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Introducing the Structural Engineering Encounter laboratory: a physical approach to teaching statics, mechanics of materials and structural analysis

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ABSTRACT: Fundamental subjects such as statics, mechanics of materials and structural analysis are the building blocks of civil and mechanical engineering knowledge. These subjects can be interesting and enjoyable to learn, or they can be dry and boring to students, depending on the teaching methods and strategies used. This article presents the teaching of these fundamental subjects by means of hands-on techniques and experimentation using structural engineering as the specific discipline and actual beams, trusses and frames as the specific tools to achieve this teaching objective. By furnishing students with the opportunity to actually *see* the structures being discussed in lecture and encouraging them to manipulate the loads, constraints and materials in the process for themselves, the authors believe students will not only walk away from the experience with far more captivation on what is being taught, but will be more apt to potentially grasp and retain challenging engineering concepts, as well. For this reason, the authors have termed their mobile instructional device the Structural Engineering Encounter (SEE) laboratory.

INTRODUCTION

A proper education is key to the success of engineering-minded high school and college students in their respective fields of interest. The engineering community, being aware of this, invested much appropriately in the way of advancing the cause of engineering education. This article focuses on the area of structural engineering education, as the authors seek to further the state-of-knowledge by introducing the use of a physical instructional device they have termed the Structural Engineering Encounter (SEE) laboratory.

A longitudinal study of engineering student performance by Felder et al was carried out in which traditionally taught students were compared with those in a programme involving active and co-operative learning, as well as a variety of other techniques similar to those explored in this article [1]. It was found that the experimental group outperformed the control group on a number of measures, including retention and graduation in the field of chemical engineering.

The interactive engagement (IE) method seizes student interest with in-class activities, and has been found to help them in their comprehension. The study of IE methods, as contrasted to that of more conventional approaches used in the teaching of science, mathematics, engineering and technology (SMET) courses, strongly suggests an overall enhancement of teaching effectiveness well beyond those obtained with traditional methods [2]. In addition, small group learning exercises have been found to have *...positive effects on undergraduates in SMET courses and programs* [3].

According to Feisel and Rosa, objectives need to be established and methods of assessment implemented in laboratory experiments in order for them to prove effective [4]. Engineering educators generally agree that students must have had some contact with nature and materials [5][6]. Moreover, multimedia and visualisation are seen as important factors in the processes of retention and comprehension by students positing the laboratory medium an effective tool to teach concepts in the sciences and engineering [7][8]. In the context of structural engineering, physical models enable students to gain a deeper appreciation of the variety of building materials used in actual practice (e.g. structural steel, aluminium, reinforced concrete, timber, composites), while affording them the opportunity to directly observe important phenomena, such as deflections and rotations of members and the constitutive relations existing between the two that, otherwise, can traditionally limit their understanding of these important considerations to mere theoretical and, oftentimes, superficial levels alone.

Hendricks et al [9] and Boyajian [10][11] have made the case for the sheer importance and pervasiveness of mathematical abstraction as found throughout the whole of the sciences and engineering, thus substantiating all the more, the pressing need to enhance learning comprehension through the medium of physical models. In this vein, citing but one example, Unterweger considered a curriculum involving cardboard models to help demonstrate to structural engineering students the application of loads and the resulting deformations and failure modes encountered in actual practice [12]. This form of hands-on and visual learning is explored further in this article.

METHODOLOGY

The aforementioned cited works speak for the benefit of applying interactive learning techniques to the engineering classroom. The aim herein will be to evaluate the efficacy of bringing a mobile structural engineering laboratory into a regular science, mathematics or engineering classroom for the enhancement of learning comprehension. In order to accomplish this, a special kind of device was conceived, designed and fabricated, as explained next.

Through the SEE laboratory (Figure 1), forces are applied to a member, while the structural responses are measured, e.g. deflections and strains. Another feature of the device is that it be adjustable in order to accommodate different structural members and models of varying dimensions. Moreover, it is important for the device to be sufficiently mobile and small enough to easily transport in and out of the typical classroom.

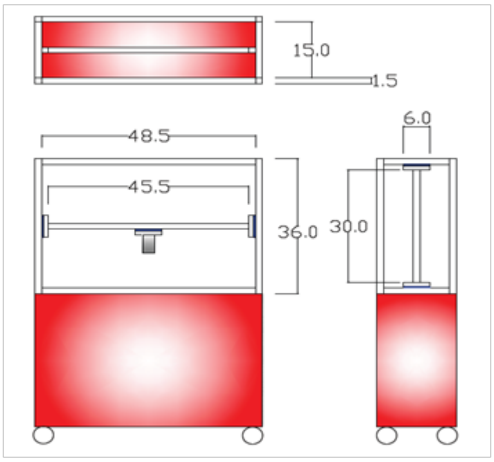


Figure 1: Structural Engineering Encounter (SEE) laboratory (units in inches).

Figure 2: Load cell.

The SEE laboratory was constructed from 80-20 aluminium members for the rendering of a durable and fully adjustable frame, capable of imparting substantial loads at a variety of orientations. Forces are measured through the use of load cells (Figure 2), and induced strains, by standard foil gauges (Figure 3); deflection readings are obtained through linear variable differential transformers (LVDTs, see Figure 4).

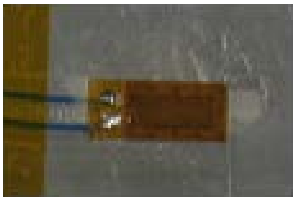


Figure 3: Strain gauge.


Figure 4: LVDT.

The SEE laboratory affords students a hands-on experience where they can manipulate a variety of structures, constraints and loadings, while measuring strains and deflections to gain an understanding of the interplay between the materials involved, the imposed boundary conditions and the resulting structural responses being obtained, for performing the required analysis.

APPLICATIONS

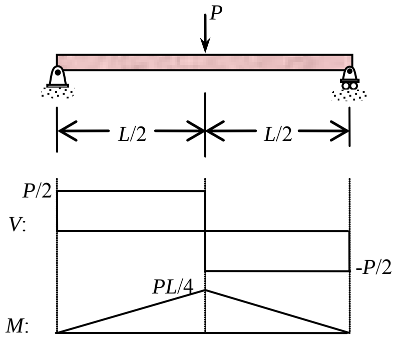
Beam Specimen

Table 1 catalogues an example of a beam specimen with a corresponding spreadsheet written to facilitate computations. As shown, the breadth, thickness, span, beam deflection and load being applied are all parameters that the students must measure to put into their tables for analysis. For the sake of simplicity, this spreadsheet is designed specifically for the analysis of beams that are simply supported with a point load at midspan. In this case, an aluminium beam of the dimensions shown was considered.

The computational cells of the sheet contain hidden equations that perform the appropriate calculations yielding the values for the highlighted variables, as explained below. Although not necessarily representative of every structural test conceivable, the authors have conducted the analysis of this particular simple beam specimen in such a way that the modulus of elasticity (E) of the material was not required a priori.

Table 1: Spreadsheet for a simply supported beam with point loading at mid-span.

Beam Testing						
	b (m)	*t* (m)	*l* (m)	Δ*h* (m)	*P* (N)	
	0.0509	0.00691	0.9	0.00822	9.81	
Simply Supported (load at midspan)						
	EI =	-18.1252281	[N*m^2]		*M* (N·m)	*c* (m)
	ϵ =	-0.000420742	[strains]		2.20725	0.003455
		-420.7422222	[micro strains]			



The first step of the analysis is to find the maximum deflection of the beam. The equation for the elastic curve is found through the double integration approach. From a free body diagram of the beam to the left of the point load, i.e. $0 \leq x \leq L/2$, the following expressions can be written:

$$M(x) = \frac{P}{2}x \tag{1}$$

$$y'' = \frac{M(x)}{EI} \tag{2}$$

By twice integrating the latter equation, an expression for the deflection, $y(x)$, can be found in terms of E, I, L and P. Substituting Equation (1) into Equation (2) gives:

$$y'' = \frac{\frac{P}{2}x}{EI} \tag{3}$$

Going through the series of two integrations with the known boundary conditions of the setup, $y(0) = 0$ and $y'(L/2) = 0$, yields:

$$EIy = \frac{P}{12}x^3 + c_1 x + c_2 \tag{4}$$

where $c_1 = -\frac{PL^2}{16}$ and $c_2 = 0$. With these new found constants, the equation for y at midspan where the beam deflection is the greatest, is found (Equation (5)), and from Hooke's law and the definition of bending stress, the strain is expressed as given in Equation (6):

$$y\Big|_{x=\frac{L}{2}} = -\frac{PL^3}{48EI} \quad \text{and,} \tag{5}$$

$$\varepsilon = \frac{\sigma}{E} = \frac{Mc}{EI} \tag{6}$$

Many other types of specimens can be analysed and used in a similar way for the purpose of teaching students the subjects of statics, mechanics of materials and structural analysis. Between the theoretical formulations and the SEE laboratory data collected, students have the opportunity to compare their calculated values with the deflection and strain readings of their own structures, and discuss any factors that might have contributed to a discrepancy between the two.

In addition to the calibration test described above, a tubular cross sectional cantilevered beam was also tested in the SEE environment with a point load applied at midspan (Figure 5). From similar theoretical calculations, the estimated strain at the middle of the cantilever beam was computed to be 77 με, which was found to be in close agreement to the actual midspan strain gauge reading of 84 με. A possible source of discrepancy may be the extent of supposed fixity at the wall as supplied through a clamping device.

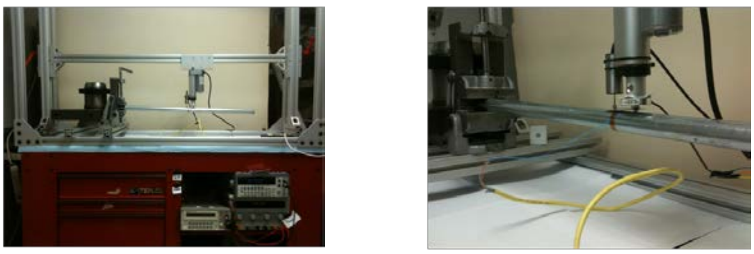


Figure 5: SEE test on a tubular cantilevered beam with point load at midspan.

Truss Specimen

Trusses are useful in teaching students the concept of axially loaded members, whether acting in tension or compression. The following three common types of truss were chosen for this project: Howe, Pratt and Warren (see Figures 6 and Figure 7). Inclined members of the truss were intentionally chosen in a ratio of 3:4:5 (Figure 8), and were used for the benefit of teaching the Algebra II high school class students, who have yet to take a class in trigonometry and would, therefore, not understand concepts of sine and cosine when attempting to calculate triangle related properties. The application of these structures was to motivate the students to build their own trusses and have an opportunity to observe how their models performed relative to those of their peers when testing in the SEE laboratory.

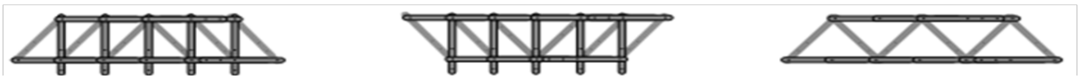


Figure 6: Howe, Pratt and Warren Truss design.

Figure 7: Howe, Pratt and Warren Truss built with Popsicle sticks.

Figure 8: Popsicle stick pre-drill design.

A Warren truss made of popsicle sticks and tested in the SEE laboratory is shown in Figure 9. Taking E = 14,500 MPa of white birch, for a load of 13 N applied at the centre joint of the upper chord, the computed strain in the adjacent (horizontal) member was found to be 26 $\mu\epsilon$, which is in close agreement to the strain gauge reading of 30 $\mu\epsilon$. Possible sources for discrepancies may include friction at the joints by the cropped toothpick connections that were used, and a slight, out-of-plane, bowing of the structure observed during testing.

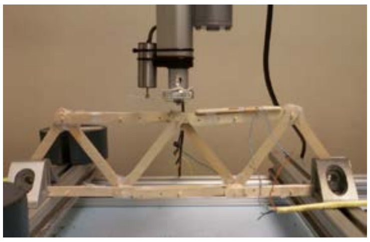


Figure 9: SEE test on a truss.

Frame Specimen

To test the characteristics of frames, a single storey, single bay frame (Figure 10) was constructed from low carbon steel and supported with two fixed joints (Figure 11). A distributed load was applied at the beam using known masses along with a lateral load imparted at the column through tension of a string supporting hanging masses. Portal frames loaded as such experience bending deformations and subsequent sidesway. Each joint deflects a given amount before the frame reaches a new state of equilibrium. Through application of the slope-deflection method, the displacements can be predicted and used to calculate the expected joint moments and, in turn, the member strains. Such an approach may be readily adapted to account for a variety of loading situations and member lengths. The classical slope-deflection equation is given by (see also [14]):

$$M_{nf} = \frac{2EI}{L}\left(2\theta_n + \theta_f - 3\psi\right) + (Fixed\ End\ Moment)_{nf} \tag{7}$$

where n = near end, f = far end, and $\psi = \Delta/L$

$$M_{AC} = \frac{2}{h}\theta_C EI + \frac{6}{h^2}\Delta EI + FEM_{AC} \tag{8}$$

$$M_{CA} = \frac{4}{h}\theta_C EI + \frac{6}{h^2}\Delta EI + FEM_{CA} \tag{9}$$

$$M_{BD} = \frac{2}{h}\theta_D EI + \frac{6}{h^2}\Delta EI \tag{10}$$

$$M_{DB} = \frac{4}{h}\theta_D EI + \frac{6}{h^2}\Delta EI \tag{11}$$

$$M_{CD} = \frac{4}{L}\theta_C EI + \frac{2}{L}\theta_D EI + FEM_{CD} \tag{12}$$

$$M_{DC} = \frac{2}{L}\theta_C EI + \frac{4}{L}\theta_D EI + FEM_{DC} \tag{13}$$

Two additional equations are afforded by the joint equilibrium considerations of the moments at joints *C* and *D* (Equations (14) and (15)); a third equation results from a free body diagram of the frame and the statical considerations of the horizontal forces (Equation (16)):

$$\sum M_C = 0 \qquad M_{CA} + M_{CD} = 0 \tag{14}$$

$$\sum M_D = 0 \qquad M_{DB} + M_{DC} = 0 \tag{15}$$

$$\sum F_X = 0 \qquad M_{AC} + M_{CA} + M_{DB} + M_{DB} = Ph - Ph\left(\frac{a}{a+b}\right) \tag{16}$$

Writing in matrix form, the unknown values for the joint rotations at joints *C* and *D* and the storey drift (θ_C, θ_D, Δ) can be found and substituted into Equations (8) - (13) to solve for the unknown bending moments.

$$\begin{pmatrix} \frac{4h+4L}{hL} & \frac{2}{L} & \frac{6}{h^2} \\ \frac{2}{L} & \frac{4h+4L}{hL} & \frac{6}{h^2} \\ \frac{6}{h} & \frac{6}{h} & \frac{24}{h^2} \end{pmatrix} \begin{pmatrix} \theta_C EI \\ \theta_D EI \\ \Delta EI \end{pmatrix} = \begin{pmatrix} -(FEM_{CD} + FEM_{CA}) \\ -FEM_{DC} \\ Ph - Ph\left(\frac{a}{a+b}\right) - (\mathrm{FEM_{AC}} + \mathrm{FEM_{CA}} + \mathrm{FEM_{CD}} + \mathrm{FEM_{DC}}) \end{pmatrix} \tag{17}$$

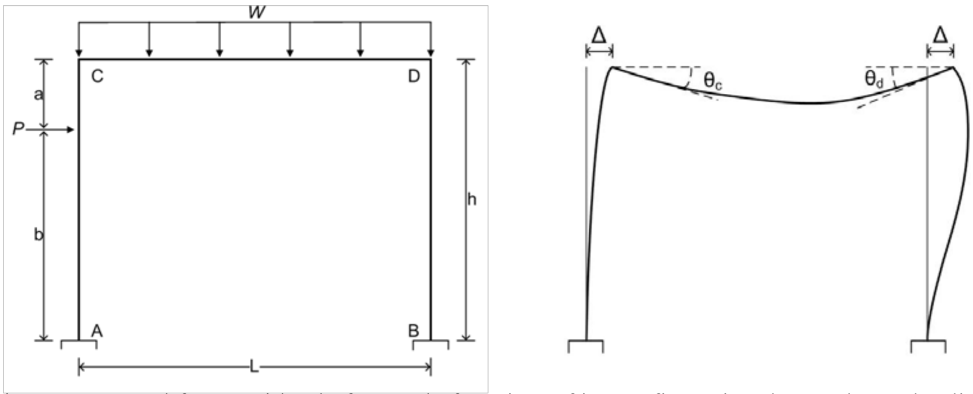


Figure 10: Portal frame with a before and after view of its configuration due to shown loading.

Figure 11: SEE test on a frame.

A frame with different vertical and lateral load combinations was also tested, as shown in Figure 11. The storey drift was measured on the unloaded column at a value of 23 mm and compared well with the calculated value of 28 mm. Possible sources for discrepancies may include friction from the rope and the depth of welds at the joints that remained unaccounted for in the analysis by the slope-deflection method.

ASSESSMENT

After having designed and built the SEE laboratory, the effectiveness of the hands-on and visual teaching methods were studied. Pre- and post-test survey questions were devised. The purpose of these questionnaires was to be able to gauge the success of the SEE laboratory environment in improving student awareness, interest and competency in the fields of science, mathematics and engineering.

The five subdivided parts of the survey are as follows. The first part involves the intrinsic motivation (IM) section, which attempts to understand student reactions to the instructional material using Cordova and Lepper's modified model [13]. A second section measures the extent to which the student values science, mathematics and engineering, and seeks to understand, if they had acquired a greater appreciation through the SEE laboratory teaching experience. The third part measures how well the subject was able to use the information presented, while working with the models and solving the associated problems. A fourth section concerns the students' metacognitive processes, and measures any possible gains to this dimension. Finally, the students' comprehension is measured based on the knowledge garnered from the theory being taught for the system of hands-on steps performed in the laboratory activities.

In summary, a 30% increase in learning occurred in helping students to communicate more effectively with one another; next, increases of 17% - 20% were found for students reporting that they had: i) been inspired to be creative with science and technology; ii) gained competency in completing tasks independently; and iii) been given the opportunity to share their ideas with others to accomplish a joint task; finally, increases from about 10% - 15% were discovered for students stating that they had a deeper appreciation: i) as to the importance of science; ii) of time management skills in order to meet project deadlines; and iii) of further pursuing engineering as a potential subject of study resulting from this personal encounter over what they had formerly considered about it prior to this study.

CONCLUSION

In an attempt to verify the hypothesis that a physical model such as the SEE laboratory has an advantage over more traditional lecture formats, arrangements were made to test the curriculum of mathematics students at a local private high school. At the end of the period, it was found that students' interests in engineering theory and engineering-related activities were raised with respect to those of the control group. Overall, observations of the class indicated a high level of engagement, and gave the researchers added incentive to pursue exploring future possibilities with the SEE laboratory.

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