruit. We were able to discover and fix procedural issues that were preventing students from generating data that had a clear correlation to the theory being applied to course project designs. Even more importantly, the disruption gave us the window to begin a needed adjustment to our core fabrication methodology, essentially switching from moment frames to trusses. An important move since the student design project involves trusses! This fairly major overhaul was made possible because the break from fabrication allowed us to fix the class joint data issue immediately while giving us a two semester window to develop and change the physical fabrication methodology.

Iterative design

Design can be defined as "*courses of action aimed at changing existing situations into preferred ones*" [7], making design a problem-solving pursuit [8]. As such, a core goal of undergraduate engineering design education has to be teaching a generalizable design methodology that can be applied across disciplines and project topics. More specifically, "design" is action by which a problem is identified in the context of a number of constraints for which a creative solution is sought through iteration [9]. The workflow can take a variety of forms, but the baseline is that general theory is contextualized by specific data and applied through an iterative design process. In each iteration, design outputs are fed back into the design infrastructure as inputs until the defined design goals are reached. To effectively teach a methodology of iteration, the problem to be solved needs to be defined upfront at the beginning of the semester with requisite theory, data, and skills to initiate the design process covered subsequently always in reference to the design problem at hand.

In the hands-on course, iterative design had come to take a backseat to fabrication of a soldered physical prototype. This development was unintentional but simply a function of logistics. Soldering is a somewhat nuanced skill. Add to that the fact that prototypes tended to include complex geometry with lots of short members because the truss project competition focused solely on final truss strength, and you end up with fabrication taking up at least one third of the total semester class time. This approach produced a single truss prototype per team that was inexpertly fabricated and therefore fated to have poor correlation to theoretical performance when tested to failure. More importantly, without the opportunity to iterate designs the linear application of theory to geometry in search of meeting design goals was considerably weakened. Projects often devolved into an informal competition to see who could design the strongest theoretical geometry without concern for an understanding of what in the form specifically manifested that strength. (See Figure 6.)

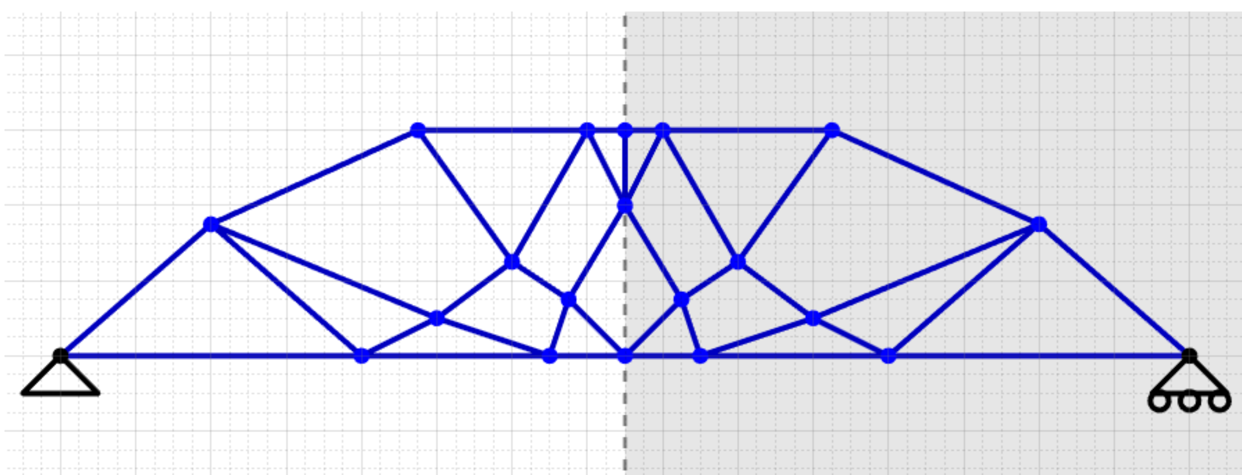


Figure 6. An impractical truss designed by a student in a previous hands-on design lab that clearly does not reflect an understanding of simple planar truss theory.

Without the possibility of fabrication due to taking the course online, considerable time was freed up in the class and we resolved to make use of that to guarantee design iteration. This was accomplished first by presenting the semester project in week one and defining the design program as a team-chosen investigation into some aspect of the relationship between geometry and performance in truss design. Instead of a focus on a single design roughed in theoretically and then fabricated and tested physically, the task would be to pick a research investigation, such as “Investigation into the role of relative member angle to truss strength” or “Starting with a 3-bay Warren Truss, how do we morph to a Bowstring design and what is the overall effect on performance?”.

After introducing the project, we organized the first half of the semester into a series of exercises that systematically introduced the requisite theory and contextualized it through data collection, analysis, and display to build the knowledge and skills to approach the design. Each exercise could in the end be used as an input for the design process. The project then took up the second half of the course. Once an investigation had been chosen, students would begin with a single geometry related to the topic and analyze it using tools taught in the first half of the semester. As a result, failing members would be identified and truss strengths and strength to weight ratios calculated. This information would then be used to change the geometry in service to the chosen investigation through the application of theory learned during the semester, in other words the initial design would be iterated. This process was repeated until a conclusion related to the investigation could be made.

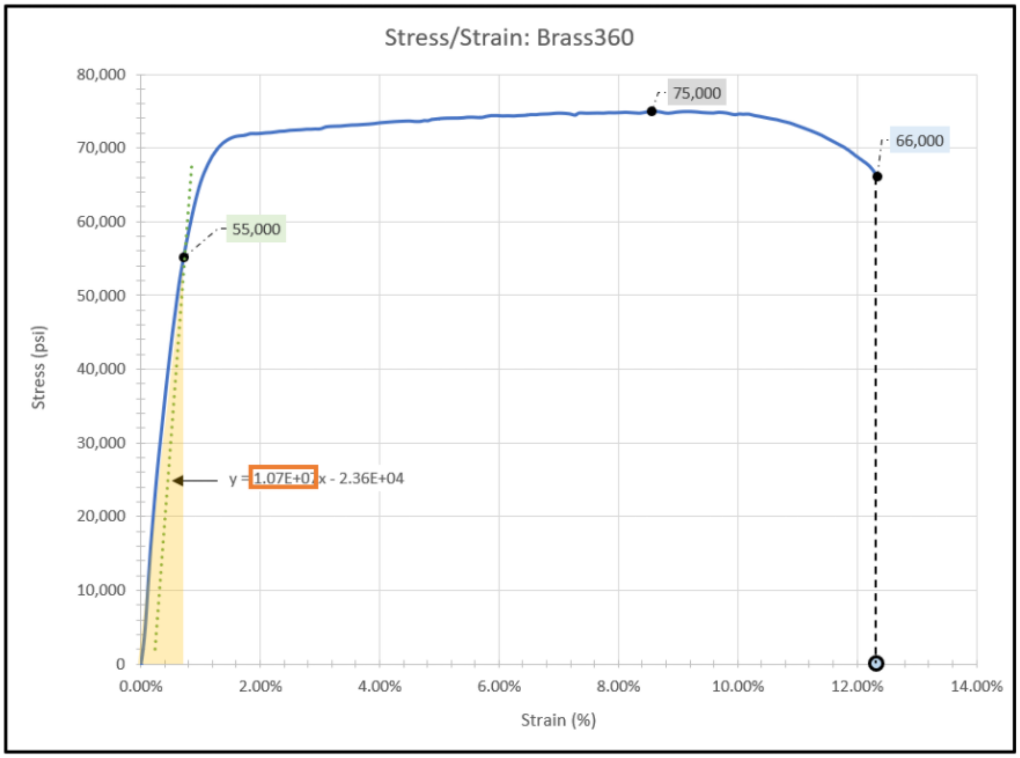
Spreadsheet apps as design tools

Truss design involves the quantitative analysis of geometry in the context of defined material assemblies. Iterating truss geometry to meet specific design goals requires clear graphic display of that geometry in the context of the quantitative analysis. To be done effectively, fairly advanced spreadsheet skills need to be applied. Though all engineering students at our university have to use spreadsheet apps in various contexts, there is no required course that teaches related skills. The result is that spreadsheet apps are often seen as tools to produce graphs to screenshot into reports, rather than as tools to organize, analyze, dynamically communicate, and archive data. Since this design lab is a required course for all engineering undergrads, we were in a position to fix that omission and determined that some of the time gained from not performing experiments would be put into more in-depth instruction in the application of spreadsheets. These skills would greatly serve the goal of improving the iterative design process in this course.

Tension: multi-variable data display of the stress/strain relationship

In the context of simple planar truss design, tension needs to be introduced as an axially pulling load that causes an internal response (stress) through the cross-section of the material and an external response (strain) in the form of elongation. Stress/strain diagrams express curves unique to the material being tested and include quantification of material parameters including Young’s modulus, yield strength, and ultimate tensile strength. Perhaps most importantly in the service of truss design, they also illustrate the fact that specimen length is unrelated to material strength because load equals stress times profile cross-sectional area, i.e. length is not relevant.

Expressing all of this information clearly in a single diagram is a detailed task making the stress/strain diagram an excellent first assignment in good spreadsheet practice (see Figure 7). Concepts/skills introduced included: locked RAW DATA sheets as prerequisites of any spreadsheet workbook, sheet layout, formula input and organization, cell naming, trendline application, datapoint labeling, and superimposed free drawing.



TERMS	
Axial load	P
Cross sectional area	A
Displacement	ΔL
Working length	L_o
Diameter	D
Stress = P/A	σ
Strain = ΔL/L_w	ε
Elastic region	
Modulus of elasticity	E
2% Offset yield strength	$Y_{2\%}$
Ultimate tensile strength	UTS
Stress at fracture	F
% elongation at fracture	ε_F
PUBLISHED SPECS (SI)	
Material	Brass 360
Source	Pasco
D (mm)	3.3
L_o(cm)	3.2
E (GPa)	80
UTS (Mpa)	500
PUBLISHED SPECS (US)	
D (in)	0.130
A (in^2)	0.0133
L_o (in)	1.26
E (psi)	1.16E+07
UTS_p (psi)	72,519
Yield offset	0.002
EXPERIMENTAL VALUES	
E_e(psi)	1.07E+07
$Y_{2\%}$ (psi)	55,000
UTS_e (ksi)	75,000
F (psi)	66,000
ε_F (%)	12.3%
ANALYSIS (% error pub vs. exp)	
E	8%
UTS	3%
CONVERSIONS	
Meters to inches	39.37
Newtons to pound force	0.2248
Gpa to psi	145,038

Figure 7. Nuanced data display tied to color coded tables in the first spreadsheet exercise in which data from specimens tested in tension was displayed and analyzed.

Buckling: equation display and trendlines to compare theory to data

In simple planar truss design, compressive buckling will be the failure mode essentially because (in contrast to tension) length has a drastic effect on member strength. Compression then needs to be introduced as the baseline response to a pushing load applied axially. Changes in specimen lengths are divided into ranges with failure load defined by different theoretical equations: pure compression [$C_{pcr} = \sigma \times A$], Johnson's parabola [$J_{pcr} = (Y - \frac{1}{E}(\frac{Y}{2\pi})^2 S_r^{\ 2}) \times A$], and Euler's equation [$E_{pcr} = \frac{\pi^2 EI}{(k_t L_u)^2}$] [10]. Moment of Inertia as a profile property (I) and a coefficient (k_t) that defines the role of end conditions are also introduced.

In the related online course assignment, data collected for Brass260 specimens tested to buckling failure were compared to theoretical calculations for three end condition configurations (hinged/hinged, hinged/fixed, and fixed/fixed) to categorize the physical experimental connections. The difference between confusion and accuracy here lies with the approach to data layout, analysis, and display. Spreadsheet skills introduced were easy equation inspection through named variables, data organization for visual clarity, and axis range definition for focused analysis (see Figures 8-10).

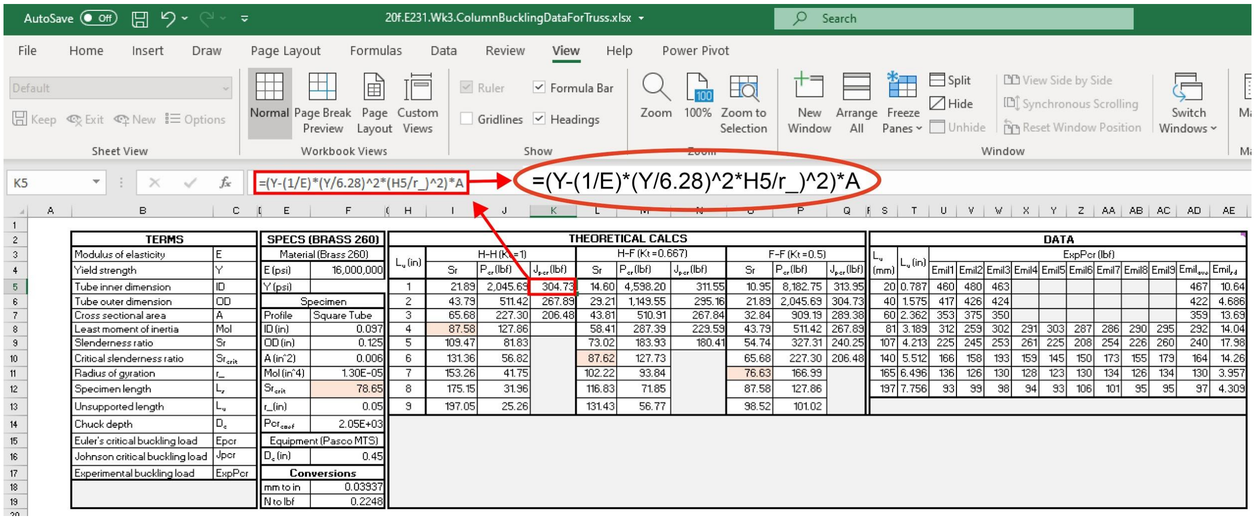


Figure 8. Terms defined with named cells create clear equation display.

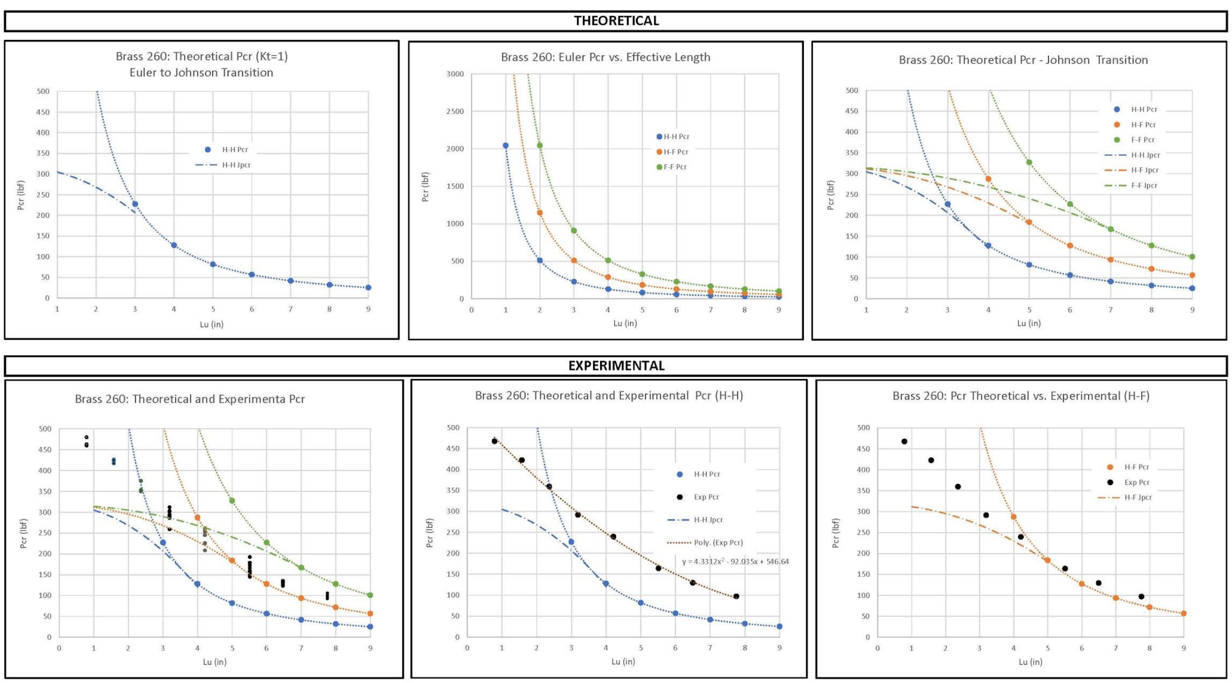


Figure 9. Clearly displayed graphs of theoretical buckling calcs for multiple connection end conditions allow an easy comparison with experimental data from physical specimens tested to buckling failure.

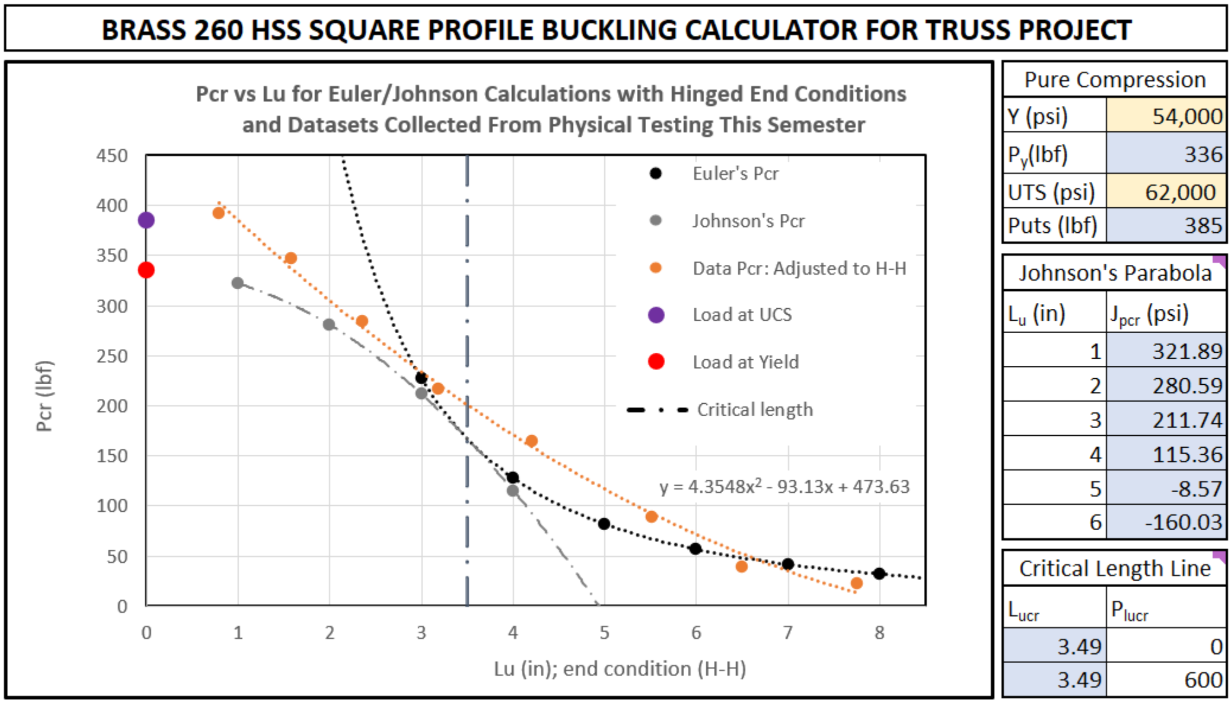


Figure 10. Final output is a simple modeler showing the relationship between material yield, column slenderness ratio, and experimental data in the context of buckling. This graph essentially summarizes all outputs that are computed with more accuracy in the truss project.

Column design: first full-fledged spreadsheet design modeler

Up to this point, spreadsheet assignments entailed detailed data display, but no design outputs. To accomplish the program for an iterative truss design process, a complex spreadsheet-based design modeler needs to be built by students. As an introduction to the process, we next devised an assignment that applied the buckling theory from the previous week. The idea was that a client had asked us to be their structural engineer on a series of warehouses they were building around the US. Right now, they were in negotiations in different regions and just wanted to be able to call us to get a quick price on the columns for a warehouse in a specific environmental context. The task was to build a column design modeler that inputs design variables including dead and live loading, material and specimen specifications, and site-specific environmental factors to output cross-sectional dimensions and costs of several available column profiles (see Figure 11). Factor of safety was also introduced and incorporated. Inputs needed to be easily modifiable and outputs immediate. Spreadsheet skills introduced included functions coding (such as IF/THEN statements) and user-friendly input mechanisms such as drop-downs, and visual packaging of the modeler as a GUI, i.e. a tool that makes its usage clear to a wide variety of users.

ATLAS STORAGE COLUMN DESIGN MODELER

INPUTS

MATERIAL		
Descr	Steel A36	
E	29,000,000	psi
E_s	26,100,000	psi
Y	36,000	psi
ρ	0.284	lb/in^3
C_u	0.77	$/lb
S	90	%
SPECIMEN		
K_t	0.50	
Lu (in)	156	in
L_c (in)	180	in
ThR	0.2	
#col	16	
LOADS		
FoS	3	
Dead Load		
MA	400	ft^2
Slabρ	160	lb/ft^3
$Slab_{th}$	0.75	ft
P_d	48,000	lbf
2nd Floor		
P_{store2}	18,000	lbf
P_{snow}	20	lbf/sf
P_{live2}	26,000	lbf
$P_{cr}2$	74,000	lbf
$P_{des}2$	222,000	lbf
1st Floor		
Pstore1	39,600	lbf
Pcr1	161,600	lbf
Pdes1	484,800	lbf

OUTPUTS

Sr_{cr}	120	
2ND FLOOR		
I_2	5.243	
Euler Column		
Profile	□	O
OD (in)	2.92	3.33
Th (in)	0.58	0.67
A (in^2	5.44	5.57
Sr	79	80
V (in^3)	979	1,002
M (lb)	278	284
C	$ 214	$ 219
Ctot1	$ 3,422	$ 3,502
Johnson Column		
Jpcr (lbf)	152,634	155,162
1ST FLOOR		
I_1	11.450	
Euler Column		
Profile	□	O
OD (in)	3.54	4.05
Th (in)	0.71	0.81
A (in^2	8.04	8.23
Sr	65	66
V (in^3)	1,447	1,481
M (lb)	410.43	420.01
C	$ 316	$ 323
Ctot2	$ 5,057	$ 5,174
Johnson Column		
Jpcr (lbf)	225,557	229,293

FAILURE MODE

Floor	Profile	Stress		
		Euler	Johnson	Yield
2nd	□	N/A	28,050	36,000
	O	N/A	27,865	
1st	□	N/A	28,050	
	O	N/A	27,865	

FINAL COST

Profile	$$	% Diff	$ Diff
□	$ 8,478	2.28%	$ 198
O	$ 8,676		
□ total price	$ 8,478		

Square HSS always less expensive, but circular HSS is a viable option.

NOTES

This modeler is for use in preliminary column design for 2-story Atlas Storage warehouse projects. It outputs profile dimensions and costs for HSS columns fulfilling given design criteria including material, unsupported length, cut length, steel derating, concrete density/dims, and live and dead loads. See "Terms, Notes, Resources" sheet for more details.

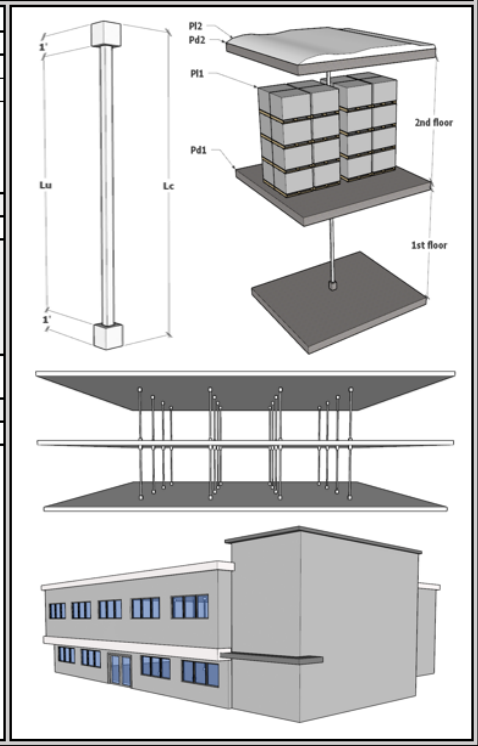


Figure 11. Spreadsheet column design modeler sample: users input detailed program specs to output dimensions of columns of several different profile options, identifying the least expensive.

Joint design: statistical analysis of data to determine correlation to theory

This is a design lab, not a theory course. Specific theory is covered in service to achieving project goals. Simple planar truss theory posits a physical condition in which a geometry assembled from triangles is constrained to a single vertical plane. Members are jointed with pinned connections so that internal moments do not develop and all loading is experienced within the plane of assembly. These imagined constraints allow for loading to be conceived as axial to the centroid of members and normal to their cross-sections, resulting in "two force members" that either experience loading as pure compression or tension.

Our theoretical and empirical investigations of tension and compression thus far cover member loading. But what about the joints? In truss theory, joints are infinitely small (mathematical points) but infinitely strong (they never fail). To apply this theory to a physical truss we need to design joints that are contextually "infinitely strong", i.e. strong enough to withstand any force the truss might experience before a member fails [11]. In a planar truss, joints are oriented perpendicular to loading while members are normal to it. In an intro class like this, the easiest way to describe this relationship is in relation to shear because the equations are so conceptually similar. A member in tension experiences the load normal to the cross-section ($\sigma = \frac{P}{A}$). A joint in shear experiences the load through that portion of the material parallel to the load ($\tau = \frac{P}{A_o}$), so the surface area of a lap joint or the cross-section of a bolt.

With this relationship, it is a fairly simple exercise to design a joint that is stronger than the strongest potential failing member. Students compared data collected testing shear failure of various diameters of brass rod to shear theory, determining if pin failure correlated with shear theory sufficiently to allow for a shear analysis to be the basis of joint design. Then, they created a simple joint modeler that output joint pin diameter based on theoretical material shear, the projected load the joint would need to withstand, and a factor of safety (see Figures 12 and 13). This modeler would be used directly in the truss design project.

SHEAR EXPERIMENT TOWARDS A MODEL FOR TRUSS JOINT PIN DESIGN USING BRASS260 WIRE

NOTES

Formulas

$\tau = P/A_{//}$
CV = SD/M
% diff = (A-B)/((A+B)/2)
% error = (Accepted-Data)/Accepted
A = πd^2/4

Terms	
d	diameter
$A_{//}$	area parallel to load
P	P load
τ	shear stress
SD	standard deviation
M	mean
CV	coefficient of variation
R^2	accuracy of linear regression
FoS	FoS
PinD	Joint pin diameter

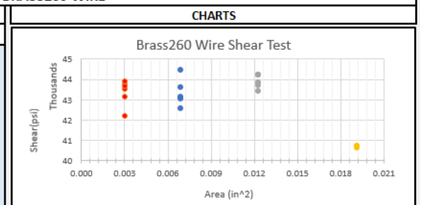
Material	
link	Brass260 rod from Mcmaster-Carr; various diameters
40.6ksi 40 ksi	Comparison source links

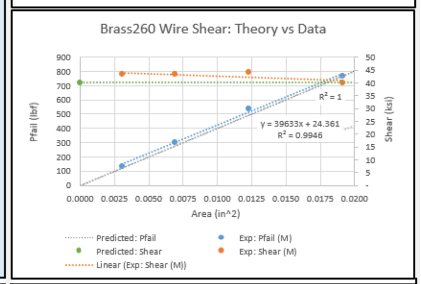
Discussion

Supplier does not give complete specs and lists the following warning: "Physical and mechanical properties are not guaranteed. They are intended only as a basis for comparison and not for design purposes." Calculated theoretical extrapolation based on sample group with average CV outpus values similar to other manufacturer specs for similar materials found on web. Therefore, derived theoretical comparison value of 40ksi for material shear strength is deemed accurate for our purposes.

SHEAR DATA					MEAN			CV		
Diam (in)	A (in^2)	P(N)	P_{fail} (lbf)	Shear (psi)	P_{fail} (lbf)	Shear (psi)		P_{fail} (lbf)	Shear (psi)	
0.156	0.0191	3,389	762	39,859	765	40,042	42,663	0.012	0.012	0.038
0.156	0.0191	3,394	763	39,918						
0.156	0.0191	3,462	778	40,718						
0.156	0.0191	3,457	777	40,659						
0.156	0.0191	3,363	756	39,553						
0.156	0.0191	3,362	756	39,542						
0.125	0.0123	2,413	542	44,202	539	43,934		0.007	0.007	
0.125	0.0123	2,413	542	44,202						
0.125	0.0123	2,415	543	44,239						
0.125	0.0123	2,393	538	43,836						
0.125	0.0123	2,371	533	43,433						
0.125	0.0123	2,385	536	43,689						
0.09375	0.0069	1,323	297	43,085	299	43,313		0.014	0.014	
0.09375	0.0069	1,307	294	42,564						
0.09375	0.0069	1,321	297	43,020						
0.09375	0.0069	1,325	298	43,150						
0.09375	0.0069	1,339	301	43,606						
0.09375	0.0069	1,365	307	44,453						
0.0625	0.0031	576	129	42,205	133	43,366		0.013	0.013	
0.0625	0.0031	597	134	43,744						
0.0625	0.0031	594	134	43,524						
0.0625	0.0031	596	134	43,671						
0.0625	0.0031	599	135	43,891						
0.0625	0.0031	589	132	43,158						

CHARTS





THEORETICAL SHEAR BASED ON EXPER BASELINE				
	0.00		0	-
	0.019		765	40,052
	0.038		1530	40,052
	0.057		2295	40,052
	0.076		3060	40,052
	0.096		3825	40,052
	0.115		4590	40,052
	0.134		5355	40,052

Extrapolation using mean of .156" diam wire

STATISCAL COMPARISONS	
Shear	
CV data	0.04
% error theory / data mean	7%
% diff theory / data mean	6%
P_{fail}	
Data mean R^2	0.995

Since we are will be adding a factor of safety and are designing a "worse case" scenario pin, these values are deemed very reasonable for our purposes

JOINT PIN DESIGN					
Inputs					
Material τ (psi)	40,000	P_{τ} (lbf)	300	FoS	2
Outputs					
	$A_{//}$ (in2)	PinD (in)	Specified pin diameter (in)		
theory	0.008	0.098	0.25		
data	0.007	0.094			
% diff	4%	2%			

Pin wire available in .125" increments; Pin needs to be able to withstand worse case scenario member loads in project truss designs

Figure 12. Data for brass rods tested in shear are statistically compared to theoretical calculations based on published specs to first correlate data to theory, then use the data as the basis for a simple design modeler that outputs pin diameter.

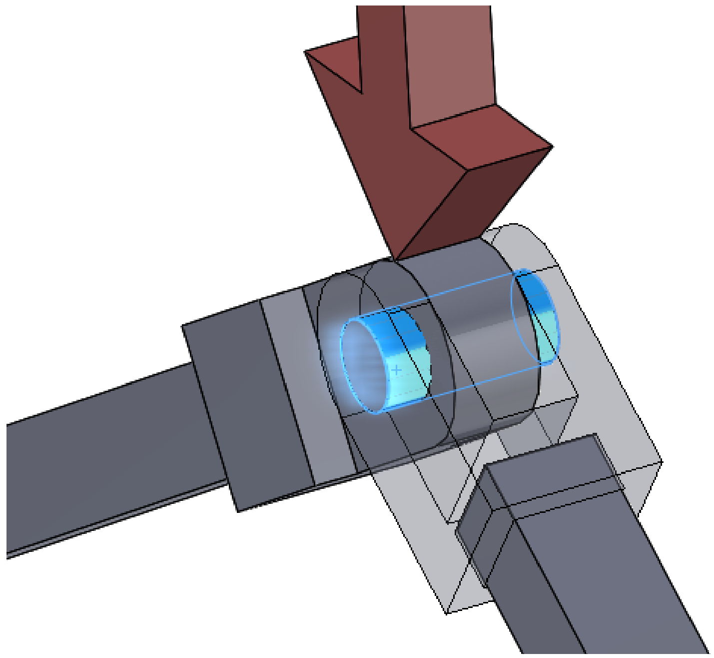


Figure 13. In this simple conceptual hinged joint, the pin is conceived to be transferring the load that is parallel to its cross-section (shear) to the members as an axial normal load (tension or compression). This is a mock-up of joints being developed for use when we return to hands-on versions of the course (see Figure 4). The joint modeler from Figure 12 is intended to output pin designs for this joint that will not fail when exposed to worst case loading in the iterations of the truss project described below.

Truss project: design research through iteration

The second half of the course is a truss design project. Armed with data well-correlated to theory and advanced spreadsheet skills tuned by specific assignments that displayed and analyzed this data, we were able to develop a project program that mandated iteration. A research question related to truss performance was chosen by each team and investigated through an iterative process, starting with one geometry and changing it through the application of engineering theory, i.e. with a clear understanding of what is being changed and how it relates to the research goal. The process was repeated creating a sequence of iterations in service to the chosen design investigation. Trusses were designed using the physical specs and performance data for the rectangular HSS Brass260 members tested in the buckling experiment earlier in the semester. Projected truss performance data was required to be organized into two versions ("theoretical" and "empirical") of each geometric iteration. The difference is that the "empirical" truss has modeled physical joints and uses collected data from the buckling assignment instead of theoretical values derived from Euler and Johnson equations. Strength and strength to weight for both versions of each iteration were calculated and then compared within and across all iterations to establish trends in service to research goals.

To accomplish this task, a complex spreadsheet modeler was required that takes material, assembly, and geometry specifications as inputs, parses members into Euler or Johnson lengths using slenderness ratio, and outputs strength, strength/weight, and statistical comparisons. The best modelers automated this process through the implementation of spreadsheet functions and included clear visual representations of truss geometry and failing members for easy comparison between iterations (see Figures 14 and 15).

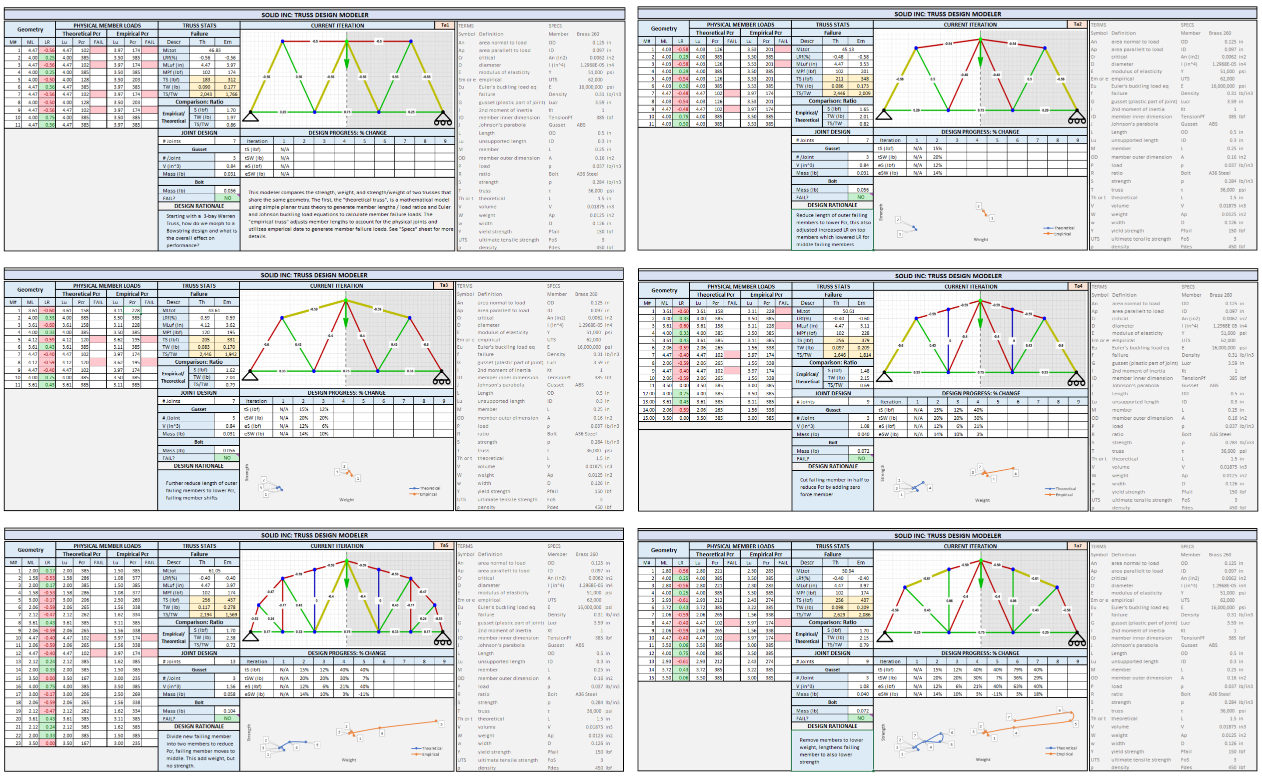
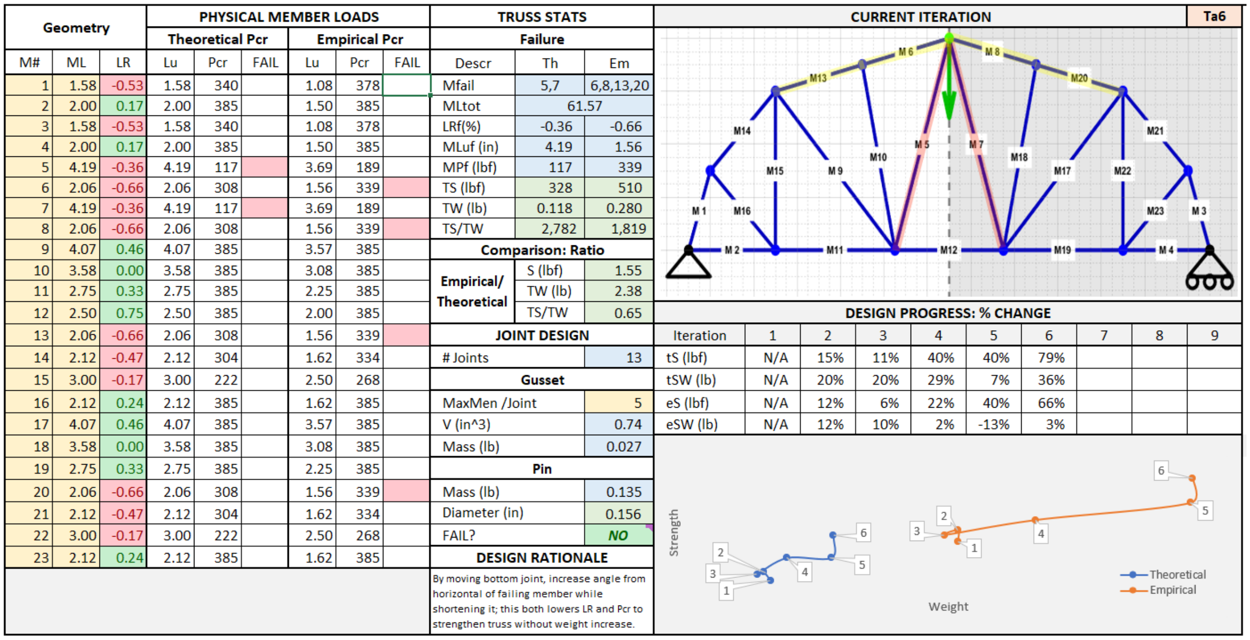


Figure 14. Sample iterative design process to answer the question: "Starting with a 3-bay Warren Truss, how do we morph to a Bowstring design and what is the overall effect on performance?" Truss member length and load ratios gleaned from free body diagrams calculations are input into the modeler and a variety of performance data is output for both the "theoretical" and "empirical" truss designs. The process automated by spreadsheet coding is repeated for each iteration on a separate sheet with statistical comparisons between iterations updated as new iterations are added. Material specs and other physical variables can be adjusted to generate new design outputs as part of the iterative process.



Geometry			PHYSICAL MEMBER LOADS					
			Theoretical Pcr			Empirical Pcr		
M#	ML	LR	Lu	Pcr	FAIL	Lu	Pcr	FAIL
1	1.58	-0.53	1.58	340		1.08	378	
2	2.00	0.17	2.00	385		1.50	385	
3	1.58	-0.53	1.58	340		1.08	378	
4	2.00	0.17	2.00	385		1.50	385	
5	4.19	-0.36	4.19	117		3.69	189	
6	2.06	-0.66	2.06	308		1.56	339	
7	4.19	-0.36	4.19	117		3.69	189	
8	2.06	-0.66	2.06	308		1.56	339	
9	4.07	0.46	4.07	385		3.57	385	
10	3.58	0.00	3.58	385		3.08	385	
11	2.75	0.33	2.75	385		2.25	385	
12	2.50	0.75	2.50	385		2.00	385	
13	2.06	-0.66	2.06	308		1.56	339	
14	2.12	-0.47	2.12	304		1.62	334	
15	3.00	-0.17	3.00	222		2.50	268	
16	2.12	0.24	2.12	385		1.62	385	
17	4.07	0.46	4.07	385		3.57	385	
18	3.58	0.00	3.58	385		3.08	385	
19	2.75	0.33	2.75	385		2.25	385	
20	2.06	-0.66	2.06	308		1.56	339	
21	2.12	-0.47	2.12	304		1.62	334	
22	3.00	-0.17	3.00	222		2.50	268	
23	2.12	0.24	2.12	385		1.62	385	

TRUSS STATS		
Failure		
Descr	Th	Em
Mfail	5,7	6,8,13,20
MLtot	61.57	
LRf(%)	-0.36	-0.66
MLuf (in)	4.19	1.56
MPf (lbf)	117	339
TS (lbf)	328	510
TW (lb)	0.118	0.280
TS/TW	2,782	1,819
Comparison: Ratio		
Empirical/ Theoretical	S (lbf)	1.55
	TW (lb)	2.38
	TS/TW	0.65
JOINT DESIGN		
# Joints		13
Gusset		
MaxMen /Joint		5
V (in^3)		0.74
Mass (lb)		0.027
Pin		
Mass (lb)		0.135
Diameter (in)		0.156
FAIL?		NO

DESIGN RATIONALE

By moving bottom joint, increase angle from horizontal of failing member while shortening it; this both lowers LR and Pcr to strengthen truss without weight increase.

CURRENT ITERATION — Ta6

DESIGN PROGRESS: % CHANGE

Iteration	1	2	3	4	5	6	7	8	9
tS (lbf)	N/A	15%	11%	40%	40%	79%			
tSW (lb)	N/A	20%	20%	29%	7%	36%			
eS (lbf)	N/A	12%	6%	22%	40%	66%			
eSW (lb)	N/A	12%	10%	2%	-13%	3%			

Figure 15. Detail of the modeler. Geometry section at left is cut and pasted free body diagram calculations from a separate app. This data feeds the theoretical and empirical calculation columns which compute the failure and comparison data in adjacent columns. A graphic of the current truss geometry iteration showing failing members and a variety of statistical comparison information can be seen on the right side of the modeler.

Developing the skills to accomplish such a detailed technical design output in a single semester is challenging but only made possible by foregoing fabrication. It is also a good mock-up of professional practice where design projects often require the development of some level of custom infrastructure within tightly defined time constraints. Every week through the semester, covered theory and skill-building was put in the context of truss design. A concurrent mechanics of solids course covered free body diagrams, so only a quick review was required. A truss geometry app was provided that automates trigonometry calculations and outputs a CSV file with member length and load ratios for all members. All theoretical calculations, data, and targeted spreadsheet skills from previous assignments fed directly into the design project. In this way, all the tools for design were front-loaded, and the project itself could be focused on design. Project "Scope of Work" as well as specifications for evaluations through oral and written reports clearly focused on the application of theory and data toward design iteration and the thoroughness by which design iterations had covered the investigation topic. This was in contrast to hands-on semesters in which a competition to create the strongest physical truss was the centerpiece of project reporting.

Takeaways

It is perhaps fitting that this is an atypical paper in response to an atypical time. As stated in the intro, the unique circumstances that engendered the design intervention described in this paper left us without data to generate a reliable comparison between student response to the online and hands-on versions of this design lab. It should be pointed out that this was an intervention necessitated by real circumstances, not one undertaken specifically in search of course improvements. In that sense, whether a student preferred or learned more from the online or hands-on versions is not really a relevant question. In a very real sense, the results were that we ran the course at all, especially during Spring 2020 when we were forced online halfway through the semester. Success! Given that, what are the lessons learned that we are sharing with the community? Here is a summary of our qualitative recommendations as takeaways gleaned from this design intervention:

1. **Plan for pandemics.** The first is obvious, but must be said. Given insufficient notice, taking any course online will be difficult, but the challenges with a hands-on design lab are particularly complex. It is possible that other pandemics are in our future. Do not be like us: plan now.

2. **Evaluate data collection.** Simply put we had not been taking student data collection seriously enough. It is important to strive to bring your data collection protocols to the highest standard. This can be a challenge because quality data can require expensive equipment and experienced technicians. Undergrad design courses may have “education” level equipment and essentially guarantee novice technicians. Data collection is not an area where we can work with a bell curve in student performance. For beginning designers, it is important that they can establish a correlation between the physical world and the theory they are learning, so that the designs they create applying that theory have meaning and do not just seem like exercises. With that in mind, create “gold standard” datasets for the equipment available and carefully define protocols that will give a majority of students the experience of collecting data of similar quality to these benchmarks.

3. **Fabricate in service to iteration.** Our previous fabrication methodology of soldering trusses took too much skill and therefore time to learn and execute. This relegated iteration to the realm of the virtual model with the physical prototype a “proof of concept” of the finished design. This is not true iteration and handicaps the design development process. Fabrication should be easy and inexpensive enough to be repeated quickly, so that numerous theoretical iterations can by physically tested. In this way theory and the physical can take shape together, with physical “failure” of a design simply being an input in the iterative process and therefore a part of the problem solution.

4. **Teach spreadsheet skills.** Planar truss theory is pretty simple, that's its beauty. Even complex geometries can be understood through a simple analysis of which members are failing. Iteration is essentially a decision as to how to change failing members to move toward some predetermined performance goal. This fact is completely obscured if the quantitative analysis of member strength in response to loading cannot be quickly and clearly displayed graphically. Students can really only understand their designs and how to iterate them toward project goals if they apply fairly advanced spreadsheet skills. We believe that this is not only true for the particular subject matter of this class, but generally applicable to engineering design education. Adjust your course content to include development of detailed spreadsheet skills. If you cannot create spreadsheet modelers of the complexity displayed in the examples in this paper, then learn these skills so that you can teach them.

5. **Don't forget this is design.** In this course we have about 600 students from different engineering majors working in teams on a complex project that requires applying theory and data in quantitative analysis toward performance goals specific to structural engineering. In this context, there is gravitational pull toward homogeneity. Many students really just want to be told what the "right" answer is, so that they can learn to produce it. This is assembly, not design. The immediate demand of the pandemic to rework the course somehow gifted us the mental space to address this problem. This entire paper is about the details of our response, but essentially switching the project deliverable from a truss performance competition to an investigation of a chosen topic related to truss performance was the infrastructural key that changed the design dynamic. The hands-on competition had an answer (highest failure load) that students could work essentially blindly toward. The online investigation required understanding how the applied theory produced the specific observed response in the truss geometry and using that information to inform the next iteration. This is design. Strangely, it took a pandemic to help us focus the design methodology for this course. If you have a similar need, don't wait. Like many wise sayings that are difficult to put into practice, this one sounds incredibly simplistic: make sure that your design course content actually encourages design.

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