AC 2012-2971: DESIGN MANUFACTURE SIMULATION AND EXPERIMENTATION OF SEVERAL TOOLS TO ASSIST IN TEACHING STRENGTH OF MATERIALS AND STATICS COURSES

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Nicholas Randall came to the University of Southern Maine in the spring of 2009. He is majoring in mechanical wngineering and is expecting at the time of his graduation to have a major in mechanical engineering and a minor in applied energy. He became interested in statics after taking a class with Dr. Ghorashi and observing the complexities of the material. He then teamed up with this professor and developed a way of teaching statics with more hands-on and simulation activities. Randall has always liked working on projects that require problem solving. The main problem solved in the current case was to find ways to make the subject of statics more easily and more deeply understood.

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Mehrdaad Ghorashi is a registered Professional Engineer (P.Eng.) in Ontario. In 1995, after receiving his first Ph.D. (on dynamics of structures under moving loads), Ghorashi joined the mechanical engineering Department of Sharif University of Technology as an Assistant Professor. In 2004, Ghorashi moved to Canada where he worked in Carleton University as a Postdoctoral Fellow. He also taught a few courses at Carleton for which he received the Best Professor Award from the Carleton Student Engineering Society. In 2006, he decided to earn a second Ph.D. (this time on dynamics of nonlinear rotating composite beams with embedded actuators) and graduated in 2009. In Sept. 2009, Ghorashi joined the Department of Engineering in the University of Southern Maine.

Design Manufacture Simulation and Experimentation of Several Tools to Assist in Teaching Strength of Materials and Statics Courses

In the bachelor degree program of mechanical engineering, strength of materials and statics are among the most fundamental and applied courses. The use of experiments and simulations in order to improve the quality of learning these subjects cannot be overstated. In strength of materials the analysis of pure bending and transverse loading are two important objectives. The similarities and the differences of the behavior of a structure to these types of loadings should be understood thoroughly. These behaviors are similar in terms of generating bending stresses; but they are different when it comes to producing shear stresses. During teaching strength of materials for many years, the second author has experienced that many students have problem in differentiating these phenomena. The problem is that students obviously cannot see the different values of internal forces and stresses in these cases. These concepts have been usually taught in lectures using diagrams, formulas and textbooks. This method can be improved by giving students the opportunity to gain hands-on experience and to use CAD software for simulations. Such an experience also provides a means for comparing theoretical, simulation and experimental results. In this research, to address the mentioned need, two devices are designed, fabricated and tested. The main question to be answered by using these devices is, "*How the transverse loading of a beam compares with the pure bending of the same beam?*" To answer this question, in this research two devices are designed and constructed. Each device consists of a beam with two polymethyl methacrylate (PMMA, or simply, Plexiglas) layers. Loads are applied on these beams in order to produce either transverse loading or pure bending moment. For analyzing pure bending, a four-point bending set up is fabricated. For shear force generation in transverse loading, tip load is applied on the cantilever beam. Pasta is used as a test specimen to identify in which of these two cases shear force generates. These experiments are augmented with computer simulation and theoretical results and used in classrooms at the University of Southern Maine (USM). The objective is to facilitate the understanding of a concept that is usually difficult for students to comprehend using traditional teaching methods.

Also, for using in a statics course, a separate test setup for analyzing the equilibrium of a hinged bar subjected to a tip force is designed and built. The tip force is applied and measured using a spring scale. There are three parameters that can be varied in this device. These are the bar mass and angle as well as the angle of the applied loading. Students will use this device in the statics course to explore the concept of the moment of a force as well as to compare theoretical and experimental predictions of the load needed for maintaining the equilibrium of the bar.

Keywords: Lab-integrated engineering education, CAD simulations, shear force, bending moment, mechanical engineering education, transverse loading, equilibrium of rigid bodies

1. Introduction

Proper design of structures and mechanisms is a prerequisite for successful construction of engineering devices. By calculating stresses produced by shear forces and bending moments, an engineer can determine what part of the structure needs reinforcement and which component is likely to fail. Such a successful design requires deep understanding of the concepts of shear force and bending moment.

One of the challenging concepts in strength of materials is the difference between pure bending and transverse loading of a beam. The students should understand that in the former case, no shear stress is generated whereas in the latter, shear exists and could be maximal on the neutral axis. In order to demonstrate this difference one strategy is to use activities like computer simulations and hands-on experiments where students can actually *see* the differences between the two types of loadings.

A search in the engineering education literature on the mentioned subject did not provide any result. Few papers that discuss related courses like materials science look at other issues like making homework more interesting[1]. In the field of chemical engineering there are many papers that discuss various aspects of laboratory experiments. The majority of these papers discuss issues like challenge-based learning, web-based teaching and multimedia laboratory manual[2-4]. In other references, the three methods of laboratory experience, i.e. simulation, hands-on and remote are discussed and compared[5,6]. Teaching methodology and educational laboratories in mechatronics and control engineering have also been subjects of a few publications[7-9]. Having performed this literature review, the authors could not find any publications on how the difference between pure bending and transverse loading of a beam can be explained by a hands-on experiment.

On a separate problem used in statics, a test setup for analyzing the moment equilibrium of a hinged bar subjected to a tip force is designed and built. The tip force is applied and measured using a spring scale. There are three parameters that can be changed in the system. These are the bar mass and angle as well as the angle of the applied tip loading. Students will use this device in the statics course to explore the concept of equilibrium of a rigid body. In this way, mechanical engineering students will gain an increased depth of understanding of the subject as well as some insight about the application of the theories.

2. Theoretical Analysis of Bending and Transverse Loading

It is well-known that if a homogeneous, isotropic prismatic beam is subjected to a transversal shear force V, the resulting shear stress τ, induced in the beam can be obtained by[10],

$$\tau = \frac{VQ}{It} \tag{1}$$

Where *I* is the cross-sectional moment of area, *Q* is the first moment of area of the part of the cross-section that is being cut and *t* is the thickness of the cut.

According to equation (1) if there is no shear force (pure bending case) there would be no shear stress in the transverse direction. The existence of shear force can produce bending in a transverse loading situation and generate shear stress.

The above theoretical discussion is mentioned in a course on strength of materials and sometimes it is hard for the students to completely understand it. In this research, to make this subject clearer to the students the aim is to physically demonstrate this fact by building test apparatuses and reinforce this activity by performing computer simulations. In this way, students can actually see these differences and observe the generation of shear stress or the lack of it. Therefore, the difference between the responses of a beam to pure bending loading and the transverse loading is clarified.

3. Clamped Two Layered Beam to Analyze Shear Force

Figure 1 demonstrates the SolidWorks model of the test setup designed for generating shear in a cantilever beam made of two separate layers.

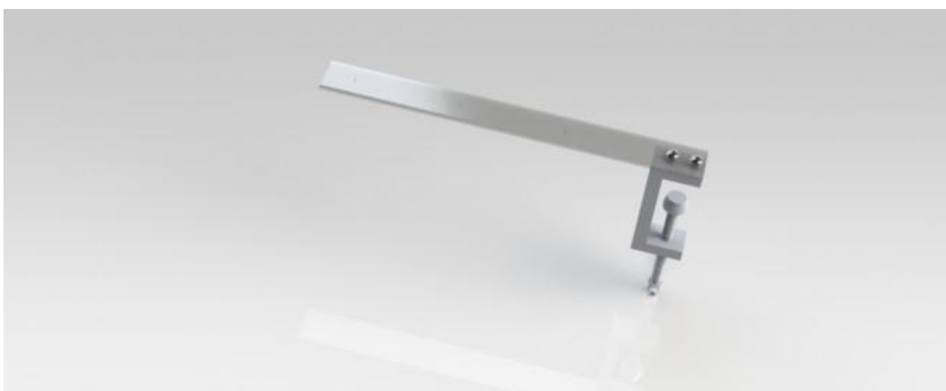

Figure 1. SolidWorks drawing of the unloaded cantilever beam used in the experiment

Figure 2 shows the manufactured apparatus made of two 300mm long Plexiglas layers (with 2.5mm by 39mm cross sections) that were laid on top of each other to form two-layer beam. This beam is first clamped on a level surface. Then a vertical load (0.5 kg in this study) is applied at the tip of the beam so that a vertical shear force is generated along the beam. This shear force produces a horizontal shear that tends to slide the two layers with respect to each other. To demonstrate this horizontal shear, a shear sensitive material like pasta was inserted into the holes that were drilled along the beam, as shown in Figure 2.

It was observed that the horizontal shear could break pasta after loading. This observation concurs with the theoretical prediction that one can get using equation 1. In fact according to this equation it is expected that vertical and horizontal shear stresses generate when lateral shear force is applied. The magnitude of the shear stress is expected to be maximal at the interface of the layers that is exactly where the pasta breaks.

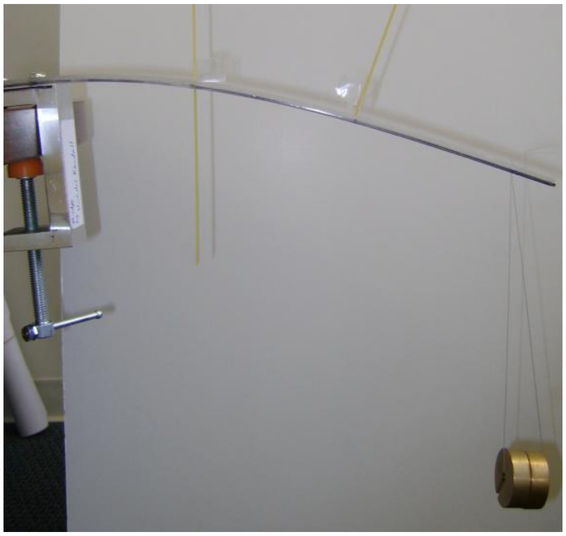

Figure 2. Two-layered beam subjected to tip loading

Having studied the cantilever beam subjected to transverse loading using the experimental and the theoretical methods, the same problem is solved using numerical techniques. A numerical solution was performed using SolidWorks Simulation tool. Figure 3 demonstrates the obtained shear force distribution and figure 4 shows the corresponding bending moment diagram. These numerical solutions are in perfect agreement with the theoretical expectations. Using all these three methods for solving a single problem and comparing the corresponding results would provide students with confidence and a better understanding of the subject.

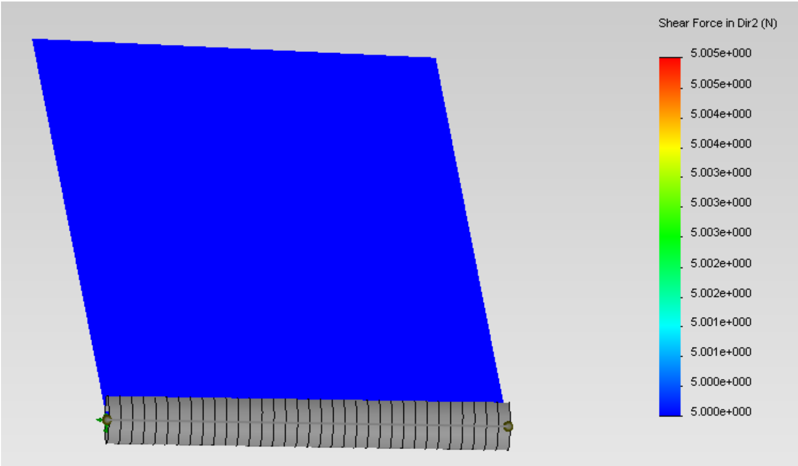

Figure 3. Shear force distribution along the beam subjected to tip loading

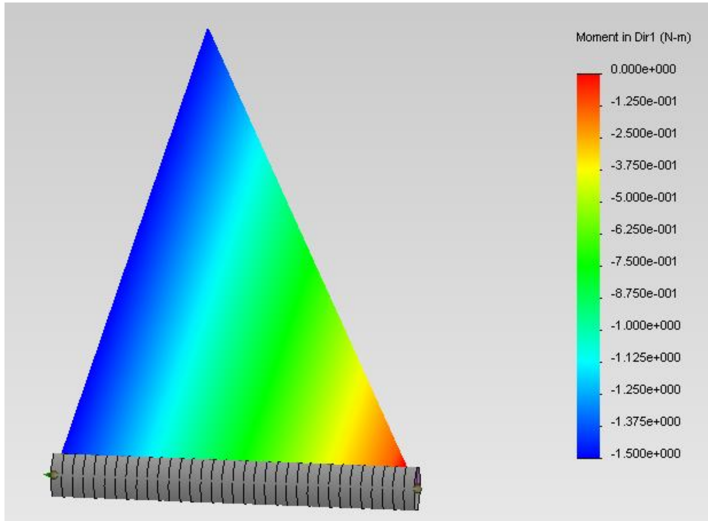

Figure 4. Bending moment distribution along the beam subjected to tip loading

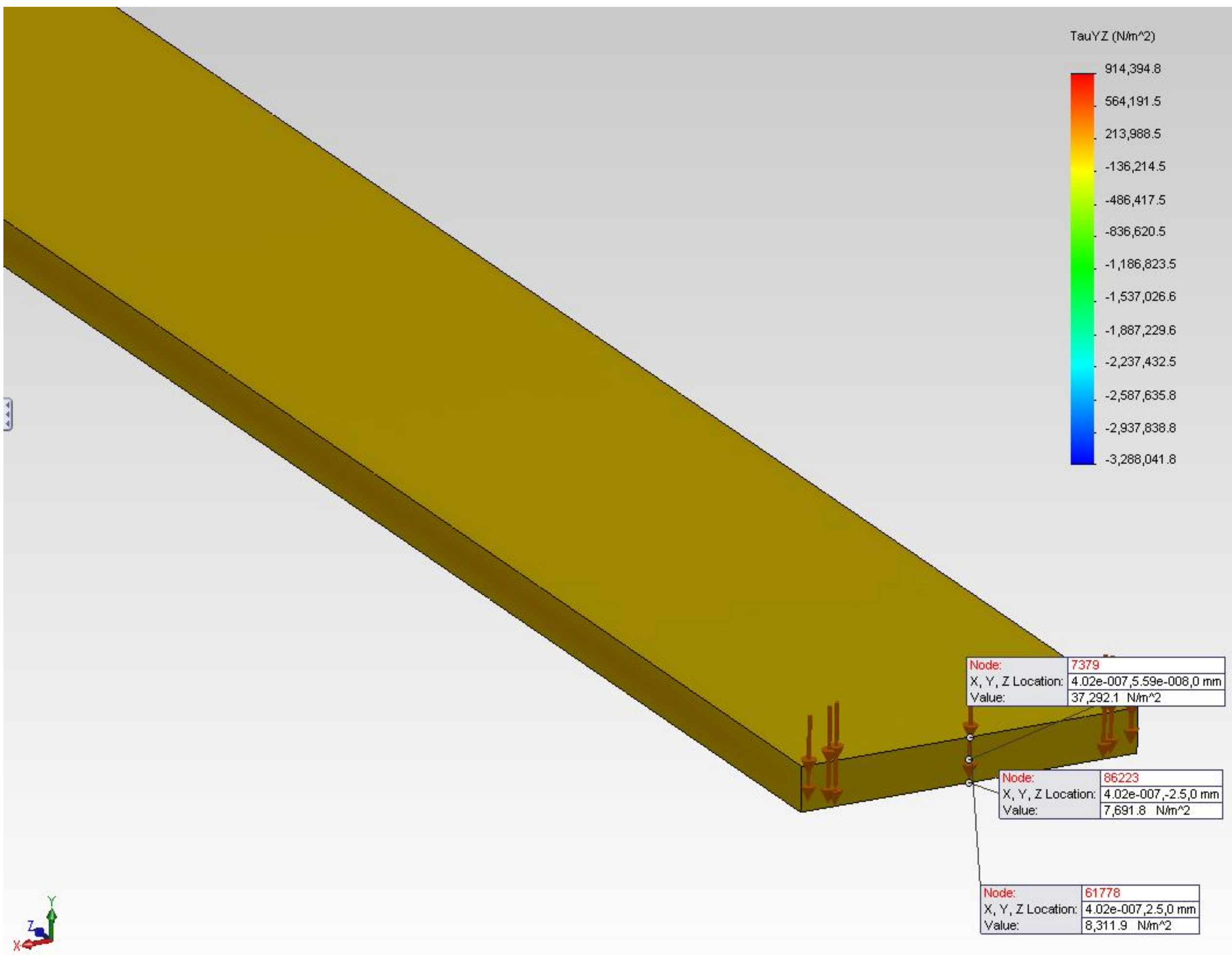

Figure 5. Nodes chosen in the FEM model of the beam for demonstrating τ_{zy} distribution across the section

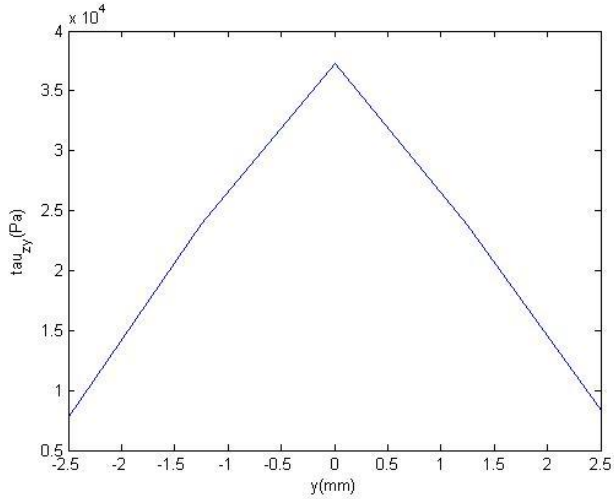

Figure 6. τ_{zy} distribution across the section of the beam

If the two layers of the beam were bonded to each other, the shear stress that would develop at the interface plane would be calculated by equation 1 as, 37.7kPa. The same problem was solved by SolidWorks and the result is shown on figures 5 and 6. Figure 5 demonstrates the Finite Elements Method (FEM) result and the nodes across the section where stress is calculated. Figure 6 illustrates the variation of τ_{zy} across the section. The maximum stress is seen to be 37.3kPa and it is in good agreement with the theoretical prediction mentioned before. The fact that shear stress is maximum on the neutral surface is in harmony with the cutting of pasta bars at this location.

4. Four Point Bending Device to Analyze Pure Bending

Figure 7 demonstrates the SolidWorks model of the test setup designed for generating pure bending in a beam made of two separate layers.

Figure 7. SolidWorks drawing of the unloaded beam used in the experiment

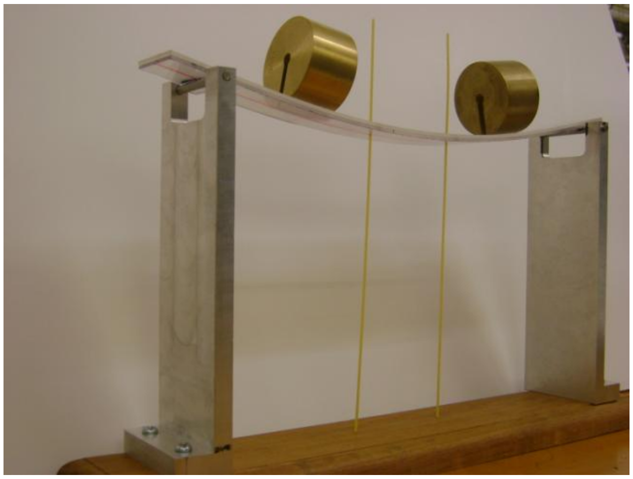

Figure 8. Two-layered beam subjected to four point bending

The manufactured apparatus, shown on figure 8, includes two Plexiglas beams, a wooden base, two machined aluminum supports, two metal pins, and two brass weights. The two 300mm long Plexiglas beams were laid across the supports and on top of each other. Excluding minor adaptation for the attachments, the Plexiglas pieces used in building this four point bending device were identical to those used in the cantilever case. To make the simply supported boundary conditions, two steel pins were inserted horizontally in the top of the aluminum supports to allow the Plexiglas beams to flex freely and without axial constraint. Then 0.5 kg weights were placed at the first quarter and the third quarter points along the beam in order to generate constant bending moments along the second and third quarters of the beam. In this mid region, between the two applied loads, there is no shear force thus the loading condition in that region is in fact just pure bending moment.

To demonstrate that there is no shear in the central region, a shear sensitive material like pasta was inserted into two holes that were drilled into the beams in this region. It was observed that even though the total applied loading was almost double the cantilever beam case; the pasta not only did not break, but also was not subjected to any lateral force. This behavior is expected since with no shear force, no shear stress will be developed to cut the pasta. In fact, one could easily move pasta through the hole and not feel any resistance. This observation is in harmony with concurs the theoretical predictions that one can get using equation 1. In fact, according to this equation it is not expected that shear stresses generate when no shear force is applied.

Having studied the pure bending moment case using the experimental and the theoretical methods, now the same problem is solved using numerical techniques. Performing all these three methods for solving this single problem and comparing the corresponding results would give confidence and a better understanding of the subject to the students. Numerical solution was performed using SolidWorks Simulation tool. Figure 9 demonstrates the obtained shear force distribution and figure 10 shows the corresponding bending moment diagram. These numerical solutions are in perfect agreement with the theoretical expectations.

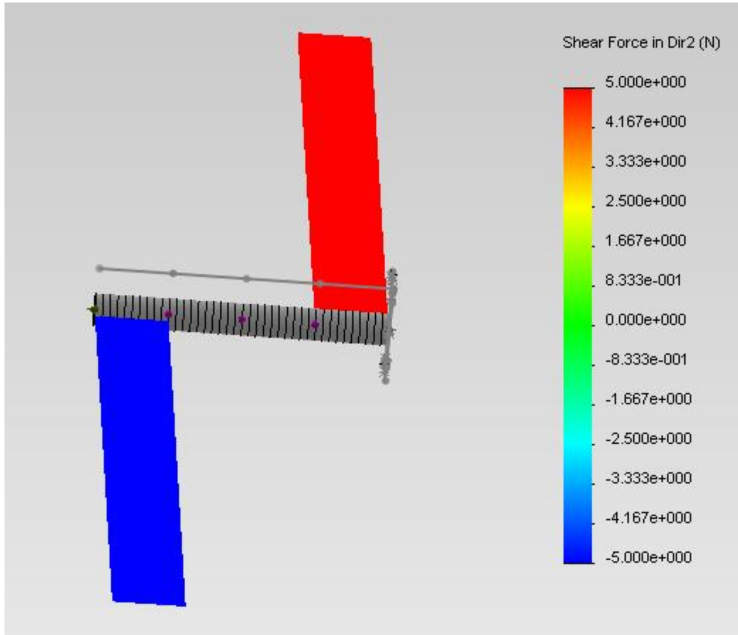

Figure 9. Shear force distribution along the beam under pure bending in the mid region

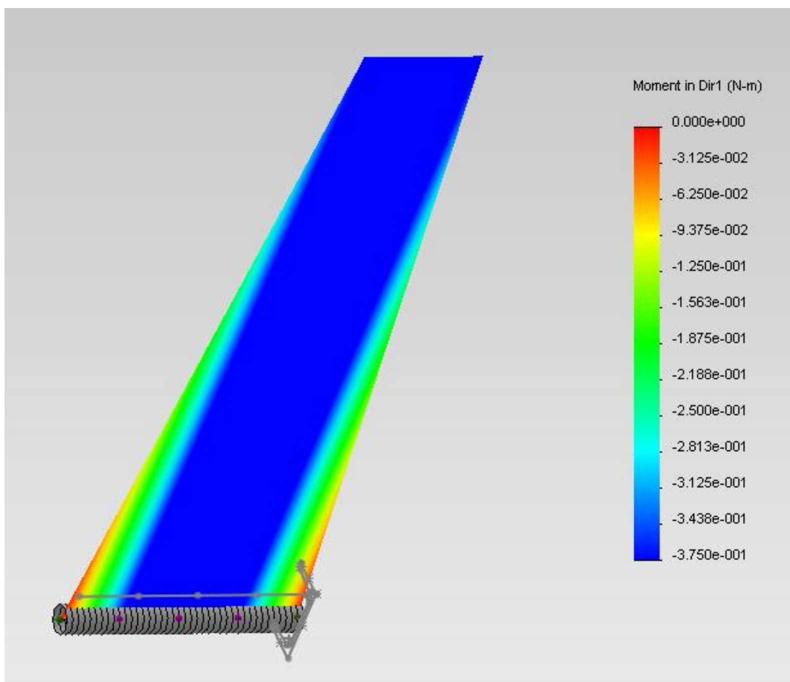

Figure 10. Bending moment distribution along the beam under pure bending in the mid region

5. Equilibrium of a Hinged Bar Subjected to Forces and Moments

As an example of studying the equilibrium of a rigid body in statics; the equilibrium of a hinged bar subjected to various loads is analyzed. Figure 11 demonstrates the SolidWorks model of the test setup designed for this purpose.

Figure 11. SolidWorks drawing of the hinged bar used in the experiment

The manufactured apparatus, shown in figure 12, includes a hinged bar that is loaded at its center of mass, a wooden base, two metal pins, and brass weights. Equilibrium of this setup depends on four factors, three of them can be modified. The four factors are the applied weight, the equilibrium angle of the bar and the magnitude and direction of the applied tip force. In each test, the direction of the applied load, the equilibrium angle of the bar and the applied weight were chosen and the necessary tip load for sustaining static equilibrium at the chosen conditions was measured by a scale as shown on figure 12.

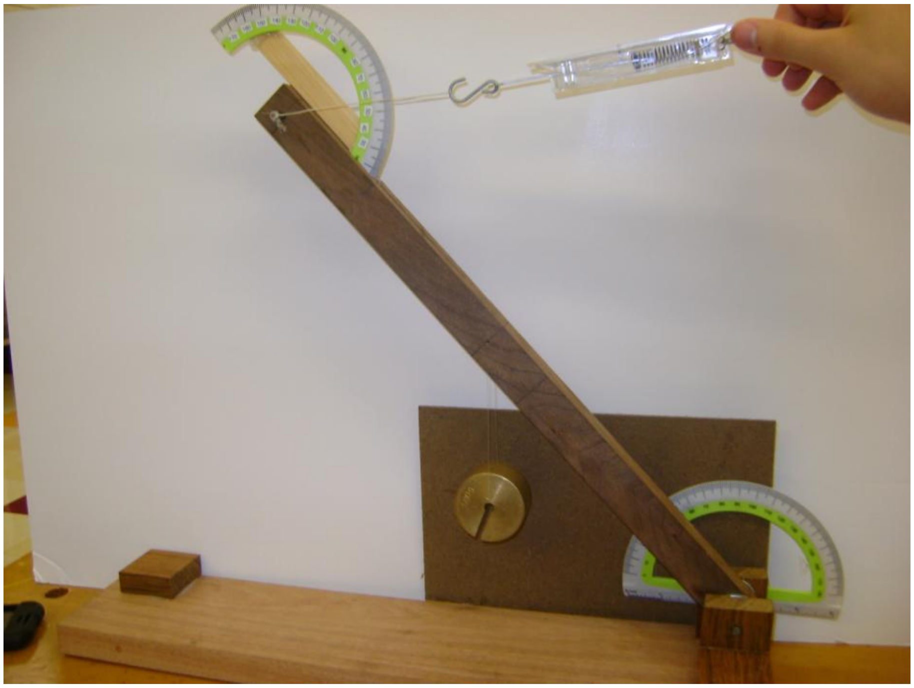

Figure 12. The test setup built for analyzing the equilibrium of the hinged bar

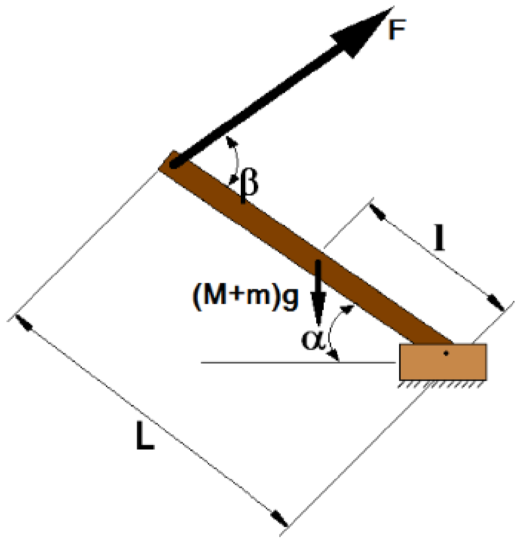

Figure 13. The notation used in the analysis of the equilibrium of the hinged bar

The applied tip force was also calculated by the application of the equation of equilibrium of moments of forces about the hinge. This equation can be written using the following parameters that are illustrated on Figure 13. The applied force, *F* is the tip load applied by the experimenter, *m* is the mass of the hinged bar, *l* is the distance between the hinge and the center of gravity, *L* is the distance between the hinge and the point of application of force F, *M* is the mass of the extra weight added to the center of gravity of the hinged bar, α is the angle between the hinged bar and the horizontal base of the device and β is the angle between the bar and the direction of the applied force. The result is,

$$FL\sin(\beta) - (m + M)gl\cos(\alpha) = 0$$

Solving for F gives,

$$F = \frac{(m + M)gl\cos(\alpha)}{L\sin(\beta)} \qquad (2)$$

The students may be asked to compare the results obtained from using equation 2 and the mentioned experiment.

As a case study, the calculated and the measured values of the tip force have been obtained using *m*=208 g, *l*=0.260 m, *L*=0.472 m and for various angles α, β and different combined mass values, *m*+*M*. Figures 14-17 demonstrate the two sets of results, i.e. the measured force applied by the experimenter in order to maintain the static equilibrium of the hinged bar and the corresponding value for the calculated force using equation 2. It is seen that the two sets of results compare fairly well (maximum error is 11%). The cause of this error is mainly friction.

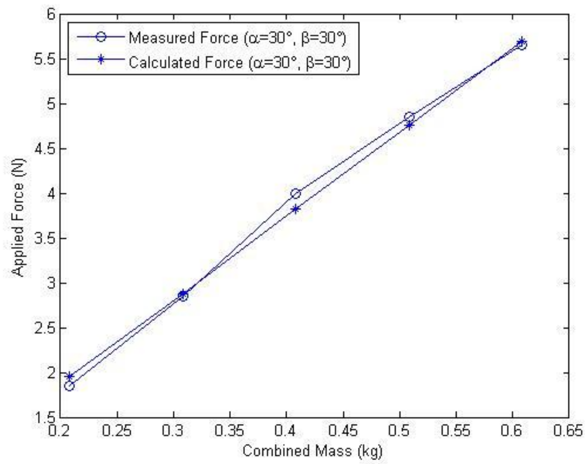

Figure 14. Calculated and measured applied force versus the combined mass (α=30°, β=30°)

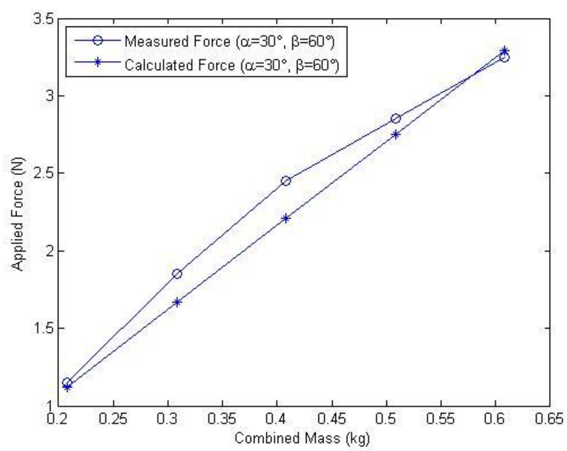

Figure 15. Calculated and measured applied force versus the combined mass (α=30°, β=60°)

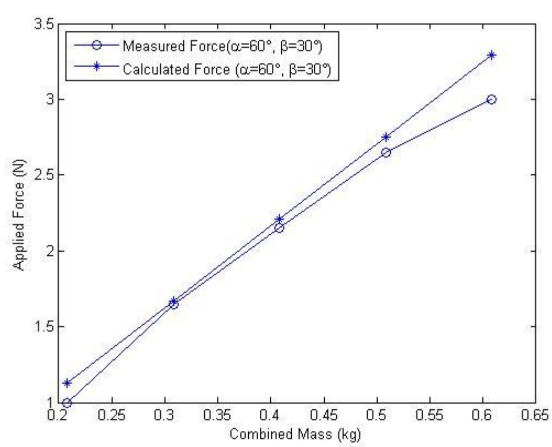

Figure 16. Calculated and measured applied force versus the combined mass (α=60°, β=30°)

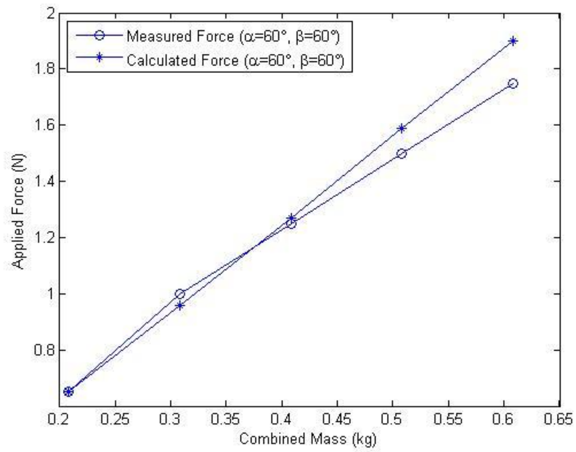

Figure 17. Calculated and measured applied force versus the combined mass (α=60°, β=60°)

6. Conclusion

To enhance the delivery of strength of materials and statics courses in the mechanical engineering program a few experiments together with computer simulations were suggested. For the strength of materials course two devices were designed, fabricated and tested. One of them was for studying the pure bending and the other for analyzing the transverse loading of beams. The main question that was answered by using these devices was, "*How the transverse loading problem compares with the pure bending case?"* The similarities and the differences of the responses of a structure to these types of loadings were demonstrated using theoretical, experimental and simulation methods. Another test setup was designed and built for analyzing the equilibrium of moments in a hinged bar subjected to a tip force. Students will apply this device in the statics course to explore the concept of moment of a force as well as to compare theoretical and experimental predictions of the load needed for maintaining the equilibrium. All these experiments and simulations provide students with the opportunity to gain hands-on experience. Such a systematic study can help students understand the mechanics and the theory and the numerical aspects of the mentioned problems. The revisions mentioned in this paper regarding statics course will be implemented in the spring 2012 semester at USM.

7. Acknowledgments

The authors wish to dedicate this paper to the late Steve Innes who while working on this project was the Laboratory Associate at USM. His assistance in the manufacture of the experimental devices that were built in the course of this research is greatly appreciated.

8. **References**

1. C. Haifeng, T. Peisong, P. Guoxiang and C. Feng, "Knowledge represent and reconstruction by *Fundamentals of Materials Science* classroom teaching mode reform," *Procedia Engineering*, 15 (2011) 4305-4309.

2. J. Vernengo and K. D. Dahm, "Two challenge-based laboratories for introducing undergraduate students to biomaterials," *Education for Chemical Engineers*, 7 (2012) e14-e21.
3. J.M.Brault, P. Medellin Milan, M. Picon-Nunez, M. El-Halwagi, J. Heitmann, J. thibault and P. Stuart, "Web-based teaching of open-ended multidisciplinary engineering design problems," Trans IChemE, Part D, *Education for Chemical Engineers,* 2 (2007) 1-13.
4. D. A. Patterson, "Impact of a multimedia laboratory manual: Investigating the influence of student learning styles on laboratory preparation and performance over one semester," *Education for Chemical Engineers*, 6 (2011) e10-e30.
5. M. Abdulwahed and Z.K. Nagy, "The TriLab, a novel ICT based triple access mode laboratory education model," *Computers and Education*, 56 (2011) 262-274.
6. J.E.Corter, S.K.Esche, C. Chassapis, J. Ma and J. V. Nickerson, "Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories," *Computers and Education*, 57 (2011) 2054-2067.
7. N.A. Kheir, K.J. Astrom, D. Auslander, K.C. Cheok, G.F. Franklin, M.Masten and M. Rabins, "Control systems engineering education," *Automatica*, 32 (1996) 147-166.
8. H. Bassily, R. Sekhon, D.E. Butts and J.Wagner, "A mechatronics educational laboratory—programmable logic controllers and material handling experiments," *Mechatronics* 17 (2007) 480-488.
9. S. Ersoy and H. Kucuk, "The effect of a new teaching methodology on learning performances of automotive – mechatronics students," *Procedia Social and Behavioral Sciences* 2 (2010) 310-316.
10. F.P. Beer, E.R. Johnston Jr, J.T. DeWolf, and D.F. Mazurek, *Statics and Mechanics of Materials*, McGraw-Hill, NY (2011).