Int. J. Engng Ed. Vol. 17, Nos. 4 and 5, pp. 446–454, 2001
Printed in Great Britain.
0949-149X/91 $3.00+0.00

Structural Design Education for the 21st Century*

TOMASZ ARCISZEWSKI
Civil, Environmental and Infrastructure Engineering Department, George Mason University, Fairfax VA 22030, USA. E-mail: tarcisze@gmu.edu

SIVAND LAKMAZAHERI
Civil Engineering Department, Catholic University of America, Washington DC 20064, USA

The paper discusses the future of the structural design education. It provides a brief description of the present situation and of factors shaping it, including information technology. Next, a vision of a future structural engineer is presented and his/her major desired abilities are identified. Structural design education is divided into teaching conceptual and detailed design. In the first area, design and inventive engineering are briefly discussed, including the initial teaching experience. In the area of teaching detailed design, three network-oriented computer tools, Dr. Structure, OleSteel, and Engineering Mechanics Digital Library, are overviewed. The first one was developed at George Mason University, while the remaining two at the Catholic University of America. Also, the initial experience with using all three tools is discussed.

INTRODUCTION

THE FUTURE of structural design education is being shaped by the educators, administrators, and by a combination of political, social, and economic factors. The ongoing information technology revolution also has a tremendous impact on the paradigm change, which can be presently observed in structural design education. In addition, the need for change in engineering education has already been realized both within academia and the USA Federal Government, as clearly demonstrated by the new focus on education reform in many engineering schools in this country and by several new education-related research programs [5, 8].

The educators are particularly concerned about the future needs of their students. For example, the authors present in the next section their vision of an engineer for the 21st century, called by them 'The New Engineer'. The concerns of administrators are more complex. In the case of private institutions, their objectives usually reflect those of faculty. However, in the state-supported universities, the administrators are under pressure from the state governments and from the local politicians. In this situation, a tendency may be observed to reduce costs and to improve the quality of education mostly focusing on the students' course evaluations, as is the practice in some states. In general, in the state-supported universities, some administrators want to produce immediate educational results, which will meet the expectations of the politicians. In this context, such administrators are not inclined to support long-term efforts to improve the structural design education and prefer to focus on immediate measures. Both groups, the educators and administrators, operate in an ever-changing environment being shaped by the IT revolution.

CREATIVE CONCEPTUAL DESIGN EDUCATION

In the above-described situation, the changes in the structural design education are driven by the following factors:

- Many state-supported universities are forced to reduce credit hours for BS graduation requirements.
- New courses, providing IT education in an engineering context are continually introduced, for example, courses on geographic information systems, on databases, etc.
- New fundamental engineering courses addressing future needs are being added, for example, courses on computational mechanics, on advanced finite elements methods, on decision science, on mathematical optimization, etc.
- The IT revolution gradually provides the technical means for changing teaching and learning models through the utilization of various IT-based methods and tools.
- The progress in engineering pedagogy results in improved understanding of the specific nature of engineering education and leads to new teaching and learning models reflecting this progress.

The first two factors are the reason why the number of structural engineering courses is being gradually reduced. However, such courses are an important part of civil engineering education.

* Accepted 3 April 2001.

Their mission is not only to teach structural analysis and design concepts, various analytical and design methods, but also to instill in students critical thinking and reasoning abilities. Most importantly, their mission is to teach students how to apply their acquired knowledge in solving real-life problems. In addition, today and particularly in the future, structural engineers will have to be much more creative, i.e. be able to develop inventive designs utilizing unknown yet feasible and patentable design concepts. The complexity and scale of structural problems are ever growing. Very often, they simply cannot be solved using known design concepts and inventive designs are sought. Also, the competition for the market share among the A/E/C companies means that the novelty of structural designs is increasingly important and an ability to produce such designs becomes a highly desirable skill, expected from our graduates. For all these reasons, the quality, nature, and effectiveness of the remaining structural courses are absolutely critical for the success of our students in their professional careers.

In the context of the imposed system of constraints, the present situation in structural engineering education is somehow disappointing as far as the quality of its outcome is concerned. Obviously, no major improvements should be expected under the traditional instructional paradigm. It is a classical situation, when a problem can not be solved without a paradigm change in order to eliminate the existing contradiction. Fortunately, during the last several years the progress in pedagogy has led to the development of new teaching and learning methods which are IT-oriented, and can be used with IT-based tools. Therefore, the existing paradigm of structural engineering education can be changed, moving from the traditional toward self-directed and computer-mediated learning, as proposed in the paper.

Teaching and learning structural design can be roughly divided into teaching and learning conceptual and detailed design. The conceptual design stage is understood here as a part of the design process whose product is a design concept or concepts, i.e. an abstract description of a future structural system in terms of nominal attributes. The detailed design stage is a part of the design process whose product is the final detailed design, i.e. a quantitative description of a future structural system in terms of numerical attributes. At present, very little is taught about the conceptual design and the majority of teaching effort is concentrated on teaching the detailed design methods and the descriptive knowledge about structural systems to be used in the detailed design process. This is not an optimal situation, because the novelty of structural designs is decided during the conceptual design stage and approximately 80% of costs are irreversibly committed during this stage.

The objective of the paper is to provide a brief overview of a vision of structural engineering education. Next, teaching conceptual and detailed structural design is discussed in the two subsequent sections. Also, the initial conclusions are presented.

CONCEPTUAL DESIGN AND THE NEW ENGINEER

We are all living and working in a rapidly changing environment and more changes are expected to come. Therefore, to survive and to be a leader of constant change, a new kind of a structural designer has to emerge, who will be able to meet the challenges of the future. He/she will have the following major abilities:

- To understand engineering design in its complexity and in the context of the ever-changing societies and technology.
- To understand engineering knowledge on both the systems level and on the level of details necessary for engineering purposes.
- To use various analytical and design methods and tools.
- To find inventive solutions to complex problems.
- To continuously learn and use new knowledge, including new inventive design methods.
- To utilize Information Technology in every-day practice for designing and learning.

All these six abilities have to be developed and nurtured as the result of a complex effort, which should include several major components. We have concluded that most promising efforts are building an active learning environment (ALE), integration of various structural design-related courses, use of situated learning, utilization of information technology (IT), and improved effectiveness of teaching and learning. ALE can be described as an Internet-based knowledge intensive environment for teaching and learning structural engineering in the context of the real-world structural systems. The ongoing process of integration of various engineering domains, methods, and tools, is the direct result of the information technology revolution. In the case of ALE, the integration of teaching structural analysis, design and optimization leads to the high degree of integration of various courses in the area of structural engineering. Also, the integration of teaching/learning of conceptual and detailed design should be considered with the focus on inventive design in the context of design and inventive engineering. The theory of situated learning provides the pedagogical foundation of ALE. Various IT technologies, including network computing, new Internet programming languages, distant learning, etc. are expected to contribute to the technological foundation of ALE. It is assumed that ever-shrinking human recourses will be used in an optimal way for the direct interactions with students while grading and monitoring students progress will be automated [3, 4, 6].

TEACHING CONCEPTUAL DESIGN

Research on design in engineering has a long history. For example, in the late 1940s, H. Altschuller in the Soviet Union initiated research on patents and on inventive problem solving in engineering design. In the 1950s, R. Wasiutynski in Poland began working on the design principles in the context of bridge design. In the 1960s S. Gregory in England initiated research on design methods, first within the framework of chemical engineering design, and later on an interdisciplinary engineering level. Also, in the 1960s, J. Dietrich in Poland, worked on the conceptual design principles in the context of mechanical engineering. In the 1970s, design methods became the subject of interest of a number of architects and engineers in England (N. Cross), Scotland (T. Mavier), Germany (W. Beitz, G. Pahl, R. Koln, J. Muller), Switzerland (V. Hubka, H. Holliger), Poland (W. Gasparski, A. Strzalecki) and in the other European countries. This overview is obviously incomplete, but it provides some measure of appreciation of the European effort in the area of design research.

Design Engineering was proposed as a new engineering interdisciplinary science in the late 1980s in the USA. Its subject is the engineering design processes and methods, and the building of design support tools. The development of *Design Engineering* has been strongly stimulated by the National Science Foundation and its Engineering Design Program and by the Advanced Research Programs Administration (ARPA), especially by the creation of the Design Engineering Program within ARPA.

Inventive Engineering is an emerging subdomain of *Design Engineering*. It is exclusively focused on the specific cases of design when inventive design concepts are sought, i.e. concepts which are unknown, yet feasible and patentable. Its name has been introduced only recently, but there is a growing interest in this new area.

When *Design and Inventive Engineering* is considered, three major components can be distinguished: General Methodology, Methodics, and Tool Development. General Methodology is focused on the methodological issues in design: design theories, general models of the design process, integration of various design methods and tools, design knowledge acquisition, evaluation of design concepts and of final designs, novelty and its formal measures, etc. Methodics is focused on the conceptual design methods, inventive design methods, detailed design methods, evaluation methods, etc. The Tool Development area is concentrated on building and testing various computer design tools to be used in different stages of the design process.

At George Mason University, an undergraduate course on the subject has recently been developed, and it is called Introduction to Design and Inventive Engineering. (The course has been developed with the financial support from the National Collegiate Inventors and Innovators Alliance, and that support is gratefully acknowledged.) The course was offered for the first time in the Spring Semester of the year 2000. (An advanced graduate course, Design and Inventive Engineering, is offered on a regular basis.) The course provides a general understanding of design processes in the context of the major design theories and teaches students various inventive design methods, including brainstorming, morphological analysis, synectics, TRIZ, etc. Also, students learn how to use computer tools utilizing the introduced inventive design methods in the context of engineering practice. The inventive problems to be solved are provided by a local engineering company. Its representative actively participates in the course, providing expertise in solving problems and in the evaluation of results in the context of their potential commercialization. In the year 2000, the students worked on the problem of pollution of a reservoir lake in an urban area. The lake receives the polluted storm water runoff and there is concern that groundwater may also contribute to the lake's pollution. The students were expected to find inventive solutions to mitigate the problems associated with the reservoir lake water pollution. In the next year, the students will work on the inventive designs of short-span low-cost pedestrian bridges. It is expected that the course will help students to understand better their engineering knowledge and to integrate knowledge from various areas of structural engineering in the context of design.

TEACHING DETAILED STRUCTURAL DESIGN

The efforts in designing an innovative structural design education began at the Catholic University of America and at George Mason University about two years ago. At this time, the authors realized that the existing model was largely ineffective and many students were unable to realize their full potential, not to mention to discover the joy of designing structures, finding creative solutions, etc. In particular, students were sometimes frustrated by the excessive fragmentation of structural engineering into the structural analysis courses (too abstract) and into the structural design courses (too pragmatic). Even worse, many students were unable to synthesize knowledge coming from various structural courses in order to develop a consistent understanding of the entire domain and to use this knowledge in practice.

The authors have already begun work on building computer tools for teaching/learning structural

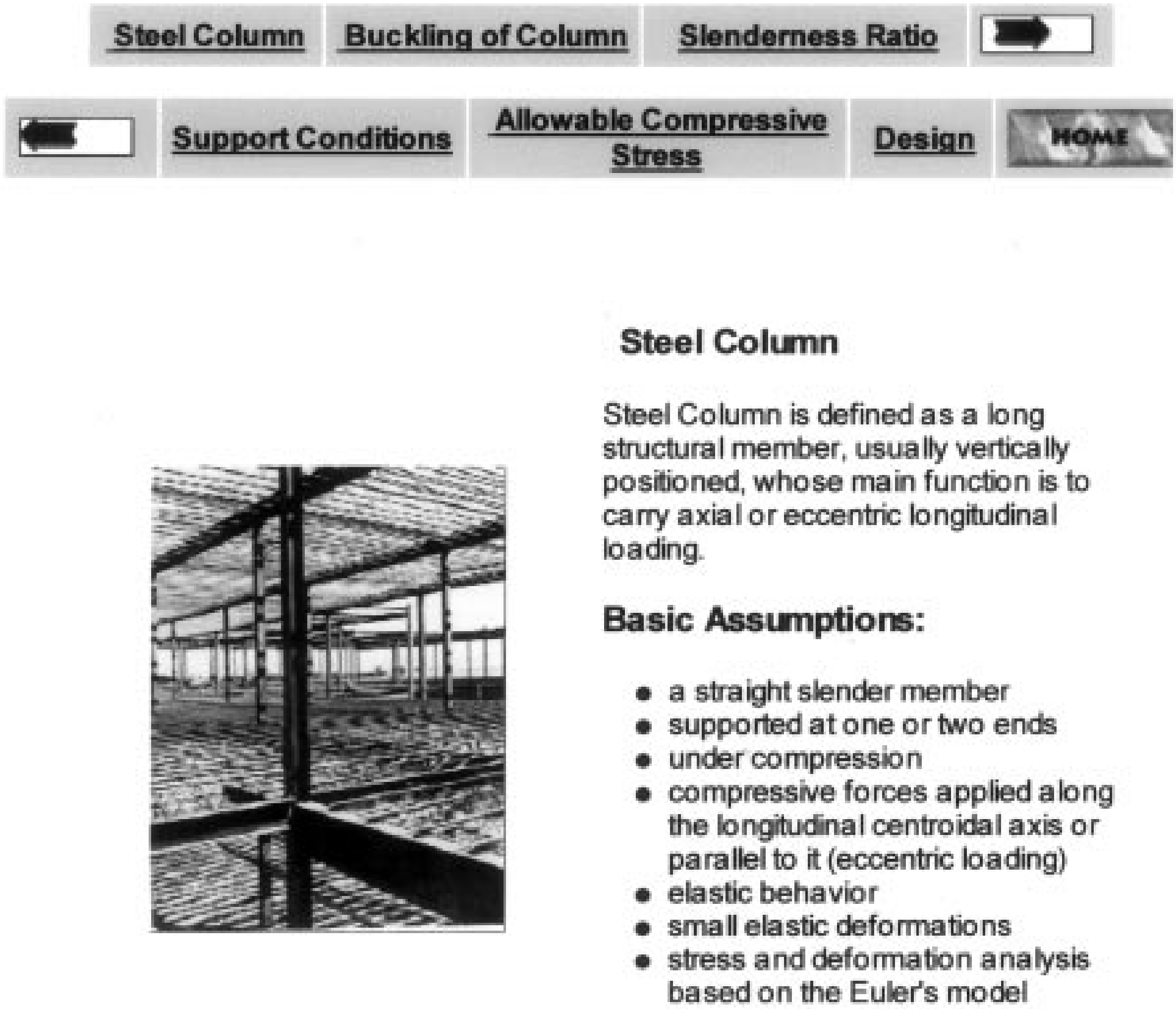

Fig. 1. *Dr. Structure*, teaching concept of a steel column.

engineering, and these tools are briefly described below.

Dr. Structure

Dr. Structure is an experimental system for teaching detailed steel structural design. It is intended for teaching only the most fundamental basics, but in an involving way, which is particularly attractive for students who do not specialize in structures, as it is the case at George Mason University's Urban Systems Engineering Program. The system was used for the first time in the spring semester of 1997. Its initial version can be used for teaching steel structural design of simple columns and beams [1, 2].

Dr. Structure was originally developed for a commercial purpose by Novel CyberSpace Tools, but it is has never been actually commercialized. Instead, it has been provided free of charge to George Mason University for its educational use. Tomasz Arciszewski has designed the system and provided structural knowledge, Witold Szczepanik has developed Java applets, and Eva Arciszewski conducted the initial HTML programming and used PageMill to prepare the recent version.

Dr. Structure contains structural design knowledge in various forms, including definitions, descriptions, pictures, procedures, and Java applets. Basic concepts (terminology) are provided as a system of interrelated definitions, which are illustrated, wherever possible, by pictures (Fig. 1). Another example, not shown here, is a picture of a member under compression with the local buckling of its web which illustrates the definition of local buckling, usually difficult to comprehend by undergraduate students. Descriptions provide additional information about the individual structural components and pictures also accompany them. Formal procedures, for example for the design of a steel column under axial loading, are intended to be a methodological foundation for structural design, which can be actually conducted using Java applets. Their development was particularly difficult and is still in progress. At this time, only an applet for the design of steel columns

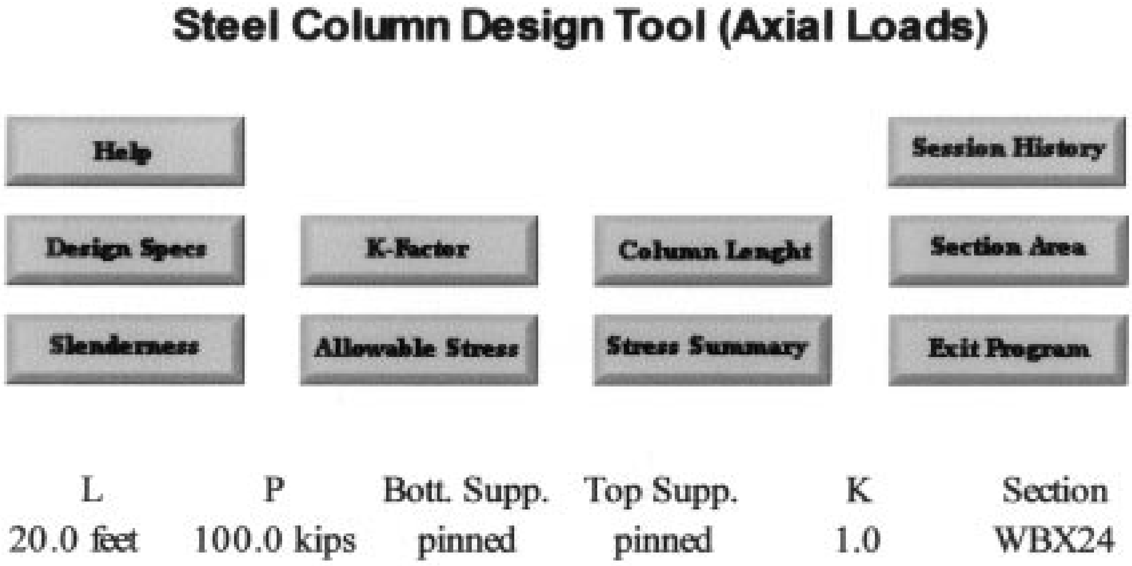

Fig. 2. *Dr. Structure*, steel column design tool.

under axial loading is available and one of its interfaces is shown in Fig. 2.

The developed applet is not a simple program for the automated design of steel columns. Its double purpose is to serve as a design and learning tool. In the first case, it supports the design process and provides all required information (for example, cross sections). As a learning tool, it helps students to understand the design process in its complexity as a multistage sequential process with a number of loops. Usually, building such understanding can not be accomplished by giving students a single home assignment. Under normal circumstances, it can be acquired only as a result of many years of structural design practice and through solving hundreds of various design problems. However, it is possible to ask students to use this applet many times in a single home assignment, for example to find a graphical relationship between the allowable axial loading and the depth of the column under the assumed support conditions, column length, steel grade, etc. In this way, students are forced to repeat the entire design process many times, gaining its intuitive understanding in a relatively short time period. Unfortunately, incorporating the use of applets in the structural education is difficult since the instructor must abolish the traditional paradigm of teaching. He/she must think in terms of applets and their capabilities while preparing home assignments to take the full advantage of this new technology, and that is sometimes difficult.

The initial experience with using *Dr. Structure* is positive. The system is usually first demonstrated by the instructor in the class, and next used by the students working in various computer laboratories at George Mason University. Building the system of concepts led to the realization that it is impossible to separate design from analysis and these two areas should be integrated for teaching purposes. Also, a surprising discovery was that no structural design textbook provides definitions, which would be entirely correct, or complete, from the point of view of structural analysis. In practical terms that discovery meant that all definitions had to be carefully prepared, and that was not an easy or trivial task.

OleSteel

Online Learning Environment for Steel Design *(OleSteel)* is an experimental environment, developed at the Catholic University of America, for promoting self-directed learning and project-based collaboration in an introductory steel design course. *OleSteel* is a web-based environment implemented using WebCT (3). It is not meant to replace classroom instruction, but has been designed as a supplemental tool for engaging students in learning activities outside classroom. Currently, *OleSteel* supports learning by examples, educative assessment and evaluation, and computer-mediated communication and collaboration.

Illustrative examples often times solidify one's understanding of basic concepts, procedures, and methods covered in class. Such examples become particularly invaluable learning tools, particularly when they provide the learner with the opportunity to ask questions and obtain answers. *OleSteel* contains sets of illustrative examples covering steel design topics presented in class. Each example is linked to a database of questions and answers, which evolves in content as students pose more and more questions. For each expression (or subexpression) in the solution, a link to the database can be established, thereby, enabling students to question each and every expression of the solution. When the answer to a question is not found in the database, the student may submit the question to the instructor electronically. The system notifies the instructor when a question is submitted and catalogs the answer in the database when the instructor responds to the question. Using *OleSteel* the learner can benefit from and contribute to the wealth of knowledge that keeps accumulating in the 'question and answer' database.

Learning can best be accomplished through the cycle of knowledge construction, performance, feedback, and knowledge reconstruction [9]. In this model, assessment is viewed as a tool for improving students' performance. In *OleSteel*, the performance of students is evaluated by asking them to take randomly generated online quizzes. Quizzes can be graded automatically and appropriate feedback, built into each question by the instructor, can be presented to students for improving their performance. Students may be given several opportunities to take a quiz in order to improve their performance. To make this possible, *OleSteel* supports the preparation of quizzes using parametric and randomly generated questions and thus ensuring the uniqueness of each quiz.

The ability to identify and use relevant design specifications from the design manual is an important learning outcome in an introductory steel design course. *OleSteel* embodies an electronic version of the Load and Resistance Factor Design (LRFD) manual. To assess the ability of students in identifying and using relevant LRFD specifications in a given problem, *OleSteel* provides a tool for composing solutions to design problems using the online LRFD manual. The tool enables the learner to search the manual, to select relevant equations, and to use the selected equations to automatically compile the solution to the design problem. The compiled solution can be graded automatically.

OleSteel supports team projects by providing a forum for communication, discussion, and sharing of technical information. For each team, a private communication forum can be established. Through this forum, students can upload and download files, send messages, and read and respond to the messages posted by other team members. *OleSteel* also supports virtual meeting where team members can discuss activities online in a chat room. Finally, the system keeps track of all communications taking place through the forum, enabling the instructor to continuously monitor the group's progress towards project completion.

Engineering mechanics digital library

Structural analysis is an integral part of the overall structural design process. An active learning environment for structural design, therefore, must include learning tools for structural analysis. Such a tool for engineering mechanics (statics), a foundational area of study in structural engineering curricula, has been developed at the Catholic University of America. The tool, called

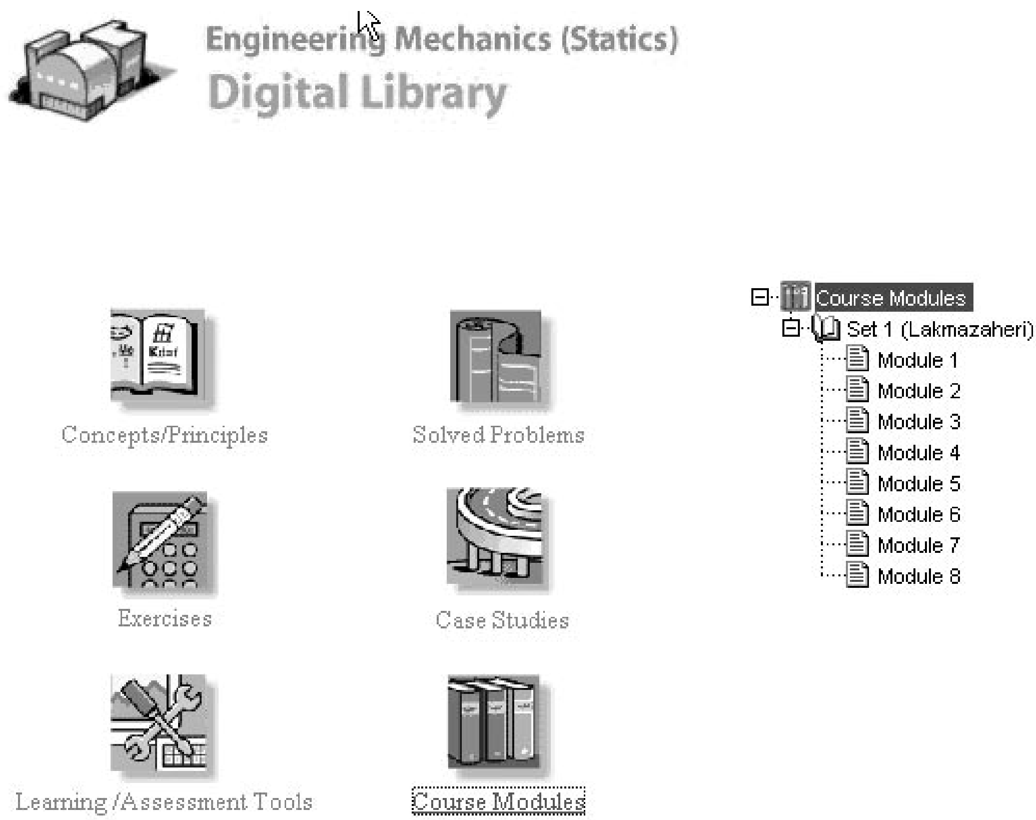

Fig. 3. *Engineering Mechanics Digital Library* of instructional material.

Engineering Mechanics Digital Library is briefly described herein.

At present, the library consists of four components including concept explanations, solved examples, exercises, and course modules, as shown in Fig. 3. Two additional components, learning tools and case studies, are also under development.

The concept explanation component of the library contains multimedia presentation of statics concepts and principles. Text, graphics, audio, and video have been used to provide intuitive explanation of concepts. Figure 4 shows the outline and a sample page of one of the concepts (force vector) covered in the library. The library contains solved problems exemplifying the applications of statics concepts and principles. The solution to each problem is presented in a manner mimicking the instructor's explanation of the solution. When appropriate, audio and video clips have been used to explain the steps involved in solving each problem. Figure 5 shows a problem definition and the outline of its solution along with a detailed explanation of a video clip.

Furthermore, students can submit questions about the presented solution electronically. The answer to each question is linked to the source page, thereby, enabling students to view questions posed by other students and answers given by the instructor(s).

The library also contains exercises. These are challenging problems that the instructor can control access to their solutions. Access to solutions of one or more problems can be disabled or enabled by the instructor at any time. This feature of the library provides instructors with the flexibility to design online self assessment and timely feedback mechanisms for students. The library is designed so as the instructor can assemble course content or course modules from the concept explanations, solved examples, and exercises. The library was recently used to assemble ten course modules for an introductory statics course at the Catholic University of America. The library made it possible for the course instructor to (the second author) to de-emphasize instructor-centered activities and to emphasize student-centered activities during class periods. A majority

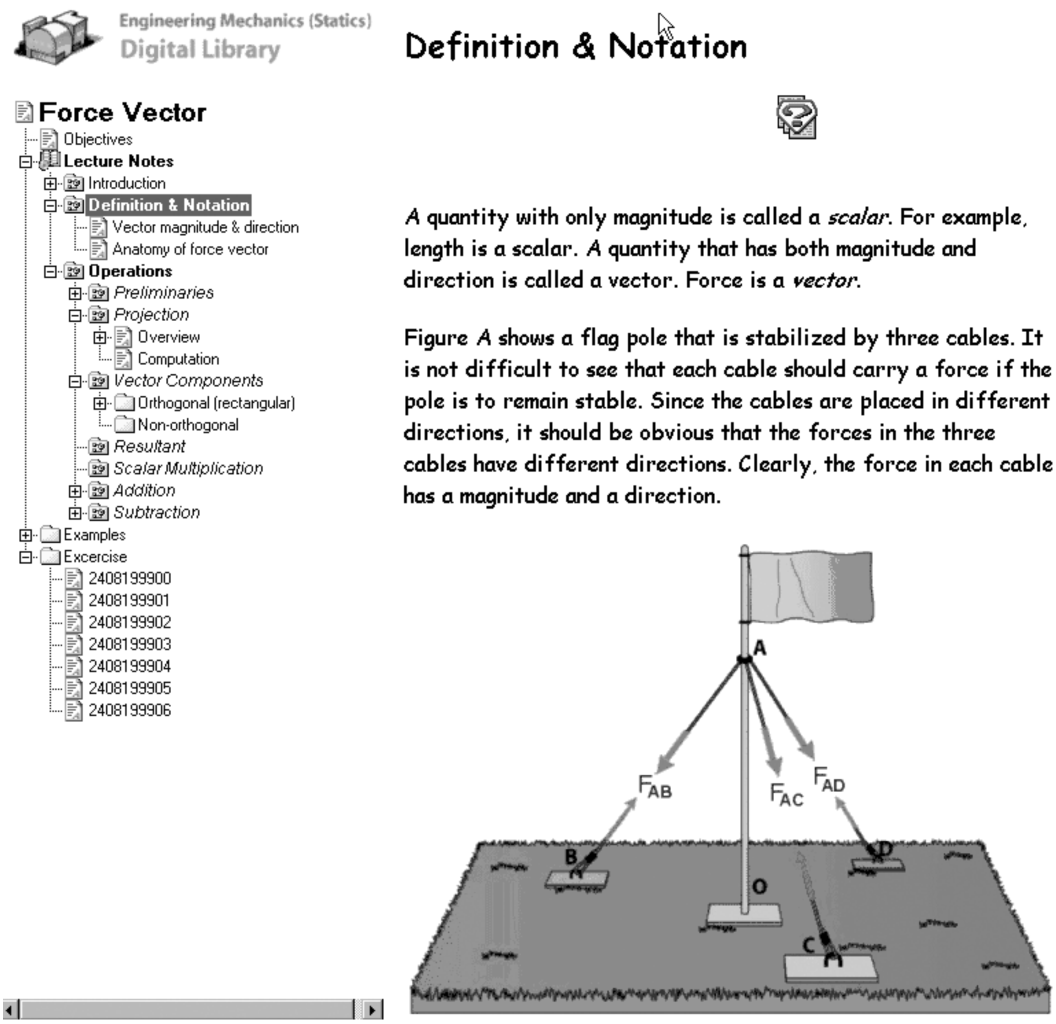

Fig. 4. A sample explanation page from the library.

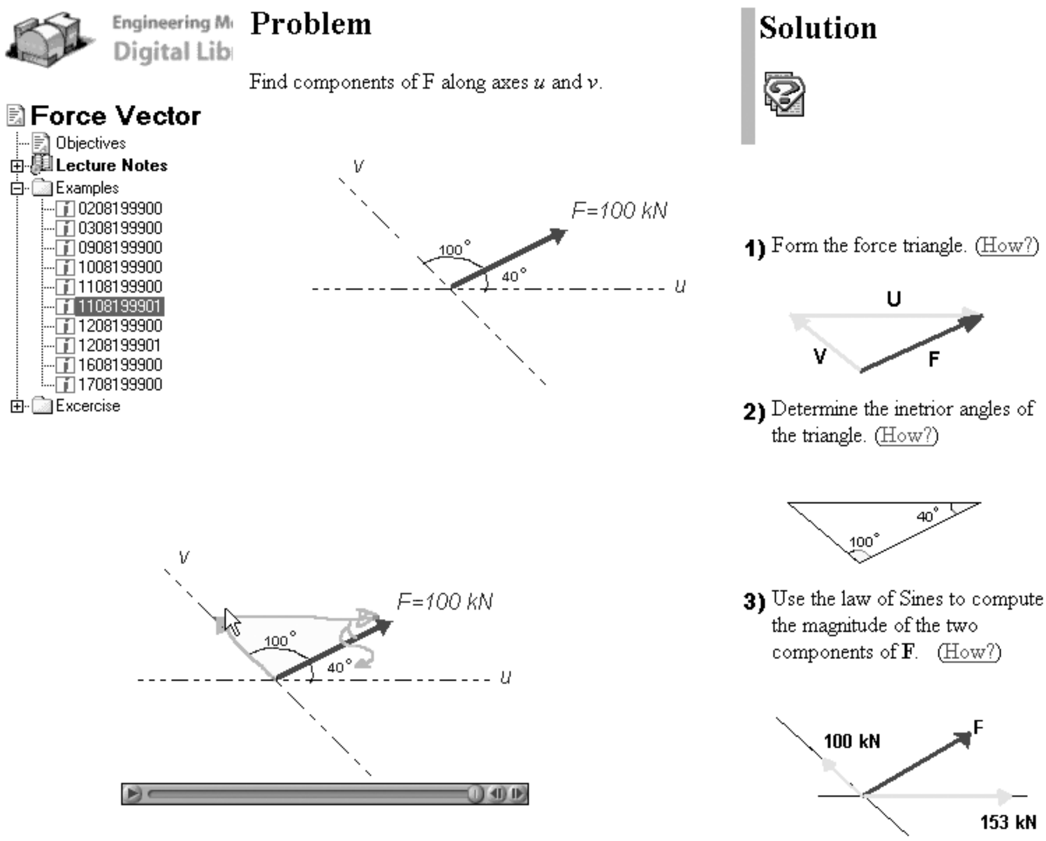

Fig. 5. A sample problem page from the library.

(86%) of the students in the course found the library a useful learning tool.

CONCLUSIONS

The evolution of engineering education is driven by the technological progress in engineering, by the progress in pedagogy, and by the ever-changing educational environment. Today, a significant paradigm change in structural engineering education is expected. The authors believe that the new structural engineering education paradigm will be network computing-based, and it will utilize the available technology for building multimedia systems.

Hopefully, the paradigm change will allow for preserving the quality of structural education while reducing the number of structural courses, although this is still an open issue. In any case, engineering faculty will remain active participants in the structural engineering education. Their role, however, will expand beyond classrom instruction. They will be expected to focus on the outcome of the educational process by creating curricula that produce desired results. Also, their motivation will become a critical factor in the implementation of any education reform.

The initial experience with using Internet-based multimedia systems in teaching structural design at George Mason University and at the Catholic University of America is positive. In the case of George Mason University, the students have accepted *Dr. Structure* as a natural extension of the other teaching means such as transparencies or the analytical computer programs being used in the class. They were pleased with an additional opportunity to learn structures on their own and at their own pace. In the case of the Catholic University of America, the introduction of *Engineering Mechanics Digital Library* of instructional materials was met with a lot of student enthusiasm and the initial experience is definitely positive.

However, successful individual uses of multimedia systems are only the first step in the right direction. The use of multimedia systems must be incorporated in an integrated teaching model, which includes lectures and recitation sessions and other meaningful learning activities supported by the utilization of multimedia systems. Therefore, a significant effort has to be made to develop an understanding of the need to reform structural engineering education, both by the faculty and administration. Next, a systematic effort has to be initiated to develop various multimedia systems, preferably to be shared by many universities to minimize costs. This is a challenge, but a challenge that has to be met.

REFERENCES

1. T. Arciszewski, Internet-based teaching/learning tools in structural engineering education, *Proc. NASA Workshop on Advanced Technology for Engineering Education and Training*, A. K. Noor, (Editor), Hampton, VA, March, 1998.
2. T. Arciszewski, Inventive design education, *Proc. University of Virginia and NASA Workshop, Advanced Technologies in Engineering Education*, Hampton, VA, November, 1999.
3. N. C. Baker and C. Srisethanil, ITS-Engineering: providing adaptive teaching in an engineering tutor, *Proc. Frontiers in Education: Engineering Education for the 21st Century*, ASEE, 1995.
4. M. W. Goldberg, S. Salari, and P. Swoboda, World Wide Web Course Tool: An Environment for Building WWW-Based Courses, *Computer Networks and ISDN Systems*, **28**, 1996.
5. M. S. V. Kumar, Engineering education environments for tomorrow: quality, virtuality and reality, *Proc. NASA Workshop on Advanced Technology for Engineering Education and Training*, A. K. Noor, (Ed.), Hampton, VA, March 1998.
6. J. M. Mendel, *Multimedia Instruction for Engineering Backbraker—Concepts*, Integrated Media Systems Center Report, University of Southern California, 1998.
7. D. L. Millard, Increasing interactivity in engineering education, *Proc. NASA Workshop on Advanced Technology for Engineering Education and Training*, A. K. Noor, (Ed.), Hampton, VA, March 1998.
8. A. K. Noor, Future university environment and scenario for engineering education, *Proc. NASA Workshop Advanced Technology for Engineering Education and Training*, A. K. Noor, (Ed.), Hampton, VA, March 1998.
9. G. Wiggins, *Educative Assessment: Designing Assessments to Inform and Improve Student Performance*, Jossey-Bass Publishers, 1998.

Tomasz Arciszewski is Associate Professor in the Civil, Environmental and Infrastructure Engineering Department, at the Information Technology & Engineering School of George Mason University. He earned his MS (Summa Cum Laude) and Ph.D. degrees from the Warsaw University of Technology in 1970 and 1975, respectively. His formal background is in the areas of structural engineering and mechanics. Dr Arciszewski taught at Wayne State University in Detroit, Michigan, at the Warsaw University of Technology, and at the University of Nigeria in Nsukka. He also gained practical design experience in Poland and Switzerland. Dr Arciszewski has authored, or co-authored, close to hundred publications in the areas of design methodology, information technology, and structural engineering, including several book chapters. He is one of the two editors of the recently published monograph *Knowledge Acquisition in Civil Engineering*, and the member of the editorial boards of the journals *Automation in Construction* and *Technological Forecasting and Social Change.* At present, he is the guest editor of the special issue of the last journal, entitled 'Innovation: The Key to Progress in Technology and Society'. During the last several years, he served as one of the Associate Editors and Technical Editor of the ASCE Journal of Computing in Civil Engineering. Until recently, he was Chair of the Intelligent Computing Committee of the American Society of Civil Engineers (ASCE).

Sivand Lakmazaheri is presently an associate professor of civil engineering at the Catholic University of America. He joined CUA in 1994 after serving as an assistant professor at Auburn University for four years. He earned his Ph.D. in civil engineering from the North Carolina State University in 1990. Dr Lakmazaheri is interested in advancing engineering education by focusing on pedagogical, institutional, cultural, and technological issues pertaining to university-based education. He is currently developing an online library of instructional materials for structural engineering education, and evaluating the use of the library for improving educational outcomes in traditional civil engineering curricula.