Educational Tools for Introductory Courses on Structures

Gustavo O. Maldonado, Ph.D., P.E. Georgia Southern University Statesboro, Georgia

This article presents two related educational tools to enhance teaching and learning in introductory courses on structural behavior and analysis. They target students with minimum or no structural background. The first tool consists of a hands-on project and two competitions. It involves the design and construction of a small bridge. It uses vinyl mini blinds as its main material. It is designed to motivate students and facilitate the teaching and learning of structural truss behavior. The second tool focuses on the use of a relatively powerful software package for structural analysis. It includes one competition. In this case, students are guided to use a software package for structural analysis. Students employ it to model the same mini-blind bridge used in the previous tool. Both tools have already been used by the author in the classroom for several years with successful results.

Key Words: plane truss, bridge, mini blinds, competition, Visual Analysis software

Introduction

Construction managers may supervise full construction processes. Consequently, they may be responsible for maintaining structural stability during the construction and erection processes. They may even be responsible for structural malfunctions or collapses after they have completely build the structures. Therefore, their knowledge of structural behavior is crucial to attain swift and safe construction practices. For this reason, Construction Management (CM) programs in American colleges and universities include introductory courses on structural behavior.

The purpose of this article is to provide instructors and students with tools that may improve their teaching and learning experiences in those types of courses. After having taught ten different undergraduate and graduate courses in structural analysis and design, the author's personal experience indicates that, usually, those courses are mathematically based, cover a considerable amount of material and involve numerous problem solving activities, especially in their laboratory sections. These activities may become routinary and this, in turn, may contribute to a decrease in students' motivation, attention, and class participation. In an attempt to avoid these negative effects, a variety of motivational activities and learning opportunities are to be incorporated without affecting, or slowing down, the learning processes. Hence, the tools presented in this article are designed to serve those purposes by generating opportunities to learn structural behavior form sources different from the classroom and the textbook.

The proposed tools and activities are intended to motivate and expand students' learning experiences. The objective is to expose students not only to classical pedagogical learning opportunities, but also to provide them with opportunities to learn in a self-directed, andragogical fashion (Knowles, 1980, 1984). Hence, the learning potential of the proposed projects, is based on both pedagogical and andragogical assumptions. That is, first, students are instructionally guided to learn about different theoretical aspects of the projects. This is the pedagogical

component. Later, students are asked to work alone, without further instruction, within a team, to design and build a competitive final product. During this second stage, students are encouraged to use their self-directedness to further explore and learn, to use their initiative, creativity, knowledge acquired in the previous stage, and any building or construction experiences they may already have to contribute to their team success. This is the andragogical component of the proposed activities.

The first proposed tool involves a hands-on project. Students are required to work in teams to produce a small bridge with limited amount of material. The structure of the bridge consists of two parallel trusses (this is a double-truss bridge). All truss elements must be built with plastic, vinyl, mini blinds.

The second tool is a computer based project related to the above mini-blind bridge. In this case, students are guided to use a relatively powerful software package for structural analysis. It is the latest educational version of Visual Analysis (Integrated Engineering Software, 2007). Even though students do not have the necessary structural background to understand the methods used by this structural analysis software package, they are computer literate and, with guidance, learn to use the software to model the mini-blind bridge.

Educational Tool 1: Mini-Blind Bridge Project and Competitions

Short Description and Objectives

This project consists of a hands-on activity performed by students working in teams. It requires each group of students (2 to 4 per team) to build a small, low-cost bridge consisting of a double-truss structure spanning 24 to 36 inches. The material to be used is affordable and readily available in ubiquitous stores. The bridge produced by each group will participate in two or three different competitions.

There are two main goals in this activity. The first objective is to motivate students to explore and learn the behavior of truss structures to produce the stiffest and strongest bridge within certain constraints. The second objective is to expose students to several aspects of a construction project. Even though the structure is a small model, the project still involves several facets of a real project. It requires proper planning, teamwork, leadership, the acquisition of materials, to follow written specifications, to perform precision construction work, to provide proper attention to details, to produce a competitive product, to meet the competition deadline, and to compete against peers.

The following sections present sample rules for this project and its competitions. In those rules, some parameters are fixed (number of team members, length of bridge span, type of trusses, etc.). However, one or more parameters, including all of them, can be modified by the instructor. This may allow the instructor to present different projects each semester.

In case of any doubt about any rule, factor, or circumstance not considered by the rules below, the instructor will make all final decisions.

Sample Rules for Mini-Blind Bridge Project

General Information and Competition Date/Deadline

This project and associated competitions will be performed by students working in teams. Each team will consist of three (3) students and will attempt to build the stiffest and strongest possible double-truss bridge using a limited amount of plastic mini blinds. Some additional materials are also allowed. They include screws, nuts and plastic conduits (see below specifications). The geometry of the trusses and the number of mini blinds to be used along each member should be appropriately selected by team members.

The date for the competitions is four weeks after the project is announced in class. This is a strict deadline. Teams with incomplete bridges will not be able to participate. During the competitions, each bridge will be subjected to a constant vertical load acting at its mid-span. The corresponding mid-span deflection should be minimized. Also, each bridge will be subjected to a progressively increasing destructive load. The ultimate load, that is, the smallest one causing structural collapse, should be maximized.



Figure 1: Sample mini-blind bridge

Specifications for Structure, Materials, and Tools

Structure. The structure must consist of two identical parallel simple trusses with three or more triangles each. They must be joined laterally by a minimum of three (3) six-inch long horizontal struts. That is, both trusses may be separated by the maximum distance allowed by those horizontal struts (i.e.: six inches). The structure must be formed by simple trusses. Frames or other structural types are not allowed. Each triangle must clearly show an open triangular area. Extremely small triangular openings are not allowed. The minimum height of each triangular opening must be at least three quarters of an inch (3/4 in.). The bridge will be simply supported at the time of loading during the competitions.

Span. The distance from the center of the first joint, at one abutment, to the center of the last

joint, at the other abutment, must be thirty inches (30 in.) with a tolerance of $\pm \frac{1}{4}$ inch.

Height. The vertical distance from the center of the lowest joint to the center of the highest joint must be less or equal to twenty-four inches (24 in.).

Main material. All elements of the trusses must consist of one-inch wide vinyl mini blinds. A box containing the allowed mini blinds can be found at Wal-Mart, or K-Mart, or a similar store. They must be 1 in. Vinyl Light Filtering Mini Blinds, 32 in. width \times 64 in. length, mainSTAYS home. Different ones will require approval from the instructor. These mini blinds are the regular ones. They are not the extra thick or the extra strong ones. The thickness of each unit should be about 0.016-0.018 in (or otherwise indicated by the instructor). The approximate price for the above box is \$4.50 plus taxes.

Maximum amount of mini blinds. The total length of available mini-blind material contained in the suggested box is more than 2,300 inches. If for any reason, students destroy the given material, they are allowed to acquire additional box(es). However, the total amount of mini-blind material to be employed in the bridge must be equal or less than 1,800 longitudinal inches (150 ft).

Truss elements. Several mini-blind units may be used for a single truss element. No glue of any kind is allowed. However, two standard staples per truss element may be used to join the various mini-blind units forming a single truss element.

Joints. They may consist of half-inch long screws (Machine screw #10-32x1/2", round head, slotted, Zinc, Crown Bolt Inc. or similar) and their corresponding nuts (Machine screw nut #10-32, Zinc, Crown Bolt Inc., or similar). At the joints where the struts are located, the $\frac{1}{2}$ -inch screws may be replaced by the corresponding 6-inch struts.

Horizontal struts. These struts must consist of six-inch long bolts or screws (Hex Cap Bolt $\frac{1}{4}$ "× 6", Steel and Zinc or similar) and their corresponding nuts (Hex Nut, Steel and Zinc $\frac{1}{4}$ " or similar). The struts must be housed inside a half-inch diameter plastic pipe (for water distribution), 200-315 psi, or similar flexible plastic conduit of appropriate length. Three of these struts are compulsory. They must be located in a horizontal line and must be equally separated. One must be the very first joint of the bridge and will rest in one of the two abutments used for testing. Other must be the very last joint of the bridge and will rest in the other abutment used for testing. The third compulsory strut must be placed exactly at the midpoint between the other two. It will carry the testing load.

Angle. A small angular (L-shaped) element should be attached to one end of the compulsory mid-span strut. This angle will be used to actuate the sensorial needle of the displacement readout gauge. This angle and the deflection measuring device can be seen in figure 2.

Auxiliary elements. From a Lowes, Home Depot, ACE Hardware or similar stores: (a) Hex Cap Bolt (sometimes referred as screw too) $\frac{1}{4}$ " × 6" (Steel and Zinc), or similar. Approximate price is \$0.50 each. (b) Hex Nut Steel and Zinc $\frac{1}{4}$ ", or similar. Approximate price is \$0.08 each. (c) $\frac{1}{2}$ in 10-feet 200-315 PSI Pressure Pipe, or $\frac{1}{2}$ in 10-feet Flexible Conduit (to house electrical cables), or similar. Approximate price is \$2.00 each. (d) Hex Nut $\frac{1}{4}$ -20 Steel and Zinc (or similar),

Approximate price is \$0.08 each. (e) Machine screw $\#10-32 \times 1/2$ ", Hex or rounded head, slotted, (Steel & Zinc), Crown Bolt Inc (or similar). Approximate price is \$0.10 each. (f) VP Flat Washers ¹/₄". Approximate price is \$4.00 for a box containing 100 of them. (g) Corner Brace (1"×1"), brass finish with two ¹/₄" holes. Approximate price \$1.50 each (only one is needed).

Suggested tools. (a) Scissors. Approximate price is \$4.00 each. (b) Hole Puncher ($\frac{1}{4}$ " diameter hole). Approximate price is \$2.50 each. (c) Plastic pipe cutter, JH $\frac{1}{2}$ " to 1" Econo Pipe Cutter (from Lowes). Approximate price is \$10.00 each. Only one may be needed.

Sample Rules for Mini-Blind Bridge Competitions

Minimum-deflection competition

At the beginning of this competition, the instructor will inspect each competing bridge to verify its compliance with the above specifications. At this time, those bridges not meeting the specifications will be disqualified. Then, the instructor will decide the magnitude of the load to be used to deflect the qualified bridges. Usually, this load is 5 or 10 lb. Each bridge will be subjected to the same load. It will be attached to the compulsory mid-span strut. The corresponding mid-span deflection will be measured and recorded. For this purpose, a displacement readout gauge will be used. It shall be able to measure a full one-inch deflection in increments of one thousandth of an inch. The ranking of each team is announced after the deflections of all qualified bridges have been measured.



Figure 2: Minimum-deflection competition

The author has noticed that more precise deflection readings occur when the process is performed in the following order: First, load the bridge and read the loaded deflection. Then, unload the bridge and read the unloaded deflection. The deflection due to the load is the difference between the loaded and unloaded readings.

Usually, bridges built under the above conditions, and subjected to a 10-lb mid-span load,

present mid-span deflections ranging from 5 to 60 thousandths of an inch.

Maximum-destructive-load competition

This competition takes place after the minimum-defection one is completed. During this competition, each qualified bridge is subjected to an increasing load until collapse. This may be performed with the help of a bucket attached to the compulsory mid-span strut (see figure 3). Several heavy elements, such us steel bolts, nuts and washers, are carefully placed in the bucket, one at time, until collapse occurs. Then, the bucket and its content are weighed to obtain the corresponding collapse load. The ranking of each team is announced after the collapse loads of all qualified bridges have been determined. Alternatively, the competition may consist in attaining a large load-to-weight ratio (Collapse-load-to-bridge-weight ratio). This will encourage students to consider both strength and economy.

Usually, under the above conditions, well-designed and well-built mini-blind bridges will resist more than 40 lb before collapsing.



Figure 3: Maximum-destructive-load competition

Educational Tool 2: Computer Model of Mini-Blind Bridge and Competition

Short Description and Objectives

This project consists in developing a computer model of an actual mini-blind bridge and using it to compete in predicting the mid-span deflection corresponding to a given mid-span load. For this purpose, students are introduced to the Visual Analysis software package (Integrated Engineering Software, 2007). This is a powerful and simple-to-use tool for structural analysis and design. Fortunately, the company allows universities and faculty members to use the educational version of the software free of charge. Also, the corresponding student version is available at a nominal cost (\$20). This program is also suggested by the adopted textbook (Onouye & Kane, 2007) for the Introduction to Structures course at the author's institution.

The main goal is to motivate students to use a software package for structural analysis in introductory courses on structures. By learning its use, students acquire a powerful tool that can be used to facilitate their understanding of structural behavior. The objective is not to convert students into experts in structural analysis and design, but to familiarize them with the new techniques and powerful capabilities of modern structural analyses. This extends and complements the current overview that students receive of the old and limited techniques pertaining to simple, by-hand structural methods. Exposure to powerful computational tools (a) motivates students to learn, (b) facilitates their acquisition of knowledge by quickly performing trial-and-error computer-based procedures, (c) increases their understanding of structural behavior, and (d) helps them to better appreciate and respect the design dimensions resulting from sophisticated structural models. This, in turn, better prepare these future construction managers and engineers to properly supervise construction and erection processes and improve their interaction with structural engineers.

Computer Model

During this project, students become familiar with the fact that some three-dimensional real structures, such as their mini-blind bridge, can be modeled as two-dimensional ones. Thus, deflections of a double-truss bridge can be calculated by saving time and modeling a single two-dimensional truss. This truss supports half of the total load acting on the bridge. The other half is supported by the other truss. This two-dimensional truss is the simplest type of structure that can be modeled by Visual Analysis. Therefore, it is the ideal structure to familiarize beginners with the use of this software.

The modeling requires drawing joints and truss members in their proper location. To perform this task, the user only needs to know the dimensions and positions of all members of the truss. For this particular bridge, each horizontal and vertical member is 5-in long and each diagonal member is 7.07-in long. The actual drawing takes place in the *model* window of the software.



Figure 4: Computer model of the mini-blind bridge shown in figure 1

Figure 4 shows the final product. It corresponds to the model of the bridge presented in figure 1. Node 1 (N1) is a pinned support with two reactions, one vertical and one horizontal. Node 7 (N7) is a roller with one vertical reaction. This information is also easily input into the program.

The next step consists in inputting the proper cross sectional areas of the different members These areas are easily calculated by measuring the cross-sectional dimensions of a single mini blind (1 in \times 0.01766 in = 0.01766 in²). Since, in this particular bridge, each member uses four mini blinds, the total cross-sectional area of each member is 0.01766 in² \times 4 = 0.07064 in².

In order to properly calculate deflections, the program needs the value of the modulus of elasticity, E, of the material. However, this quantity is not readily available for mini blinds. Therefore, to approximately determine it, it was necessary to perform a series of tensile test.

Figure 6 shows the stress-strain curves obtained by performing 8 tests. The instantaneous tangents to these curves represent the instantaneous modulus of elasticity. Test 1 to 6 used a single mini-blind specimen. They are indicated by traced lines. Tests 7 and 8 used two mini-blind specimens each. They are indicated by thin solid lines. They are close to the average curve (thick solid line) obtained by considering all 8 cases.



Figure 5: Exaggerated deflected shape of the mini-blind, single truss subjected to half of the 10-lb bridge load.

From figure 6, it is clear that the stress-strain relationship of the mini-blind material is nonlinear and, consequently, the corresponding modulus of elasticity is not constant. However, the slope of a linear approximation to the average curve will be used to estimate a constant modulus of elasticity.

The adopted linear approximation is based on a least squares regression analysis involving the first 16 strain-stress data points of the average curve. Only the first 16 data points were selected (including zero) because the horizontal yielding plateau is reached near point 16. Those points in (strain, stress) format are: (0.00000 %, 0.00 psi); (0.06873 %, 29.49 psi); (0.13746 %, 102.52 psi); (0.20619 %, 176.95 psi); (0.27491 %, 283.69 psi); (0.34364 %, 516.82 psi); (0.41237 %, 769.61 psi); (0.48110 %, 1042.06 psi); (0.54983 %, 1263.95 psi); (0.61856 %, 1425.46 psi); (0.68729 %, 1525.17 psi); (0.75601 %, 1586.96 psi); (0.82474 %, 1610.84 psi); (0.89347 %, 1630.50 psi); (0.96220 %, 1636.68 psi); (1.03093 %, 1638.93 psi).

The regression analysis involving the above 16 points was performed by using the "trendline" capability of the graph function in Microsoft Excel (see figure 7). The resulting linear equation is $y = 1878.2 \ x$ (%), where stresses (y values) are in psi and strains (x values) in percent. If strains were used with their actual values (not percent ones), the corresponding equation would be $y = 187820 \ x$. The slope value of the latter equation is the approximated modulus of elasticity, **E** =187820 psi. This value was used in the Visual Analysis program to obtain the deflected shape shown above in figure 5.



Figure 7: Approximated linear stress-strain relationship

The following table shows mid-span deflection results obtained with the computer program and the actual deflections measured in the mini-blind bridge. As indicated in table 1, there is good correlation between the displacements measured in the actual bridge and the calculated ones via

Visual Analysis. However, the measured displacements are sensitive to the tightness attained by the horizontal struts. If the struts (and nuts) are loose, the whole bridge is loose and the measured deflections are larger than those indicated in table 1. This is due to the presence of small imperfections. They cause some members of the truss to move outside the truss plane. This, in turn, generates detrimental nonlinear geometrical effects that tend to increase the deflections. On the other hand, if the struts (and nuts) are extremely tight, they highly compress all elements concurring at the same joint. This results in smaller measured deflections than those shown in table 1. This decrease in deflections is due to constrained relative rotations between concurring members at the joints. That is, the truss is no longer behaving as a truss. It becomes a frame. Therefore, good correlation is only attained with moderately tight struts. They must be tight enough to maintain both trusses in their respective planes, and not too tight to constrain relative rotational motion at the joints.

Table 1

Mid-span Load	Measured Deflections (in)			Calculated
(lb)	First Attempt	Second Attempt	Average	Deflection (in)
5	0.017	0.017	0.017	0.0138
10	0.028	0.027	0.0275	0.0277

Results for mid-span deflections

Computer Model Competition

This competition consists in predicting the actual mid-span deflections of mini-blind bridges by using the Visual Analysis software. Each team must submit its predicted results before the miniblind bridge is completely built. Comparison of the calculated deflections against the measured ones forms the basis for this competition. The team with the smallest percent error ranks in the top position. In order to obtain accurate results, students may decide to estimate the modulus of elasticity corresponding to the material of the mini blinds. This can be done without the need of a specialized testing machine. An affordable and simple testing device is described by Ressler (2007, December 28). It is capable of performing tensile and compression tests.

Conclusions

This work presents two related educational tools to enhance teaching and learning in introductory courses on structural behavior. One involves a hands-on structural project and the other the computer modeling of the same project. They both may be employed in CM or engineering courses. The tools and activities are designed for students with minimum or no background on structural behavior. The objective of the presented tools is not to convert students into expert structural analysts, but to help them learn structural behavior from hands-on projects and from modern computational tools.

The author has used these tools for several years. By judging from numerous written and verbal comments, it is apparent that these tools cause several positive effects on the students. They are exposed not only to the classical, basic, by-hand, introductory structural analysis techniques, but

also to a hands-on project that simulates actual structural behavior, and to modern and powerful computational tools that also model and simulate structural performance. It is the author's perception that students become motivated by these projects and their related competitions. This motivation helps them to attain a more positive attitude towards the material presented in the course facilitating the learning process.

By participating in the presented activities and competitions, students become familiar with the behavior of trusses, identify critical bottom- and top-cord members, identify zero-force members, realize that most collapses are due to local or global buckling, realize that closed tubular members are able to resist higher compressive loads than similar ones with open cross sections, develop their own creativity in attempting to produce competitive structures, become familiar with the use and power of an state-of-the-art commercial software package for structural analysis, and in general, acquire a positive attitude towards the course and the topics being covered. In turn, this improves the overall performance of the whole class.

This work does not include before/after formal studies to quantify the improvements in learning that might be attained by using the proposed tools. However, by considering numerous positive comments, and various ingenious designs produced by young college students, including the reshaping of the mini blinds (in boiling water) to attain cross-sectional shapes with improved buckling strength (see figure 3), the author is confident that considerable learning occurs by using the proposed tools.

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