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Multiple-Feature/Multidisciplinary Design Project in an Introductory Engineering Mechanics Course*

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A simple truss bridge design project for a one-semester sophomore-level combined course in statics and dynamics, taken by a multidisciplinary class of students from civil, electrical, and industrial engineering at Morgan State University (MSU), is described. Patterned after a continuing and popular annual Student Steel Bridge Design/Building Competition, the design project problem statement incorporates conflicting constraints and simple scoring or objective formulas. As a result the design problem is open-ended; however, an added benefit is that the same basic project can be repeated in successive classes due to the manner in which the constraints are prescribed. Class members who participate in the MSU Steel Bridge Team also get to experience more detailed design iteration, realization of the eventual bridge design, testing of the product and even validation of the bridge's performance in the corresponding year's Student Steel Bridge Competition (SSBC). Preliminary results from the first two semesters of introducing the project suggest some improvement in student performance and learning in the engineering mechanics course. As a sophomore level course, the design project also contributes to the integration of design across the engineering curriculum at MSU.

INTRODUCTION

THE ENGINEERING MECHANICS CEGR304 course at Morgan State University is a four-hour lecture, four-credit school-wide course that is required for students (mainly at their Sophomore level) in three departments: Civil Engineering, Electrical and Computer Engineering, and Industrial Engineering. Students thus come to the course with diverse backgrounds and expectations. CEGR304 is a combined statics and dynamics course with the current catalog description:

> *Resolution, composition, and equilibrium of forces; analysis of force systems; center of gravity, and moments of inertia; motion study; Newton's Laws and work-energy, impulse-momentum, and power. Prerequisites: MATH 242 (Calculus II) and PHYS 205 (University Physics I).*

Prior to the inclusion of a design project, the course had a full array of lectures such that certain topics were not covered in significant detail. Therefore a constraint on the project planning was the need to preserve content and if possible enhance coverage. The project had to be short-term to minimize its share of class time, which could otherwise affect coverage. Further, the truss bridge design exercise is considered a component of the module on analysis of structures.

As a member of the Engineering Coalition of Schools for Excellence in Education and Leadership (ECSEL), design is introduced at the freshman year of engineering at Morgan. The various departments typically have a major capstone design course and a few other courses with design at the senior and perhaps junior years. Thus some gap between the introduction at the freshman level and subsequent design courses is typical of the engineering curriculum at MSU, as well as in some other engineering schools. Howell, *et al.* [1], has characterized sophomore and junior design experiences as the 'missing link' between freshman and senior design experiences, and many engineering schools have in recent years moved to provide such missing links through vertical integration of design across their curriculum [2]. In a few cases, [3] and [4] for example, some of these design experiences have been introduced in mechanics courses. Besides helping integrate design across the curriculum at an intermediate level between freshman and seniors, a major objective in introducing design projects to the engineering mechanics course at MSU was to stimulate student enthusiasm for the material and generally to improve their understanding and performance. A consequent constraint on the project planning is that the design problem must be such that the effort can be sustained from semester to semester.

Other considerations in the design project planning

In 1998, Morgan participated for the first time in the SSBC sponsored annually for student chapters of the American Society of Civil Engineers

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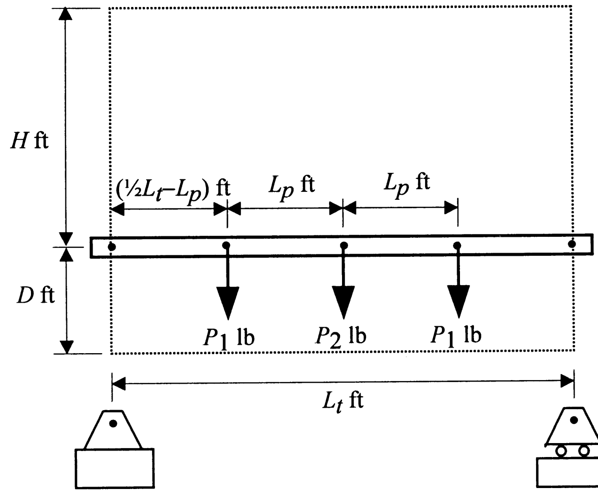

Fig. 1. Bridge supports, loads, and design envelope.

(ASCE) by the American Institute of Steel Construction (AISC) and others. This is an event that generates in the participating schools, a lot of student enthusiasm and effort. There is also a measure of permanence to the event. Most schools that participate in the SSBC field teams every year. The competition includes first a regional event and then a national competition for qualifying teams. The student steel bridge design problem is representative of a 'real-life' structural design problem and the competition judging categories of strength, stiffness, lightness, economy, construction speed, efficiency, and aesthetics, and primary concern for safety, are all typical of a practical engineering project. Moreover the bridge specification is varied from year to year to ensure that participants in the competition enter different bridge designs each year.

An attempt was made to incorporate some of these attributes of the SSBC in the CEGR304 project by (1) designing an exercise similar in some aspects to the bridge specifications for the SSBC but requiring no more analytical background than would ordinarily be available from CEGR304, and (2) having the project executed and presented in groups (teams). With an MSU entry into the SSBC, experiences from the class project can be applied as inputs to preliminary MSU design efforts for the SSBC in a particular year. Furthermore, if class members are also members of the MSU SSBC team, then they have the opportunity to not only continue to practice and execute the design process but to experience the full spectrum of tasks typical of an industrial environment including fabrication and testing of the bridge. This integration of the class activity and the bridge competition has the additional advantage of making student enthusiasm for SSBC activities and resources developed in the SSBC such as peer advising, software proficiency training, and teamwork, available to the CEGR304 class.

A plane truss bridge design exercise requiring about two weeks for completion was selected as a project that met the requirements on project duration and analytical content, and had sufficient depth to model the essential elements of the SSBC and serve as a significant input to the preliminary solution or concept stage of the SSBC. The Bridge Design exercise as described to the students is essentially as follows.

DESIGN PROJECT PROBLEM STATEMENT

A L_t-ft. span truss bridge is to support the loads shown in Fig. 1. The pin supports at the abutments where the bridge is to be attached are shown in the figure.

The Department of Transportation (DOT) has requested for (plane truss only) design proposals for consideration and selection. The bridge truss members must be cut from the DOT's surplus stock of rolled-steel shapes (to a given *specification*, for example L2 × 2 × 1/8 angles). Because of limitations on access to the construction site, no truss member can have *length* (pin to pin) exceeding L_m ft.

The DOT requires each competing firm (group of about 5 students) to submit on or before *date* a written report including a drawing of the bridge (plane truss) design and calculations of (a) the *force* in each truss member, (b) the *deformation* (under load — extension or compression) of each member, and (c) the total *weight* of the bridge. Further the firm must make a 10-minute presentation of its proposal and defend/justify its design before the DOT's Chief Engineer on *date* + 2 or 3 days.

Selection criteria

The Chief Engineer would rank the designs according to the following criteria:

1. *Report:* 20%.
2. *Presentation:* 20%.
3. *Stiffness:* (Let N = number of members, d_i = absolute deformation of member i (in feet),

then score = $\min\{20, S1[1-(N \cdot S2 \times 10^{-4}) -1\Sigma_{i=1}^{N} d_i]\}$): 20%.
Note: Only member *deformation* is considered. Bridge *deflection* is ignored.

4. *Lightness:* (score = $\min\{20, 20(S3\,\text{lb/total weight in lbs}\}$): 20%.
5. *Construction speed/cost:* (score = min[20,2($S4-N$)]): 20%.

(A typical set of *weighting factors and lengths* could be: $S1 = 30$, $S2 = 9$, $S3 = 90$, and $S4 = 21$, with $L_t = 17$, $L_m = 5.5$, and $L_p = 3.5$)

Further specifications

1. The plane truss (all pins) must be contained within the rectangle shown extending H ft. above, and D ft. below, the bridge attachment pins.
2. No truss member can have a deformation (extension or compression) under load exceeding $S2 \times 10^{-4}$ feet.
3. The bridge should be as light as possible (see selection criterion No. 4).
4. The bridge should be such as can be constructed quickly and with little cost. (Selection criterion 5 implies that the number of members is the measure of this requirement).
5. The cross sectional area of L2 × 2 × 1/8 angles is 0.484 in^2, the weight per foot is 1.65 lb/ft, and the modulus of elasticity should be taken as 29×10^6 psi.
6. You are required to use computer tools to accomplish this project. An example utilization of computational math software such as MAPLE, MATLAB, and MathCAD is attached. (The attachment includes free body diagrams and equilibrium equations for a simple truss bridge design that however does not satisfy all project requirements, and interactive and graphical output from the software analysis.)
7. You should also use L. Bucciarelli's `trusswrk.ctb` [5]; a similar program is John Hopkins University Virtual Laboratory Bridge Designer and truss wizard [6], or if you prefer, another high-level design tool to first explore your truss configurations. However note that the output data from `trusswrk` are joint x- and y-displacements and not directly member axial deformations.

PROJECT FEATURES AND IMPLEMENTATION ASPECTS

The above description suggests an open-ended design project due to the absence of constraints on what truss configuration can be used (only the position of the supports and load joints are fixed) and the multiple interacting constraints which are generally conflicting, and the approach to scoring the exercise. These same features also allow the same problem to be used repeatedly.

For a limited illustration, consider as shown in Fig. 2, seven simple truss configurations derived from common types of plane trusses used as bridge trusses [7]: Pratt, Baltimore, Howe, K, and Warren trusses. The seven configurations are identified by the letters P, B, H, H2, K, K2 and W. Given a set of project geometric bridge constraints and scoring factors, the feasibility of each configuration can be determined, and for the feasible designs the sizing of the members can be optimized with respect to the total score (excluding of course the report and presentation scores). Table 1 summarizes the results of carrying out this exercise for a few of the possible conditions on geometric constraints and scoring factors: L_t, H, D, L_m, P_1, and P_2 fixed at 17, 5.5, 0, 5.5, 833, and 833, respectively, and six values of L_p (3.0, 3.5, 4.0, 4.5, 5.0 and 5.5), two value ranges of $S2$ (9 and 5 or 6), and two

Table 1. Feasible and optimal plane truss configurations

Conditions	B	H	H2	K	K2	P	W
$L_p = 3'$, $L_t = 17'$, $S2 = 9$, C = on	1	0	1	0	1	0	1*
$L_p = 3'$, $L_t = 17'$, $S2 = 9$, C = off	1*	0	1	0	1	0	1
$L_p = 3.5'$, $L_t = 17'$, $S2 = 5$, C = on	1*	0+	1	0+	1	0+	0+
$L_p = 3.5'$, $L_t = 17'$, $S2 = 9$, C = on	1	0+	1	0+	1	0+	1*
$L_p = 3.5'$, $L_t = 17'$, $S2 = 9$, C = off	1*	0+	1	0+	1	0+	1
$L_p = 4'$, $L_t = 17'$, $S2 = 5$, C = on	1*	0+	1	0+	1	0+	0+
$L_p = 4'$, $L_t = 17'$, $S2 = 9$, C = on	1	1	1	1	1	1*	1
$L_p = 4'$, $L_t = 17'$, $S2 = 9$, C = off	1*	1	1	1	1	1	1
$L_p = 4.5'$, $L_t = 17'$, $S2 = 5$, C = on	1*	0+	1	0+	1	0+	0+
$L_p = 4.5'$, $L_t = 17'$, $S2 = 9$, C = on	1	1	1	1	1	1*	1
$L_p = 4.5'$, $L_t = 17'$, $S2 = 9$, C = off	1*	1	1	1	1	1	1
$L_p = 5'$, $L_t = 17'$, $S2 = 6$, C = on	1	0+	1	0+	1	0+	1*
$L_p = 5'$, $L_t = 17'$, $S2 = 9$, C = on	1	0+	1	1	1	1*	1
$L_p = 5.5'$, $L_t = 17'$, $S2 = 6$, C = on	1	0	1	0	0	0	1*
$L_p = 5.5'$, $L_t = 17'$, $S2 = 9$, C = on	1	0	1	0	0	0	1*

Key
0 Not feasible due to member length (L_m) or other constraint
0+ Not feasible due to member deformation ($S2$) constraint
1 Feasible but not highest scoring
1* Feasible and highest scoring

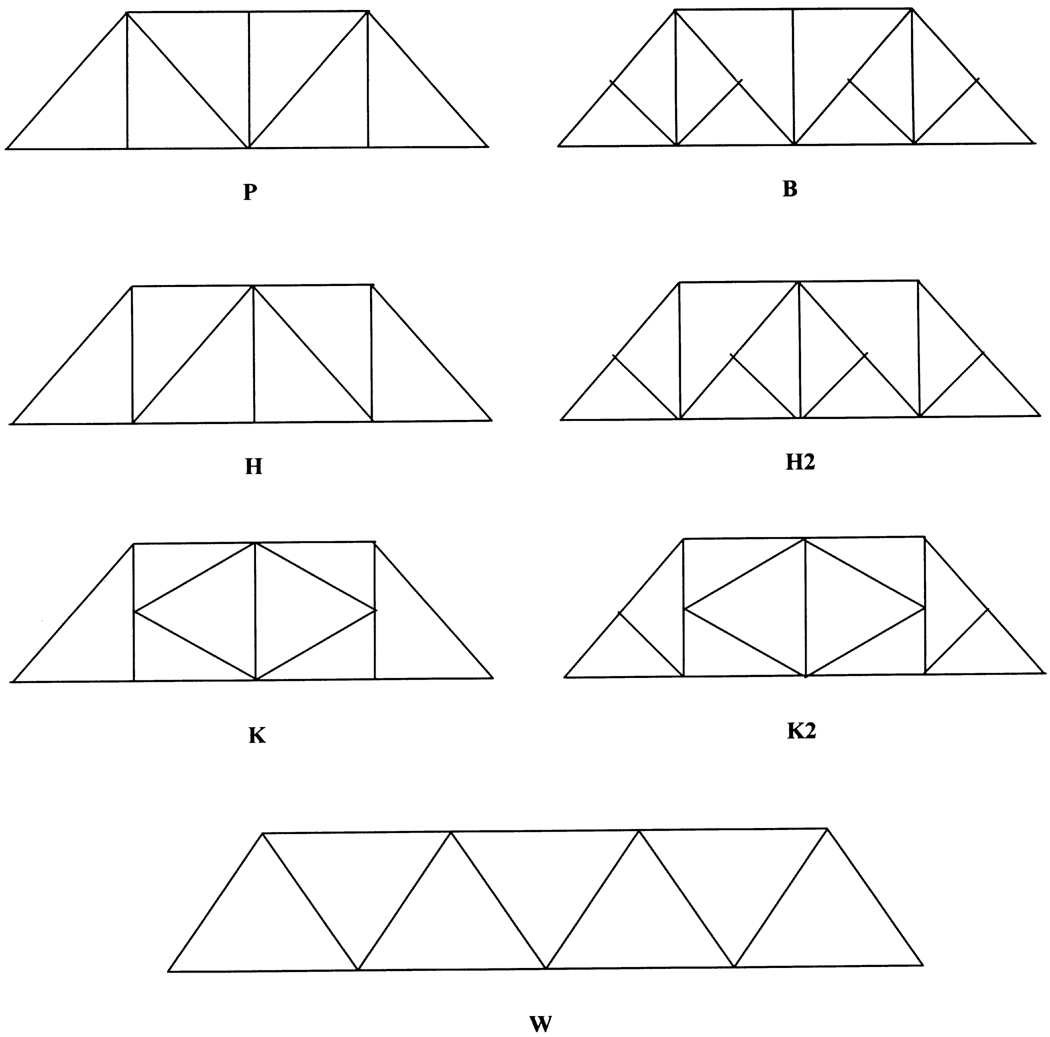

Fig. 2. Some representative trial bridge truss configurations.

conditions on the construction speed objective ($C =$ on, that is $S4 = 21$, and $C =$ off, that is $S4$ very large).

It can be seen that even for this limited set of conditions, there is significant variation on what configurations are feasible and what configuration within the feasible set is optimal. Thus by properly changing from time to time the geometric constraints and scoring factors, the same project can be sustained without significant risk of recycled solutions.

The project is executed and reported (both written and oral) by groups of five or fewer students. A typical class section of about twenty students would have four to six groups. The primary scoring is also per group but individual student scores within the group are moderated by anonymous internal assessment of each member by the other members of the group. The project exhibits other features: it is short-term (it is intended to be executed in two weeks); it requires the use of computers and information processing tools, as well as formal analysis as part of the solution process. The bridge design problem specifically combines the use of intermediate or higher levels of design software for conceptual design with the application of computational mathematics programs like Maple, MATLAB, and MathCAD for analytical and detailed design. The project is thus not a black-box exercise in the application of high-end design software.

A desirable feature that derives from the capacity to offer the same project repeatedly is that of continuity. This means that, as in the real world, there would exist a reservoir of experiences in the bridge project that, without compromising the design exercise, can always be available to students to learn from the work of their peers. Continuity is also available to students who go on to the SSBC through the close relationship between the CEGR304 bridge project and the problem description of the SSBC.

Since the project groups or teams are set up simply by dividing an alphabetical list of the class, then just as in the world off campus, the teams normally reflect the multidisciplinary pool from which the students come. However some communication problems typical of such multidisci-

Table 2. Students' evaluation of bridge design project

SURVEY QUESTION	FALL 1997					SPRING 1998				
	5	4	3	2	1	5	4	3	2	1
1. Did having a design project for the course increase your interest in the course?	2	6	9	4	2	3	3	6	2	0
2. Did having a design project help improve your understanding of the course material?	4	8	9	0	2	3	3	7	1	0
3. Do you feel that the project would make a difference in the grade you finally get in this course?	6	12	4	1	0	6	6	1	0	1
4. Did you find that working in a group enhanced your comprehension of the project itself?	1	11	8	2	1	3	3	6	2	0
5. Do you feel that doing the project in groups was helpful to your turning in a good work?	4	5	9	4	1	3	4	4	3	0
6. Do you agree that having a project grade that is based on a group grade is a good way to determine your score for such assignment?	2	9	6	5	1	2	6	2	2	2
7. Considering that the project covered only a portion of the entire course, would you agree that you were allowed enough time to do the project?	1	10	9	2	1	1	5	4	4	0
8. Do you feel that the introduction of a project prevented some topics from being covered or from being covered adequately in the course?	0	6	9	8	0	1	0	1	11	0
9. Would you recommend the truss bridge project and/or other design projects be included in this course the next time it is taught?	6	5	5	6	1	6	4	2	1	1

Key for Questions 1 – 8
5 = a whole lot
4 = a fair degree
3 = a slight degree
2 = not at all (zero)
1 = negative (effect)
Key for Question 9
5 = recommend truss bridge and additional projects
4 = recommend truss bridge only
3 = recommend other projects
2 = no opinion
1 = no projects

plinary teams are avoided since the truss bridge problem is built around such concepts as deformation or elongation (as opposed to stress or strength), lightness, and speed of construction or assembly, that are understood in all the represented disciplines. In addition, the entire project group also writes one report, makes one presentation, and receives one score. This enhances the team concept and underscores the significance of being able to work in a team.

RESULTS AND DISCUSSION

The results have been generally positive. Although the bridge project has been implemented in only three classes over two semesters so that the sample size is limited, and there are other factors simultaneously at play such as changes in course content, context, and assessment, some improvement in the performance of the students is apparent. Using the fraction of students in the class (all sections taught by the author) scoring B and higher, as a measure of class performance, we find 24.1% for the control semester (Spring 1997) for which there was no project and 39.3% and 41.9%, respectively, for the two subsequent semesters Fall 1997 and Spring 1998. Perhaps because the project is interesting and fun for the students, they are motivated to persevere through difficult analytical content and are able to do better.

Students' enthusiasm for course material and other objectives are addressed by the results of a survey (Table 2) conducted at the end of each of the semesters with projects. The table gives the actual number of students responding to the survey questions and not the number or percentage of students in the class. The students apparently had a clear expectation that the project would affect their grades positively. Some of the students consider the project to have increased somewhat their interest in the course and understanding of the course material, and most of them recommend the continuation of the project and even its expansion to additional projects.

Impact on content and context

Although, with some effort, the introduction of the bridge project has not considerably impacted the course content, it has affected the approach to the content delivery. While in the past the introduction of structural analysis—especially analysis of trusses (method of joints and method of sections), would have been followed by several solved examples, with the project, the students could be left to develop some of this proficiency on their own. Projects obviously demand a different way of relating to students and hence of teaching them. With the students operating in groups an additional source of information is introduced. For instance, a student who normally is reluctant to meet with the instructor for additional explanation or information may now readily consult with group members even if it takes another group member consulting the instructor to provide the explanation.

The bridge project requires considerable resources to administer and assess. These include software/maintenance and presentation resources/facilities and instructor's time, not only to deal with issues and questions from the project and related class material but to evaluate the project reports and presentations (it is necessary to completely and independently analyze each submitted design in order to generate a fair and accurate score). No solutions have been recycled in the short history of the projects.

CONCLUSIONS

A multi-feature, short-term, truss bridge design project introduced in a combined statics and dynamics course, taken by engineering students of multidisciplinary backgrounds, has helped to stimulate student enthusiasm for the course material and resulted in improvement in student performance and some learning. Using the existing scheme of SSBC the project can be used to provide students at the sophomore level with a design experience that includes such valuable real-world design elements as analysis and iteration, open-ended, optimization, decision-making, application of conceptual and analytical computer tools, written and oral communication, team work, and even potential fabrication and testing. The project features and assessment method also allowed it to be introduced with minor changes to the existing syllabus and to be sustained with minimal effort.

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