Tenth LACCEI Latin American and Caribbean Conference (LACCEI'2012), Megaprojects: Building Infrastructure by fostering engineering collaboration, efficient and effective integration and innovative planning, July 23-27, 2012, Panama City, Panama.

Models, Computers and Structural Analysis

Alberto Gomez-Rivas
University of Houston Downtown, Houston, Texas, USA, gomez-rivasa@uhd.edu

George Pincus
University of Houston Downtown, Houston, Texas, USA, gomez-rivasa@uhd.edu

Jorge A. Tito
University of Houston Downtown, Houston, Texas, USA, gomez-rivasa@uhd.edu

ABSTRACT

There are three basic components of the structural design problem: the real structure, the physical model, and the computer model. To avoid the typical problems of scale and similitude in the physical models, it is assumed that if the computer model predicts the behavior of the physical model, then it can also predict the behavior of the real structure. This method would be very useful in engineering education because by using models it is possible to allow students to visualize complex phenomena learned in theory but not seen in practice. The use of models in structural engineering is motivated by the work in small boxes performed by Karl Terzaghi; the current diminishing budgets in universities; and because the women students that worked with the models seem to have a better understanding of the basic structural principles.

Keywords: ABS Model, Plastic Model, Structural Model, Grid, Alamillo Bridge

1. INTRODUCTION

Structural Engineers graduating from the Structural Analysis/Design option in engineering technology program at the University of Houston-Downtown are exposed in their undergraduate education to courses in fluid dynamics where they learn about the immense difficulties of similitude in the construction of hydraulic models. During their professional careers, dealing with unusual structures they then tend to think about models but the idea is quickly abandoned because of difficulties of scale and similitude. This paper describes a different view of models used in structural engineering.

This paper deals with three objects: the real structure, the computer model, and the physical plastic model. The relation of these three entities is important for the paper. The basic hypothesis is that if the computer can predict the behavior of the model it also can predict the behavior of the structure. Structural software based on finite element principles applies to any structure regardless of the size of the elements. The critical point then is to verify that the behavior of the model and the computer are in close agreement. Adjustments to the computer model and its assumptions may be required to obtain satisfactory results. The issue of similitude that complicates a relationship model structure is not present here because the relations are: computer with model and computer with structure. The computer is used to avoid the similitude problem that complicates immensely physical modeling of structures (Starvridis, 2010)

After the computer has been properly tuned to predict the behavior of the model, it is reasonable to assume that the computer will be able to predict the performance of the real structure. To achieve this goal, the model must represent the structure in a reasonable manner. This paper describes the best practices to build models that represent the structure. The case of the model of the Alamillo Bridge is used to illustrate these principles.

The proposed use of models in structural engineering is very useful in engineering education because the models allow students to see and experience phenomena that they have not seen in practice. In some branches of engineering, hydraulics for instance, it is possible to see the real world relation between variables. The effect changes in velocity in a pipe can be visualized by the height of the fluid in a Pitot tube. This is not the case in structural engineering where the most important relation between loads and deformations is not visible due to the very small relative size of the deformations.

Learning and comprehending structural engineering is a matter of faith in mathematical formulas without having physical experiences. The high values of the modulus of elasticity of materials used in civil structures and the normal proportion of the structural members do not allow for visualization of the deformations that are thousands of the dimensions of the members of the structure. In other cases, structures are made very rigid to avoid human discomfort as is the case of floors. Common people and freshman students do not believe that structures deform under loads. A first step in structural engineering education is to show students that structures deform in predictable manner under the action of loads.

Three important reasons motivate the use of models in structural engineering. First, it should be remembered that the founder of Theoretical Soil Mechanics, Karl Terzaghi performed his fundamental research in a cigar box. Second, during times of diminishing budgets in universities, models can provide an economical approach to education and research in structural engineering. Third, women students seem to obtain a better understanding of the behavior of structures when models are used to illustrate basic principles of mechanics.

The paper discusses selection of materials for construction of the models. The basic principle is to make the model behave as a magnifying lens to the deformation of structures under the application of loads. The figures presented in the paper illustrate ABS plastic model experimenting large deflections under the action of small loads. Other considerations indicate why ABS plastic is an ideal material for construction of models of structures.

Simplicity of instrumentation is important for success in the use and applications of the model to comprehend structural behavior. Since the model is a device to magnify the deformations of the structure to visualize behavior, the measurements of deformations do not need to be electronic sensors that clutter understanding of the behavior. Simple mechanical deflectometers communicate well the value of the deformations.

Considering that the model should be very flexible, it is not necessary to use specialized devices for the application of loads. Simple weights and pulleys allow for the application vertical and horizontal loads. Great accuracy can be obtained in weighting the loads before they are applied with ready available electronic balances.

Several models are presented in the paper: A simple supported beam used to determine the material properties of ABS plastic and the rigidity of the connections, specialized models dealing with torsion, multistory frames, grids for floors, and the model of the Alamillo Bridge. Each one of the models is described in detail.

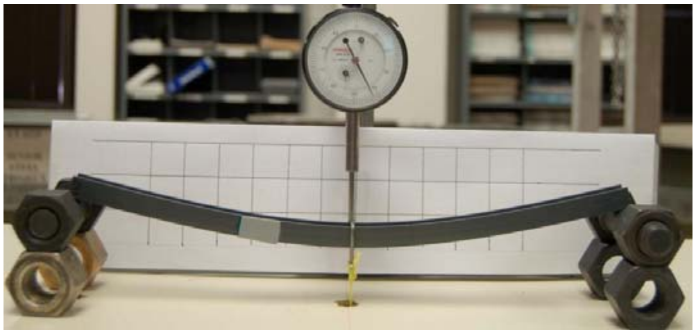
2. MODELS USING ABS PLASTIC

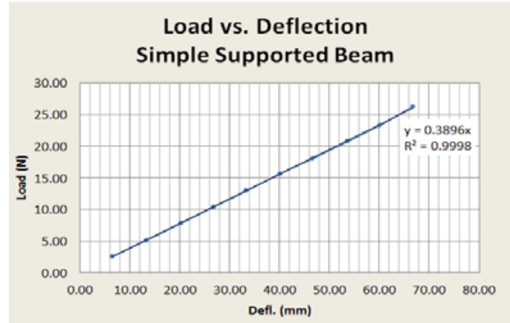
2.1 SIMPLY SUPPORTED BEAM

The objective of the model is to magnify deformations in complex structures. This magnification allows for visualization and measurement of the deformations. Materials that meet the objective of magnification of deformations must have low modulus of elasticity (E). To model a real steel structure using steel elements would not serve the magnification and visualization objective, mainly because the deformations of this steel model would be too small. Figure 1a presents a model of a simple supported beam with large deflections due to the low modulus of elasticity of ABS plastic.

The moduli of elasticity of common structural materials are very high, for example the value for Steel is 200 GPa and for concrete about 25 GPa. On the other hand, plastics such as ABS have values of about 3.50 GPa. The same beam made of plastic will deflect sixty times more than the steel one.

Steel has an elastic linear range that extends almost to the yield point and covers the range of structures under the action of service loads. For the model, it is desirable to find a material with a good elastic linear range. Tests conducted for this project indicates that ABS has elastic linear behavior within the range necessary to present significant deformations in models. Figure 1b presents the load deflection graph for the simple supported indicating a linear elastic behavior up to the point of failure. The elastic linear behavior of ABS is interesting and valuable for testing of the models because this property guaranties that if the model is not broken the behavior is linear elastic.





a) Beam tested in the weak axis **b) Load vs. Deflection curve at 23°C**

Figure1: Flexure test of a simple supported beam

Dimensional stability that is the uniformity of dimensions of the cross sections of structural shapes is an important characteristic for construction of reliable models. ABS structural profiles have great dimensional stability along the axis of the elements. The shapes have not fillets and the cross section is completely defined by straight lines. Filets connecting webs and flanges in most structural shapes contribute to the sectional moment of inertia and their measurements are complex because it involves the determination of the radius of curvature. Not having fillets and straight boundaries the dimensions are determined with digital micrometers of high precision. The area, moments of inertia, and other cross section properties are obtained easily from AutoCAD drawing.

Complex structures worth to model involve rigid connections. These connections are welded or bolted in steel structures or cast in place connections between columns and frames in reinforced concrete. The material to be used in the model construction must provide the opportunity to build rigid connections. Research on the ability to weld plastic materials indicates that ABS glue and acetone provide connections that are as rigid as the connected elements. The beam presented in Figure 1a consists of two pieces welded with acetone and, as observed, it undergo to large deformations up to the point of rupture without failure of the connection. All tests conducted for this project indicated that properly detailed connections are stronger that the elements.

2.2 Beam Model in Torsion

A main concern of the project is the behavior of structures that induce torsion in structural shapes. This problem is of interest because open structural shapes like wide flanges are weak in torsion. Furthermore, the computer models using linear representation of the beam do not present a visualization of the elements in torsion. A torsion model is presented in Figure 2 indicating again, that properly detailed connections of ABS can sustain very large torsional deformations and that the ABS material is ideal to magnify deformations due to torsion because of the low shear modulus.

Accurate determination of the span and properties of the cross sections produces reliable values of the modulus of elasticity (E) and the shear modulus (G) and the modulus of Poisson (ν), as shown in Figures 1 and 2. These mechanical properties, which are essential for analyses of the behavior of all models, are checked for consistence using the equation:

$$E = 2\,G\,(1 + \nu) \qquad (1)$$

Typical values for the ABS plastics used are E=3,50 GPa, G=1,35 GPa, and ν =0,30; measured at room temperature of 23 °C.

Figure 2: Torsional deformation of ABS beams and connection

The models presented in Figures 1 and 2 so far indicate that ABS is ideal for the construction of models. Acrylonitrile butadiene styrene (ABS) (chemical formula $(C_8H_8)_x\cdot(C_4H_6)_y\cdot(C_3H_3N)_z$) is a common thermoplastic. Its melting point is approximately 105 °C (221 °F). It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The nitrile groups from neighboring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. The styrene gives the plastic a shiny, impervious surface. The butadiene, a rubbery substance, provides resilience even at low temperatures (Wikipedia, 2012).

ABS is found in hobby shops and other retail stores in the form of structural shapes, pipes and sheets at reasonable prices. An ABS beam of the proportions required for models cost less than 3 dollars, depending on the size. The materials used for most models in the project cost less than 15 dollars in total.

2.3 Multistory Frame

Figure 3 shows the model of a multistory. This is a common type of structure for offices and apartments and the most critical structural consideration is the type of connections. The term moment-resisting connection is used in earthquake engineering to describe rigid connections of both steel and concrete frames represented in this model.

The objective of the model is to verify that ABS plastic allows for construction of moment resisting connections between columns and beams. The model is tested under lateral loads that are the most important for this type of structure. Lateral deflections of the model agree with the deflections determined by the computer.

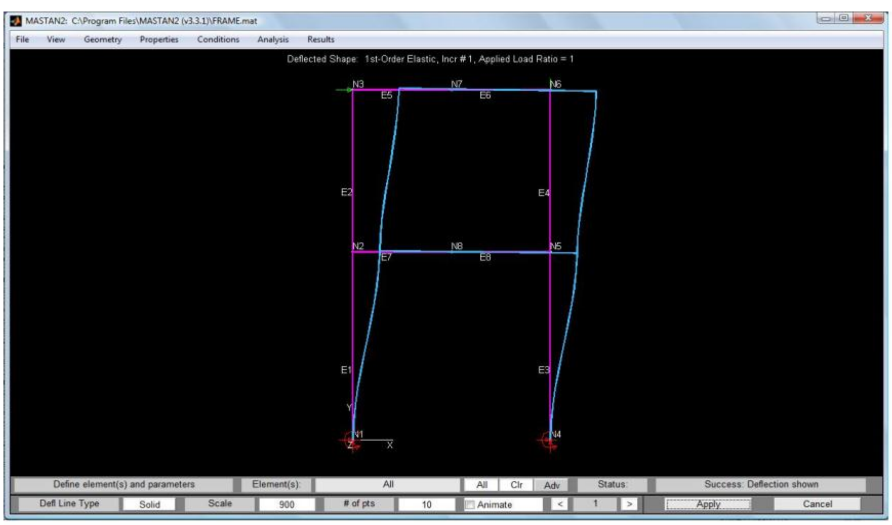


Figure 3: MASTAN computer simulation of the frame model.

2.4 MODEL OF A GRID

The model is of interest because it involves bending and torsional behavior of all elements and the questions that arise about this type of model related to the distribution of loads to the different components of the grid. The model is built using ABS structural shapes rigidly connected using acetone as a welding agent.

All dimensions are determined with instruments of high precision and the properties of the materials established by the procedures described above. A computer representation is developed using these parameters. The tests consist on application of concentrated loads at a node of the grid and determination of the deflections at other nodes. Figure 4 presents the grid under load experimenting large downward deflections in the front bean and upwards deflections in the beam in the back. The computer simulation shown in Figure 5 illustrates this interesting behavior. Deflections in both the computer and the model agree with only minor deviations.

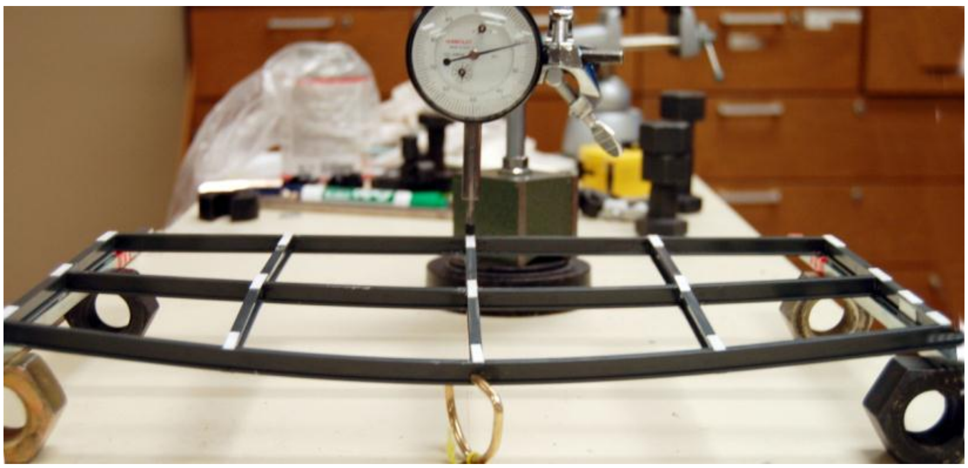


Figure 4: Model of a grid showing downwards deflections in front and upwards in back.

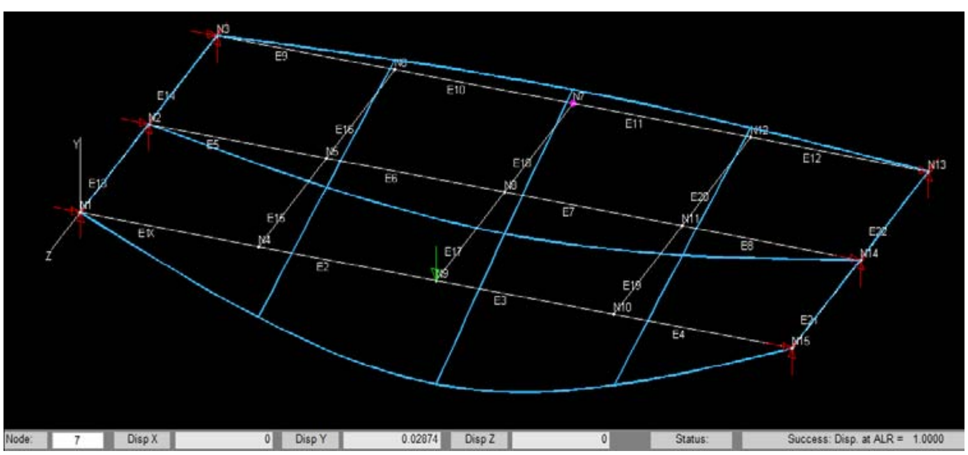


Fig. 5: Computer simulation of the grid.

2.5 THE ALAMILLO BRIDGE, STATIC AND DYNAMIC MODELS

The beautiful and interesting bridge in Seville Spain, designed by Santiago Calatrava and built for the 1992 Universal Exposition (Expo '92) (Pollaris, 1999) is presented in Figure 6. The structure is used in several of our courses because of its beauty, structural concepts and extensive available documentation.

Figures 7 and 8 present the model and the computer simulation respectively. The model is about one meter long and built using ABS plastic for the components of the deck and a steel rod simulates the pylon. The stays are made of "fish line" the common material used in this activity.

The question that motivates the construction of the model is: Professor Angel Aparicio of the School of Civil Engineering at the Technical University of Barcelona developed a model where each pair of stays is attached to a single node at the center of the deck [4]. This is different from the real structure where the stays are attached to the two sides of the central longitudinal box beam of the bridge 4 meters apart. Intuition indicates that the arrangement with the stays on both sides of the box will increase the torsional rigidity of the bridge. The model of the bridge has the stays at the sides as presented in Figure 7. Two different computer simulations are compared with the plastic model. The computer simulation with stays on the sides represents better the behavior of the model. Professor Aparicio assumption is conservative because it does not include the contributions of the stays to the torsional stiffness of the bridge.

The plastic model of the Alamillo Bridge shown in Figure 7 is used to compare the deflections given by the computer model shown in Figure 8, and to compare the natural frequency of vibration of the computer with the one of the model. A very small accelerometer is used in order to not affect the mass of the model. The frequencies of vibration of the plastic model and from the computer model are in complete agreement.

Fig. 6: The Alamillo Bridge, Seville, Spain

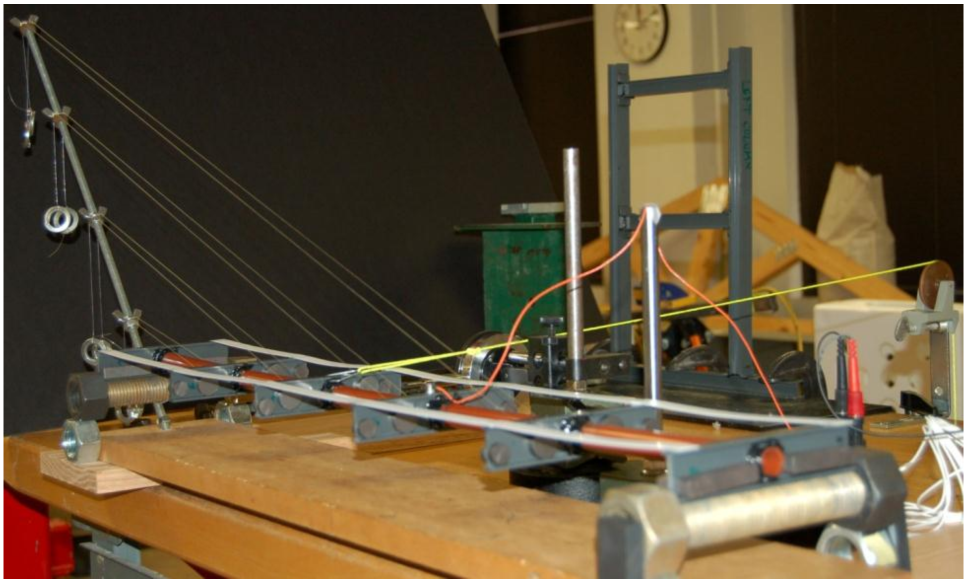


Fig.7: Model of the Alamillo Bridge under the action of a transverse load applied to the deck

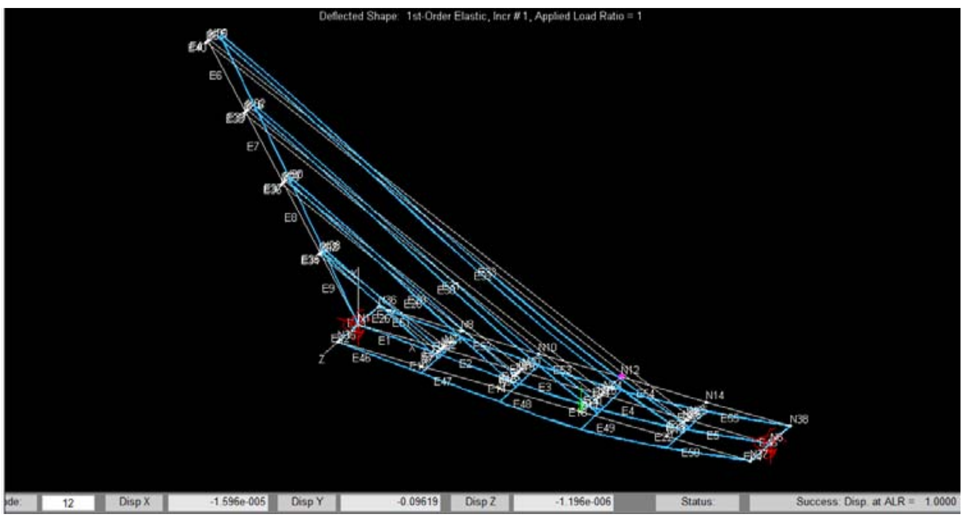


Fig. 8: Model of the Alamillo Bridge with stays attached to the sides of the main box girder

2.6 THE COMPUTER MODEL

All computer models are developed using MASTAN the software that accompanies the textbook *Matrix Structural Analysis* used in our courses in structural analysis (McGuire et al, 2000). MASTAN is an advanced program that includes linear and non-linear matrix analysis of structures. The program is easy to learn due to a user friendly graphic interface as presented in Figure 8. However the visualization of element deformations is difficult because of the representation of elements as simple lines. Most finite element programs have the same limitation. The use of models as presented in this paper allows for the visualization of complex torsional behaviors.

2.7 SUMMARY OF RESULTS

Table 1 present a summary of the results of the models studied in the project. The values in the table present an excellent agreement between model and computer with exception of the vertical deflections of the bridge. The difference is attributed to insufficient information on the material properties of the fish line. This material will be studied at depth because it is important for modeling stayed structures.

Table 1: Summary of project results comparing defections of model and computer.

Description	Simple Beam	Torsion Dial 1	Torsion Dial 2	Frame	Grid	Bridge Vertical Load	Bridge Lateral Load
Maximum Load in model (N)	60,1	2,0	2,0	2,0	28,9	4,9	2,0
Deflection in model (mm)	1,83	2,74	0,09	0,09	2,16	0,30	0,51
MASTAN deflection (mm)	1,82	3,17	0,09	0,08	2,11	0,24	0,48
Deflection Difference %	0,7	-15,6	5,7	8,3	2,4	20,8	5,0

3. CONCLUSION

Structural models are excellent tools for the verification of computer simulations and the visualization of complex structural behaviors. There is an important relationship between the computer representation and the structural model, taking into consideration that if the computer can simulate well the structural model, it can also simulate a real structure. Based on this relationship the problem of structural similitude between the real structure and the structural model is irrelevant.

The model acts as a magnifier, helping to visualize the behavior of the real structure, using materials that magnify deformations and permit measurement of displacements. To achieve this goal, the selection of proper materials for the construction of the model is critical. The material selected for modeling linear elastic behavior must remain linear over a large range of deformations, and its modulus of elasticity needs to be low to allow large deformations under small loads.

Structural models give to structural engineers and students the opportunity to visualize element displacements, especially torsion effects that are not presented by computer simulations where the representation of the element is typically a single line. The small deformations of structures at service loads do not allow for practitioners to visualize the effect of loads in structures. Models using appropriated materials give the opportunity to see the structure as an active system responding to the action of external loads.

The material of the model must be easy to weld. Complex structures involve rigid connections that require also rigid connections in the model. A model with poor unreliable connections is completely incompatible with computer simulations. It is also important to find elements of the material for construction of the models, pipes, structural shapes and plates of different sizes in regular shops, ready available and at reasonable prices.

ABS plastic meets all the requirements for the construction of structural models. ABS has very low modulus of elastic over and extended linear range, is available in common stores, and is easy to weld using cements or acetone. The ABS elements have excellent dimensional uniformity, which is important for construction of the models. Furthermore, the costs of ABS shapes are very reasonable.

Instrumentation for measurement in the models should be simple because the large deflections required for visualization allow for simple mechanical deflectometers for determination of displacements. Loads in the model are simple combinations of weights and small pulleys. A small and weightless accelerometer is also needed to obtain the natural frequencies.

The experiments discussed in this paper involve different models that show excellent relationship between the deflections obtained by the software and by the model. The models involve beam deflections, torsional rotations, and rigid behavior of joints. A model of the Alamillo Bridge, studied for bending and torsion, also gives good results. The natural frequency of vibration indicated by the computer model of the bridge is verified by the physical model with excellent results.

Structural models and computers are used in the first structural analysis course at the university. The content of the course is the same as the previous year, but the comprehension of structural behavior by students is significantly higher because they can see beams deflecting and twisting under the action of loads.

All model construction and testing are conducted by female students who demonstrated interest, great enthusiasm and understanding of the problem. The advancement in comprehension of structural behavior by members of the modeling team has been impressive. This achievement agrees with the faculty's goal for the structural program, to enroll more female students.

At the present, universities throughout the world are under substantial pressure to reduce educational costs. ABS models provide a low cost alternative to the testing of structural elements that are expensive in materials and space. Furthermore, the models can be replicated to give testing opportunities to several groups that would not be possible when using full size elements.

Future developments in modeling will involve buckling of structural members, and models of plates and shells. The faculty plans to demonstrate this methodology for structural modeling and visualization to pre-college students, to interest them in this discipline by presenting how structures behave under the action of forces and its agreement with Structural Engineering theory.

REFERENCES

McGuire, W., Gallagher, R.H., and Ziemian, R. D. (2000). "Matrix Structural Analysis", Second Edition.\

Pollaris, S.N., (1999). "What is a Bridge? The Making of Calatrava's Bridge in Seville". The MIT Press, Cambridge, Massachusetts.

Starvridis A., Sling B., and Conte J. (2010), "Design, Scaling, Similitude, and Modeling of Shake-Table Tests of Structures", University of California, San Diego.

Wikipedia (2012). "Acrylonitrile butadiene styrene". February 13, 2012 http://en.wikipedia.org/wiki/Acrylonitrile_Butadiene_Styrene

Authorization and Disclaimer