Models, Models, Models: The Use of Physical Models to Enhance the Structural Engineering Experience.

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Abstract

The increasing use of the computer in both the workplace and the classroom brings with it many dangers in addition to many exciting opportunities. In structural engineering, the user of analysis and design programs must also visualize and understand the physical "structural reality" to properly use the programs. Physical models have been integrated into the curricula of four structural engineering courses to enhance the “physical” understanding of both classical and numerical techniques and programs. The five models described herein were specifically developed for both in-class and out-of-class demonstrations and exercises. Photographs and student comments accompany the descriptions. Student response has been positive. Address to a web site is included for additional descriptions, photographs, and student comments.

Introduction

Significant advancements have been achieved in recent years in the visualization and animation capabilities of computer-based structural analysis and design programs. These computer programs and the necessary hardware bring with them their own costs, however, costs that are not necessarily measured in monetary units. One particular concern is that as students become increasingly competent with computers, their understanding and comprehension of “structural reality” may suffer.

This author firmly believes that physical models are an essential part of a balanced structural engineering curriculum.[†] This belief is particularly made firmer in light of the increasing use of computers in all facets of engineering practice and education. Physical models also appeal to different modes of learning. Testing laboratories traditionally provided opportunities for “hands-on” learning yet are expensive in both equipment, space, and labor needs. At the University of Alberta, eleven short demonstrations of basic fluid mechanics principles have been developed for 50 minute seminar sessions as an alternative to full scale lab experiments. These demonstrations were specifically intended to “fill the gap between teaching resources and learning needs.”[1]

In a paper focused on an undergraduate steel design course, Meyer, *et.al.*[2], stated that “to fully understand a particular design strength equation, the student must also understand (and be able to visualize) the associated structural behavior.” Those authors further stated that they “believed

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[†] For the purposes of this paper, the author limits the discussion to the structural engineering field but believes the argument could easily be generalized.

that the best means of communicating steel member behavior in the classroom is through the use of physical models."

This paper describes the integration of physical models into four structural engineering courses at the Pennsylvania State University. These courses are comprised of an introductory junior-level structural analysis course, a senior-level elective structural analysis course, an introductory undergraduate structural steel design course, and a graduate-level structural dynamics course. Photographs and descriptions of several models are included in the paper as are student comments. Additional photographs and descriptions are available on the web[3]. The development of these models has been inspired in great part by the extensive collection held by the Civil & Mechanical Engineering Department at the United States Military Academy (USMA), only a small portion of which is detailed in Meyer, *et. al.*[2].

The specific objectives of integrating the models were to:

a) enhance understanding and comprehension of structural behavior,
b) re-inforce the understanding that analytical and computer models are approximations of real physical behavior,
c) introduce and remind students of "the big picture" within structural engineering,
d) appeal to different learning styles, and
e) create an engaging classroom environment.

The five models described in this paper are representative of the many models developed at Penn State over the past 2 years. The first two models are actually building kits from which many other models have been created.

Girder & Panel Building Set

Having focused on two-dimensional structural drawings in "line-art" form in basic mechanics and materials courses, students frequently have difficulty intrepreting a set of structural drawings and visualizing a real structure. In a design of steel structures course, it is of paramount importance that the student not only visualize the three-dimensional structure but also correctly interpret the orientation of the major and minor axes of the columns.

The Girder & Panel Building Set is an ideal teaching aid for assisting the student in intrepreting structural drawings. The Girder & Panel Building Set is a commercially available children's toy consisting of plastic beams and columns, each cast in a wide-flange ("I-beam") shape. Figure 1 shows a typical 10-story office building constructed from the set. From the constructed models, the student can see first hand the "actual" structure that is represented by the drawings. Additionally, the small scale of the model

Figure 1: 10-Story Office Building made from the Girder & Panel Building Set.

facilitates an understanding of the entire structural system.

These sets are also exceptionally useful for demonstrating the behavioral differences between rigid frames, braced frames, and shear wall systems. Understanding these differences enables the student to correctly identify structural systems as sway “inhibited” or “un-inhibited.” Student response to the Girder & Panel Building Set when used to illustrate these ideas has been the epiphanic, “ah HA!” or “Ohhhhhh.”

Structural Engineering Toolkit

Creative modelling ideas don't always arrive a month in advance. Nor is there always a large budget available for making sophisticated models even if there is sufficient time. The Structural Engineering Toolkit (SET) shown in Figure 2 was developed by the author; it is composed of color-coded rods and connectors from the commercially available children's toy K'Nex. The rods and connectors are easily and quickly assembled to produce a wide variety of models that represent structural elements and/or entire structural systems. The resulting models are not as realistic in appearance as the “I-beam” structures of the Girder & Panel Sets but do provide numerous additional possibilities. The SET is quite durable and can handle rough treatment by both instructors and students.

Figure 2: The Structural Engineering Toolkit (SET)

The SET was initially developed during the Spring 1997 semester and has been used in both informal and formal ways for a variety of purposes that range from architectural display models to behaviorial models of both members and entire structures. For example, the SET has been used to create initial design examples, demonstrate truss behavior (both ideal friction-less and realistic truss behavior), demonstrate “sway” and “no-sway” of moment-resisting and braced frames, etc. At last count, over 30 models have been created from SET.

One model is the roof truss shown in the lower right corner of Figure 2. Although simple in concept, many students struggle with using the concept of tributary area and projected areas to determine equivalent loads. This roof truss model facilitated the calculations of point loads on a truss that resulted from distributed area loads such as wind, snow, and dead loads. Other documented models that may be viewed on the web[3] include bridge models and a dynamic model of a 3-story office building that was utilized in a graduate-level structural dynamics course. The quick and easy assembly nature that is such an advantage of the SET also has a down-side. Models are frequently created on the spur-of-the-moment and dismantled before photographs have been taken. For example, the SET has been used to simulate the sidesway web buckling failure mode of a steel "I-beam." And, the 1981 Kansas City Hyatt Regency collapse was simulated using the SET.

Each SET is sized to accomodate exercises for teams of two to four students. One specific exercise that has been tailored specifically to the SET is the "Truss Intuition Exercise." The specific objective of this in-class exercise is to develop within the student the ability to predict whether truss members are in tension or compression with as few numerical calculations as possible. Teams of two or three students first build a 4-panel Warren truss. The team then disconnects a specified member-end and loads the truss; the team must observe whether that member "pulls" away from (is in tension) or "pushes" towards (is in compression) the previously connected joint. The member is then re-connected and the process is repeated for other members. In this manner, the team visually associates the "sense" of the member force with a specific action, i.e., they develop a "physical-feel" for members that are in tension or compression. The exercise is then repeated for a slightly altered truss, but now the predictions are performed without the aid of the physical model. Students then verify their newly developed intuition with hand calculations. Finally, an out-of-class computer analysis is performed to complete the assignment.

Moment Distribution Training Aid

The moment distribution method for analyzing indeterminate beam and frame structures is one of the few analytical methods for which there exists a specific physical analogy for each analysis step. The moment distribution training aid shown in Figure 3 permits the sequential "fixing" and "releasing" of joints in a three-span continuous beam that correspond to each calculation step in the analysis of a 3- or 2-span beam by the moment distribution method. Loads may be applied in any or all of the spans; vertical support movement is possible at one interior support. The cross-sectional properties of each beam may be easily adjusted by inserting other beam specimens. The prototype for this aid was graciously provided by the USMA.

This training aid enables the students to directly observe the physical meaning of fixed end moments, the joint rotations induced by the "unbalance" moments when joints that were previsously "locked" or "fixed" are released, and the carry-over moments to the far-end of each beam when a joint is released. This analysis method and training aid have proven to be effective tools by which to introduce and explain the importance of relative stiffness in the response of indeterminate beam and frame structures.

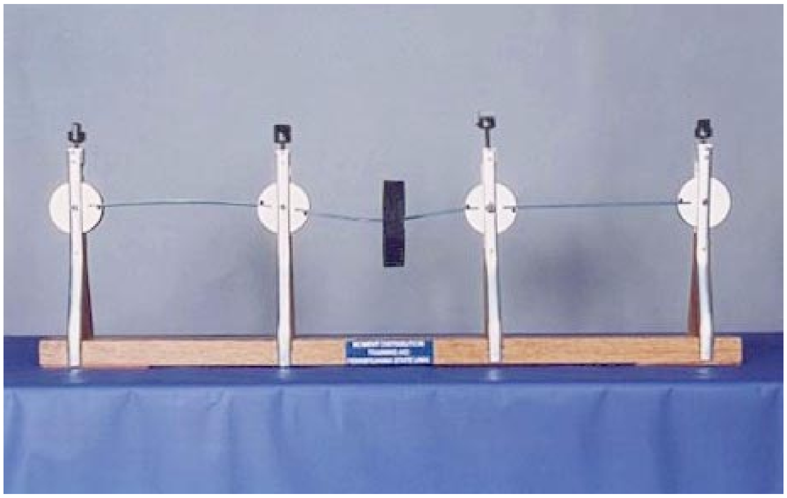

Figure 3: Moment Distribution Training Aid

Large Scale Models

The models described above have primarily been developed to enhance in-class lesson presentations and/or exercises and therefore have been sufficiently small so that they may be easily transported to class. Larger scale models have also been developed such as the the model of the George Washington Bridge shown in Figure 4. The model was constructed from six SETs by a team of three students as an extracurricular activity in support of a college-sponsored open house. The model has a main span of 3 meters and approach spans of 0.95 meters; the towers are 1.3 meters high.

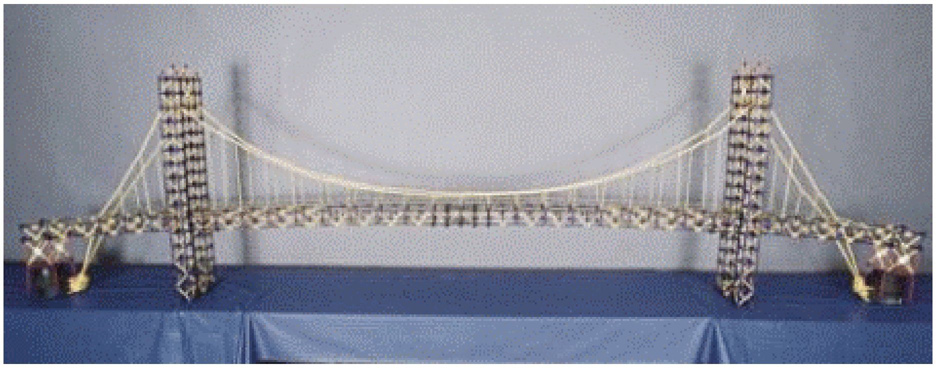

Figure 4: The George Washington Bridge

Originally intended for architectural-only purposes, the model facilitated a discussion of construction and erection issues and provided an initiation point for the construction team to investigate the underlying theory of suspension bridges. The towers have also been utilized in the senior-level elective structural analysis course as a part of a modelling exercise. Additionally, a 1.5 meter model (not shown here but documented on the web) of an offshore oil-production (jacket) platform has been constructed by the author for various graduate seminars. The model has been useful in introducing these unique structures and for explaining the author's technical research.

Pasta Bridge Model

Often times, students (and even practitioners) are tempted to accept unquestioned the results from computer analyses. And, even when carefully reviewed, the results may not be reviewed with an eye towards realistic behavior. Reasons for this are many and include laziness, lack of intuition, incompetence, etc. There are a limited number of approaches for the former, but the latter can be addressed by the instructor.

The pasta bridge project was integrated within a senior-level elective structural analysis course specifically to motivate an investigation into the differences between real behavior and the models that are used in engineering practice to predict that behavior. Related to this objective was the goal of understanding the relationship between the sophistication of the model used, the competency of the modeler and modelling tool, and the desired result. In other words, what model is good enough? What tool is good enough? What has been left out?

The primary task-level objective was to design, construct, and test-to-collapse a 1 meter bridge made entirely of pasta. One example is shown in Figure 5. Re-inforcing fibers were not permitted but virtually any bonding agent was permitted. Hence, many bridges were composed of more epoxy than pasta. Serviceability and strength criteria were nominal (a 1:24 scale model of a Ford Mustang GT had to be able to travel along the bridge and a 22.2 N (5 lb) load was applied at the mid-point). No additional credit was available for exceeding these requirements. Ninety per cent of each team's grade was based upon the pre- and post-testing analysis of the bridge's performance. The analyses were presented both in formal written reports and presentation boards such as observed at poster sessions of conferences.

Figure 5: Pasta Bridge Model “Big Blue”

A variety of failure modes were observed that included joint failures, member failures, and stability-induced failures. Some failure modes were easily predicted, others were simple but overlooked, and still others were a complete surprise. Most bridges had capacities in the range of 90 to 270 N (20 to 60 lbs). The largest official capacity was 580 N (130 lbs) although the bridge shown in Figure 5 (affectionately known as "Big Blue") supported 1,236 N (278 lbs) before the supply of testing weights was exhausted.[†]

Although the students felt that construction phase of the project needed to be extended and given greater weight in the overall scoring, student response was in general quite favorable. Interestingly, the SETs were not used extensively in pre-planning by the project teams. Those that did felt that they were of some use but that the different dimensions (non 45 degree angles between members) of their proposed plans made using the SETs difficult. Typical overall comments were:

> "Our group worked really hard and put in a lot of time. It was really satisfying to me that our bridge withstood a larger load than anticipated."
>
> "At first I was very skeptical about this project, but Saturday (the testing day) I completely understood."
>
> The most important lesson learned was "the difficulties of transferring ideas on paper into a real model (structure)."
>
> "This was the first time in any of my structures courses that I was able to apply what I had learned to a real model."

Detailed comments from the student's evaluations are available on the web[3].

Student Response to the Physical Models

Data of student response to this date has focused on the general response to the physical models as a whole and not necessarily to specific models unless such information was volunteered. On the whole, the response has been positive. Physical models were first used by this author in a significant manner during the Spring 1996 semester for an introductory steel design course. Student responses at that time indicated that the models (particularly the Girder & Panel) were "helpful and that more models were desired."

Integration of physical models such as the Moment-Distribution Training Aids began in earnest during the 1996-1997 academic year. These models were generally speaking of the "spur-of-the-moment" variety and were made from readily available scrap material such as pvc pipe. Again, students indicated that the models were helpful and that more should be developed and hence effort was directed towards developing the SET.

More consistent data was collected throughout the Fall 1997 semester in the introductory structural analysis course: immediately after two interim exams and during the last week of

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[†] Big Blue's official capacity was 420 N (95 lbs) and was associated with the failure of a loading platform member. A stronger loading bar was than installed and the applied load reach the reported value.

classes (for a total of three data sets). This was also the first semester that the SET saw consistent use. After the first exam, students strongly agreed that the "physical models helped me to understand the material presented in class." (The average response was 6.25 on a scale where a “7” indicates strong agreement, a “3” indicates neutral, and a “1” indicates strong disagreement). After the second exam, the students agreed somewhat less strongly (5.0/7) “that *more* physical models would help me to understand the material.” And, at the end of the semester, when given the choice between spending departmental money on physical models or additional computer programs, the class responded that the money should be spent on the physical models (4.86/7).

Although few definitive conclusions can be determined particularly in terms of increased student learning and performance, students appear to particularly enjoy the SETs. Typical comments were:

- *“We should use K'Nex (SETs) more often in class - they're fun and interesting.”*
- *“These are so cool!”*
- *“When are we going to get to use the K'Nex* (SETs) *again?”*

The author's anecdotal evidence would suggest that both student enthusiasm and understanding has significantly improved by the use of the phyical models. This was particularly in evidence during office hours where epiphanic phrases of "Ah Ha" were frequently heard when the models were used. Indeed, it was perhaps during office hours that the flexibility of the SET was clearly demonstrated. Models often were constructed on-demand to students' questions.

However, it is not at all clear whether student performance as measured by timed exams and homework has improved. Indeed, exam and homework scores have only seen nominal improvement. The author is currently seeking ways by which to more precisely identify the influence of the physical models on student learning. And, the author is continuing to learn more about active-learning models and how to effectively and efficiently integrate them within the typical 3-lessons (lectures) per week engineering course. The primary lesson learned thus far about this latter aspect is the old adage of “plan, plan, plan.” The use of physical models as training aids, demonstration models, architectural models, or as devices for active-learning exercises must be planned out in detail if the students are to walk-away from the exercise with the intended experience. Although self-discovery is a wonderful experience, it is the author’s opinion that in the classroom setting the instructor sometimes must take a strong and firm guiding hand in order to bring that experience to meaningful fruitition.

The Future: The Structures Demonstration Laboratory

The previously described models have been developed utilizing only tuition surcharge monies. During the Fall 1997 semester, the Structures Demonstration Laboratory[3] (SDL) was established. It is currently housed in existing space in the structures testing facility at Penn State. The SDL will move to Valparaiso University along with the author at the beginning of the Fall 1998 semester. The initial mission of the SDL was to develop physical models for in-class demonstration purposes. That mission is now being extended to provide a hands-on environment in which students may experience structural behavior first-hand rather than only via computer simulation or classical hand-calculation techniques.

Material for additional models has already been purchased and construction is planned for Spring 1998. These models include many that have been detailed in Meyer, *et.al.*[2], such as static connection models, the lateral torsional buckling demonstrator, the flexural buckling demonstrator, and the rigid and braced frame demonstrators. The static connection models are accurate three-dimensional representations of typical steel connections (tension, simple beams, semi-rigid, and rigid connections). Also slated for Spring 1998 is the construction of a Steel Connection Sculpture, a ten-foot steel sculpture consisting of various real-scale beam-to-column connections, steel joist-to-beam connections, etc.

Conclusions

The author has found that physical models enhance the ability of the students to visualize and understand structural behavior. The models have also been particularly useful in explaining and providing a context for classical and numerical analysis techniques. A serendipitous effect has been that the models have facilitated group and collaborative exercises. By carefully planning, the author has found that the physical models facilitate in-class, active-learning exercises without disrupting the typical fast-paced course syllabus.

Any engineering educator interested in additional information about these models or those on the web[3] may contact the author at:

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