Simple Structural Models for the Education of Structural Engineers at Graz University

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Introduction

As a part of the reorganization of the civil engineering curriculum at the Graz University of Technology, a new course entitled "Design Models" was developed about 10 years ago. This course is scheduled during the first period of study, along with courses primarily dealing with natural sciences (e.g., mathematics and mechanics). Therefore, the course is the first lecture in structural engineering for the students. The objective of the course is the presentation of the fundamentals on modelling and design in structural engineering. Furthermore, lectures include a presentation of design rules for simple structural elements such as beams, columns and trusses in steel, reinforced concrete, and timber. The design rules include cross-section design and member design, with a discussion of flexural and lateral torsional buckling of beams and columns. As a part of design exercises, every student must design a specific simple structure made from each of these individual materials. So the students get an idea of the different cross-section dimensions, depending on the specific material.

Professor Greiner, the former lecturer of the course, proposed the idea of using structural models as a learning aid. Implementation was achieved by the writer, who is now the lecturer of the course. The main reason for the use of structural models is to show the different failure modes, such as cross-section failures, flexural and lateral torsional buckling of structural members, local buckling, and failures under concentrated loads, which are the basis for theoretical design rules. An important requirement for structural models is that they are simple, with respect to the stresses and internal forces within the individual structural members, because of the student's limited knowledge of statics.

Practical Implementation

General

This section presents a practical implementation of the structural model competition within the course. Experiences with materials are described for the models and load capacity testing done over the past 10 years. Moreover, the specifications for the models, including geometry, loads, and support conditions are shown. Every year these specifications are changed. Later, some results are shown, based on the structural model load tests.

The yearly course is concentrated over 6 weeks. The specifications for the structural models are presented at the start, with details concerning fabrication. Groups of three or four students must complete the models within 2 weeks. The load tests of the models are made after about 60% of the course period has passed, with participation by all the students. Final presentation of load carrying behavior and failure modes of representative models is given in the last lecture of the course. At this time, awards are presented to the groups with the strongest models. Every year about 120 students attend the course.

Materials of Models

The material used for the models is cardboard, similar to that used for shoe boxes, but thicker. Every group gets the same amount of material, usually three sheets with dimensions of $650\times500\times1$ mm. Glue is also provided. The advantages of this material compared to others are that it is very cheap and is easy to handle without special skill (Fig. 1). The material requires the fabrication of thin-walled sections for the structural members. These structures are very similar to actual steel structures. They show a higher variety of failure modes compared to solid members (e.g., models made of timber), because local buckling and local failures can occur in the regions of concentrated loads.

Specifications and Variety of Design

Fig. 2 shows the specifications for the structural models from the 1996 class. A 1,000-mm high tower had to be made, and it was loaded by a vertical force P at the top. The maximum dimensions for the shaft are 100×140 mm. At the foot of the tower, an additional horizontal structural member had to be designed because the four supports of the tower are situated outside the shaft.

A very important aspect of the specifications is that they avoid placing restraints on the design. Therefore, the amount of material is specified in such a way that plated structures as well as frames and trusses are possible. In Fig. 3, some of the towers can be seen. Every year it is a great pleasure to see the creativity of the students, which leads to models with widely differing designs.

To keep the load behavior of the models simple as well as to reduce the efforts for testing, the load capacity and the loading are limited to a single concentrated load, P. By using additional plates, distributed loads are possible.

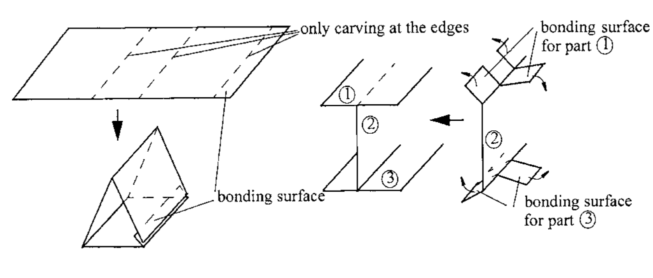

Fig. 1. Examples that show the easy handling of cardboard. Member with boxed section (left) and open H section (right).

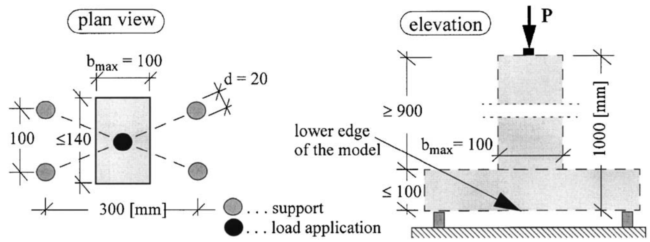

Fig. 2. Example of the specifications for the structural models

It is important to change the specifications for the models every year. Otherwise, the students will copy the structural forms with the highest load capacity from past years. Some of the specifications of the past 10 years are summarized in Fig. 4.

Ultimate Load—Requirements of Testing Facility

The measurement of the ultimate load (maximum force P) for every model is made in the laboratory of the structural engineering department, directed by Professor Kernbichler. Due to the small forces in a range of $P = 10-1{,}500$ N, a special test rig was developed (Fig. 5), which is slightly modified every year. It is important that the test is deformation controlled. In other words, the deformation is increased during testing but not the force. This is done by a thread rod guided onto the frame, which in turn is driven by an infinitely variable electric motor. A load cell is integrated into the thread rod behind the cylindrical loading device. Only with the deformation controlled test it is possible to study the structural behavior after formation of the individual failure modes, especially if buckling effects occur (postbuckling behavior). Also, the deformation at the loading device in the vertical and horizontal direction (if possible in the test) is measured. The measurements of force and deformation are continuously made. The data are recorded and analyzed on a computer to plot the force-deformation curve. This curve is visible on a monitor near the model.

Some of these load-deformation curves can be seen in Fig. 6. Here frames were tested under both vertical and small horizontal concentrated loads, and the horizontal deformation directly under the load is plotted.

Recording the load deformation curve is very important for explaining the load carrying behavior of the models. For example, the danger of buckling failure of structural members is only visible in the curve because, after exceeding the ultimate load, the load suddenly drops down (e.g., Model 18 in Fig. 6). With the load deformation curves, the different risks of individual failure modes can also be analyzed by comparing the remaining load capacity after failure with the ultimate load. In addition, the ductility of structures can be observed and compared for different types of structures.

Note that with the test rig in Fig. 5, the models are always horizontally restrained by the loading device (see also Fig. 8). To model real structures, such as towers or frames of buildings without restraint at their tops, the thread rod must include a hinge. The frames in Fig. 6 were tested this year with this modified test rig. With the measured horizontal deformations, the importance of frame stiffness (gradient C of the curves) for the ultimate load (including second-order effects) can be clarified for the students.

Because the students' model dimensions are highly variable, it is important that the loading device provide flexibility for the position of the supports. Because of this, in general, only compression forces can be transferred to the supports.

Structural Models—Results and Benefits for Teaching

Comparison of Ultimate Loads of Models

Interestingly, the frequency distribution of the ultimate loads of all models is similar every year. In Fig. 7, the results for the tower models of Fig. 3 can be seen. The scatter is high, moreover, the models with the highest load capacity have significantly higher ultimate loads than all others (mean value MW in Fig. 7).

Also interesting is the high scatter of the weight of the models, although the amount of material is equal for every group. In Fig. 7, the dependency between weight and ultimate load of the models is plotted. It can be seen that more material (higher weight) doesn't always lead to higher ultimate loads. The measurement of the weight of each model is very important to separate those groups from the competition who have used more material than allowed.

Failure Modes

Different failure modes can be seen on the structural models, depending on the type of structure. They can be classified as follows:

- Cross-section failures. For members under bending, this is sometimes only noticeable because of the high deformations (Fig. 8, left).
- Local failure in the region under concentrated loads, often due to missing diaphragms (Fig. 8, right).

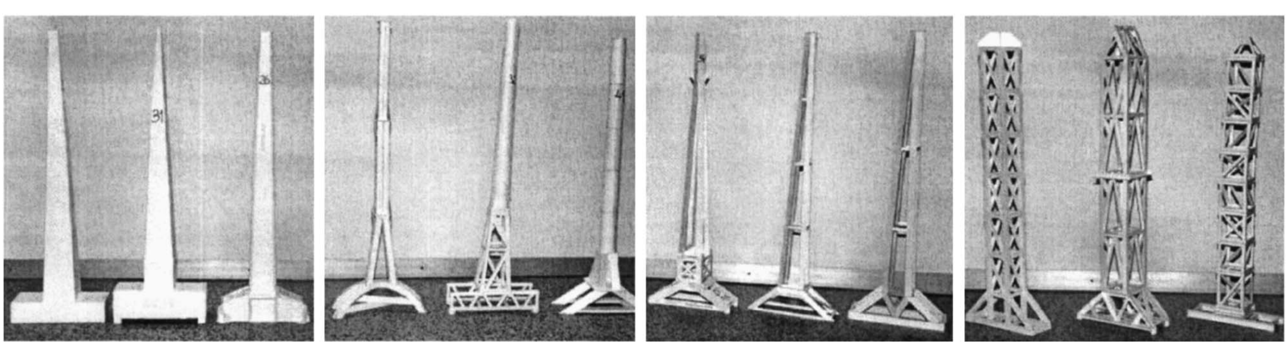

Fig. 3. Tower models

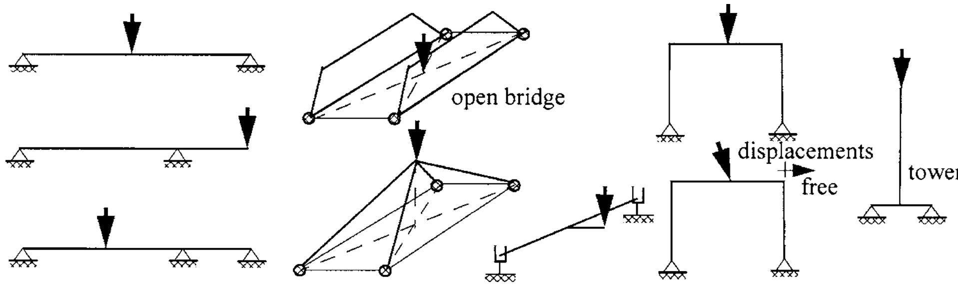

Fig. 4. Specifications of structural models from the past (schematical)

- Buckling of members (flexural buckling or lateral torsional buckling, Fig. 9).
- Local plate buckling of thin-walled sections caused by compressive or shear stresses (Fig. 9).

Load-Deformation Behavior of Models

The recording of load-deformation behavior, also after exceeding the ultimate load is important to show to the students the following effects:

- failure modes with/without remaining load carrying capacity; and
- ductile or brittle behavior of structures.

It is useful to analyze some significant models during the final lecture. Every group gets the load-deformation curve for their model.

Benefits of Structural Models in teaching

Based on the experiences of teaching 10 courses, the advantages of the integration of the structural models into the course include the following:

- The failure modes of the structural models can be seen, similar to those on real structures. They are the basis for the design rules presented in the course.
- Load-carrying behavior is sometimes directly visible on the models. After reaching the failure mode, the regions with compressive and tensile stresses can be seen.
- With the help of the load-deformation curves, the ductile behavior of structures can be explained and the remaining load-carrying capacity can be shown for the different failure modes.
- Teamwork within each group is very helpful for students to learn to communicate with each other. This is very important, because at this university the students do not live on campus and at this period in their studies they are trained to work alone.
- Competition motivates the students. At the final presentation, also the group that has best estimated the ultimate load of their model is rewarded. All participating students have a chance to win.

These benefits are only assured if the following requirements are fulfilled:

- Simple fabrication of the models.
- Deformation controlled testing of the models, continuous measurements of load and deformations, and plotting the load-deformation curve for every model.
- Explanation of the load-carrying behavior of the models when they are tested. For better understanding, additional graphics are helpful to show the internal stresses.
- Summation of all the results in a final report and presentation of them in a separate lecture. This includes illustrations of the failure modes with acting stresses and the load carrying behavior of significant examples.

Fig. 5. Test rig to measure the ultimate load P and the deformations of the structural models

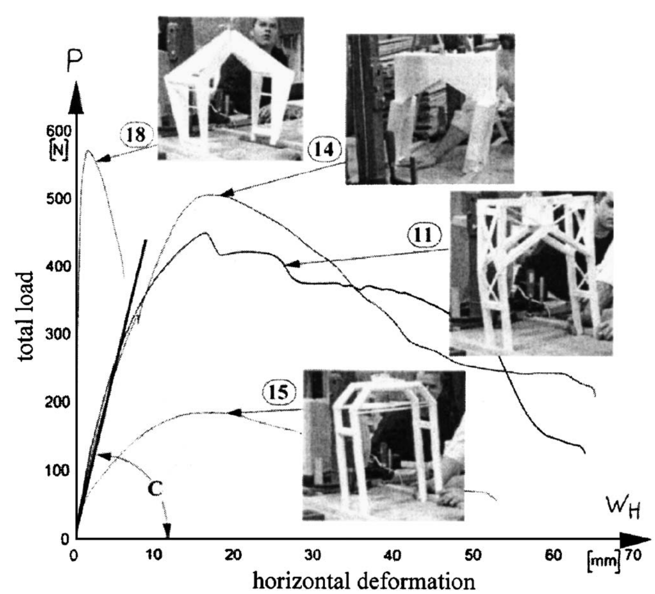

Fig. 6. Example of the load-deformation curves for different frames under vertical and small horizontal loads (w_H=the horizontal deformation under the load)

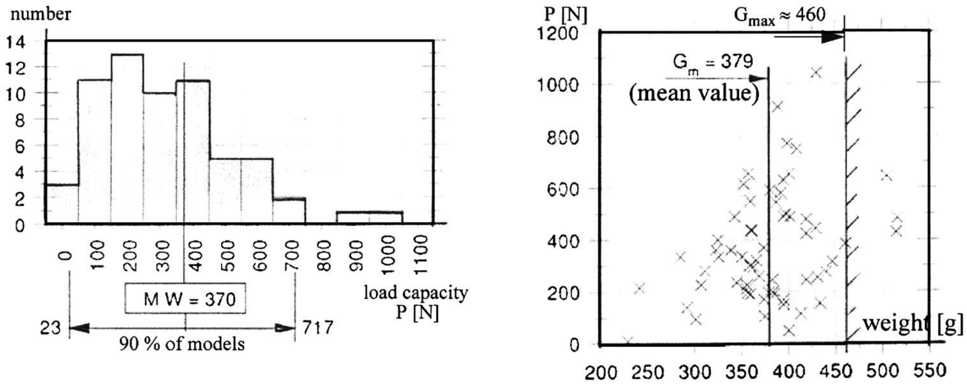

Fig. 7. Scatter of the ultimate load *P* of all 62 tower models (left) and correlation between weight and ultimate load

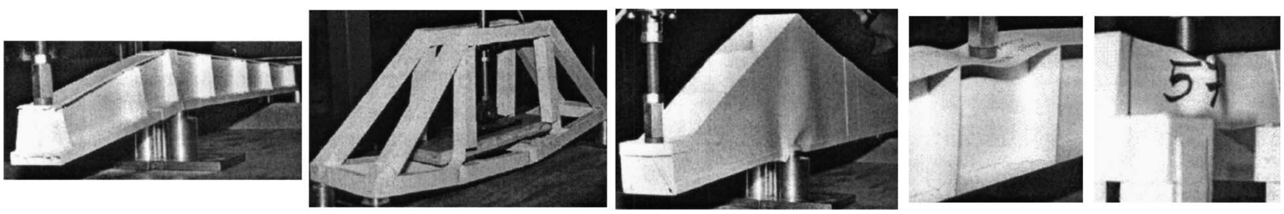

Fig. 8. Different failure modes of the models. Cross-section failure under bending and under tension at the bottom of the vertical members, local failure modes under concentrated single loads (from left to right).

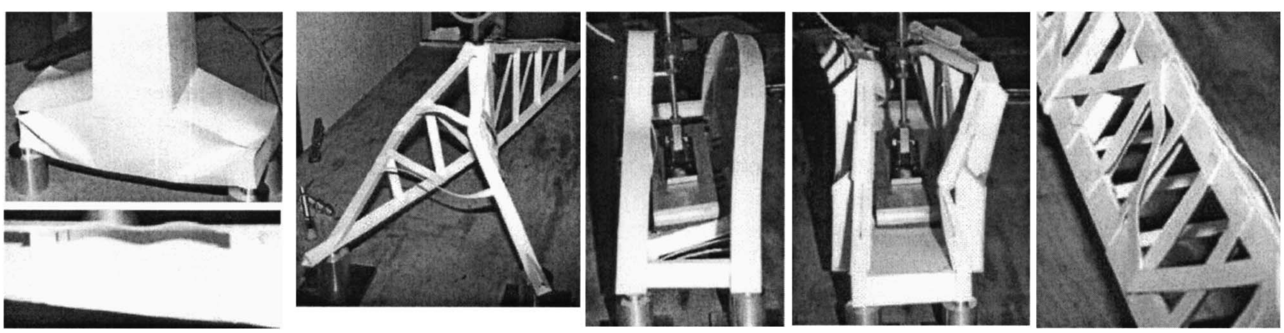

Fig. 9. Different failure modes of the models. Plate buckling under shear and compressive stresses, flexural buckling of structural members, lateral torsional buckling of girders of open bridges, flexural buckling of a diagonal in a truss girder (from left to right).

Summary

In the education of civil engineers at the Graz University of Technology, structural models made of cardboard are a helpful teaching aid in the basic courses of structural engineering students. The load-carrying behavior and failure modes of real structures can be observed on the models. Analysis of the load-deformation curves also show the remaining load capacity for the different failure modes, and ductile or brittle overall behavior can be seen. The fabrication of the models is done by groups of three or four students, and the students with the models with the highest loads are rewarded. This procedure motivates all students also to work together.

Acknowledgments

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