Integrating Web-based Visualization with Structural System Understanding to Improve the Technical Education of Architects

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***Abstract*—The relationship between structure and form has become an important topic of educational research in architecture. The new trend in architecture is to create elegant and efficient designs that are adequately responsive to environmental conditions such as various applied loads. This has created a challenge in architectural education to train architects who are aware of the relationships between structure and form. This paper provides the results of a collaborative effort among the schools of Architecture and Design, Computer Science, and Education at Virginia Tech to develop a web-based learning tool called "Structure and Form Analysis System" (SAFAS). SAFAS consists of a "Knowledgebase" and a "Structure and Form Experimentation" module, both of which were used in an undergraduate structures course as supplemental learning materials. Evaluation of the results of several assignments given to students demonstrated that the developed educational materials were effective in helping students (a) gain a better understanding of spatial structures and (b) comprehend the relationships between structure and form. From this study, it is concluded that the SAFAS and the associated educational tools could be used in undergraduate architecture and structures courses to foster a better understanding of various structural concepts.**

***Index Terms*—Structure and Form, Spatial Structures, Experiential Learning, Structural Behavior, Loads.**

I. Introduction

In today's increasingly complex environment, architecture students face the challenge of learning and understanding not only the important aspects of design in terms of form and aesthetics, but also the technical intricacies of building structures and assemblies. The building structure is one of the most important components in the overall design process that has to be considered by the architect. In practice, due to the professional liabilities and design complexities involved, the structural design is typically carried out by engineers. Regardless, architects have an important role in determining the most appropriate system to comply with the architectural design.

The National Architectural Accreditation Board (NAAB), which establishes criteria for architectural programs, mandates technology as one of the four major areas of competence the student must possess to graduate with a professional degree in architecture. NAAB subdivides technology into four areas: structural systems; environmental controls and communications systems; construction materials and assemblies; and life safety and accessibility. It states that "The graduating student should be able to apply their knowledge of each technical system in the context of an architectural design project" [1].

The teaching methods and curriculum for these technical competencies at architectural schools are mostly based on the theories and conceptual systems developed for engineering students, who do not share the same needs as architecture students. The emphasis in undergraduate engineering education is on the subcomponents, focusing on the detailed behavior of structural elements. In contrast, architecture students need to gain a better understanding of the overall role and impact of the structure in design; learning about the complex engineering details in a structural design is less important to them.

Architecture and engineering practitioners rely heavily on the use of computer tools in their work. Both professions routinely employ Computer Aided Drafting (CAD) programs for the creation of contract documents (such as [2] and [3]) and they are increasingly working with manufacturers to help automate fabrication processes. Engineers have been using Finite Elements programs for structural analysis and design since the 1970s and they routinely use sophisticated graphical tools to process geometric and analytical data. In most architecture schools, however, the use of computers has been limited to computer-aided drafting that emphasizes design and form, not structural analysis.

There have been a few experiments with a wider application of computer visualization and simulation as architecture teaching tools. A six-year experiment was conducted using commercial computer software to teach structures to architecture students at the University of California, Berkeley. This study showed that the use of computer software helped students focus their attention on the overall behavior of structures as systems rather than the analysis and design of a single beam or column [4]. In another study [5], a CD-ROM was produced that

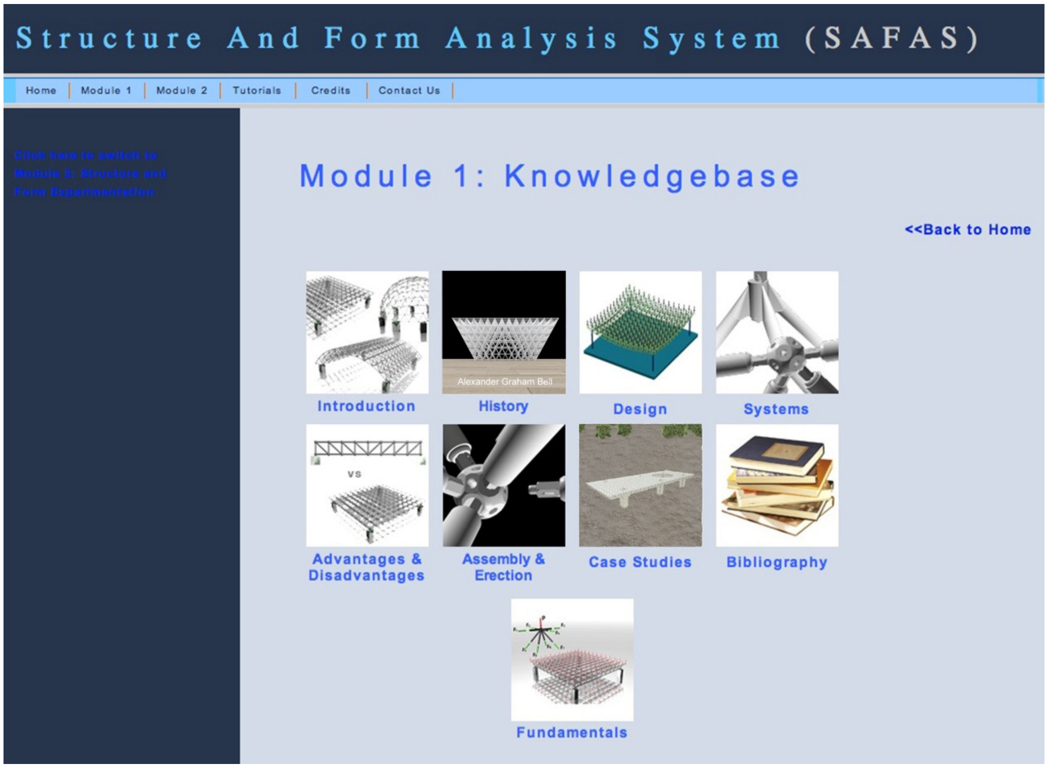


Figure 1. Links to the various sections of SAFAS module 1

contained information on various structural systems of well-known buildings along with the basics of the structural design.

The efforts mentioned above have been successful in providing a better understanding of structural behavior among architecture students. However, the purpose of these project was not to try to help students with better understandings of both structure and form in an integrated way. We believe that this is an important area of study and that new 3D digital design tools can be used to assist students to become better and more innovative practicing architects. We seek to apply principles of Human-Computer Interaction (HCI) and best pedagogical practices to build online resources and tools that bridge this design gap between structure and form in architectural education.

This paper provides details on the development and initial evaluation of an educational tool called Structure and Form Analysis System (SAFAS) for architectural students to study the relationship between structure and form using spatial structures. It consists of two modules: a Knowledgebase website, which provides explanatory information and multimedia about different aspects of spatial structures, and the Structure and Form Experimentation system (a computer software to study the relationship between the form and structure using spatial structures).

II. SAFAS Educational Tools

Before discussing details of the developed educational materials and their impact, we will describe our web-based approach and explain why spatial structures have been used as the main structural type for SAFAS development. Recent years have seen a remarkable exponential proliferation of information and services accessible over the World Wide Web. Because our goal was to publish our educational tools for the broadest possible impact, we chose to use Web-based multimedia with Dublin-Core metadata as a means to publish explanatory resources in an accessible and searchable way [6, 7]. Given the wide variety of client platforms at our university alone, we decided to build our system on Web3D standards and open-source libraries using Java [8, 9] .

The design and implementation of e-Learning systems presents some unique challenges to the typical usability engineering (UE) process of interface design. The *Pedagogical Paradox* of UE is that the end-users of the system (students) cannot describe the requirements of the system. For this asymmetric situation, we have engaged the latest evidence and principles of cognition to help map learning requirements to features of information design for interactive learning systems [10].

In this paper "spatial structures" refer to structural systems made of interconnected linear elements. These structures, which are mostly made of steel, aluminum or wood, are highly redundant and have light weights. They can also provide aesthetically appealing geometries; and due to their large stiffness, can be used as long span systems.

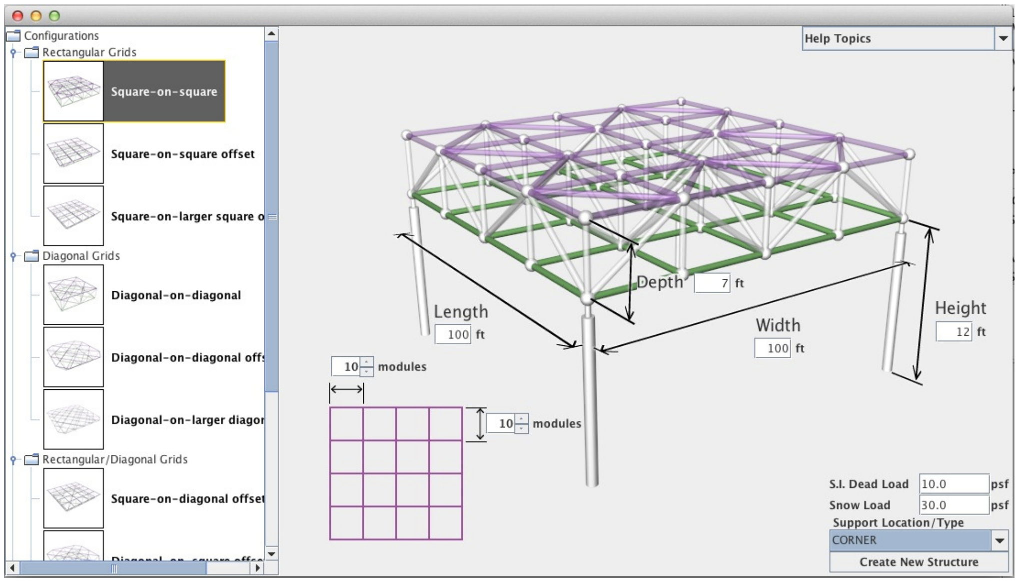


Figure 2. New model definition (SAFAS module 2)

The members of spatial structures used in SAFAS are assumed to be pin-connected and loads applied at the nodes or joints. As a result, the members are only subjected to axial (tensile or compressive) forces. This assumption provides a simple way to model and visualize the behavior of a structural system. We believe that such representations provide a suitable basis to demonstrate the crucial inter-relationships between structure and form. Until now, there has been no open tool that integrates and enables both sides of this design activity.

Different Modules of SAFAS

As mentioned before, SAFAS is made of two modules, available at [11]:

(a) Knowledgebase Module

The Knowledgebase Module provides textual, graphic, and animation information on various aspects of spatial structures. The selection and organization of the concepts and material is targeted for undergraduate architecture students learning about long-span spatial structures. Figure 1 shows the initial page, which includes links to different sections of this module. These are:

Introduction: This page defines the spatial structures and provides brief discussions on space frames and trusses, and single, double, and multilayer grids that have been used in different sections of this module.

History: This section provides a brief history of the development of spatial structures.

Design: This section includes information related to the design of spatial structures. It covers different issues such as: (a) general design of spatial structures, (b) different configurations of spatial structures, (c) components of spatial structures, and (d) spatial structures under loads. In addition, it discusses several topics as related to the design of spatial structures such as proportioning of spatial structures, connection types, effective buckling lengths, support types and placement, stability requirements, deflection limitations, cambering, effects of fire on spatial structures, and progressive collapse.

Systems: Different commercial systems developed for the construction of spatial structures are discussed in this section. These systems are classified as nodular, modular and lattice grid systems, and discuss various proprietary systems such as: Mero System, Triodetic System, Unibat System, Space Deck System, Nodus System, and Unistrut System.

Advantages and Disadvantages: This section includes a list of advantages and disadvantages of spatial structures as compared to other long-span structural systems.

Assembly and Erection: This section discusses the various methods of assembly and erection of spatial structures, including: cantilever method, lift slab method, and subassembly erection method.

Case Studies: This section contains brief descriptions of several built spatial structures. It uses photos and animations to help users better comprehend the assembly and erection processes used for the construction of these structures.

Bibliography: This section includes a list of references used for the development of the materials in this module.

Fundamentals: This section provides brief descriptions of fundamental structural concepts used in the other parts of the module. Even though it is not an integrated part of the module, the descriptions, static images, and animations significantly help students comprehend the materials discussed in various sections of the module.

(b) Structure and Form ExperimentationModule

This module consists of software that one can use to create computer models of spatial structures, subject them to various loading conditions, and observe the effects in terms of member forces and joint deflections. The user

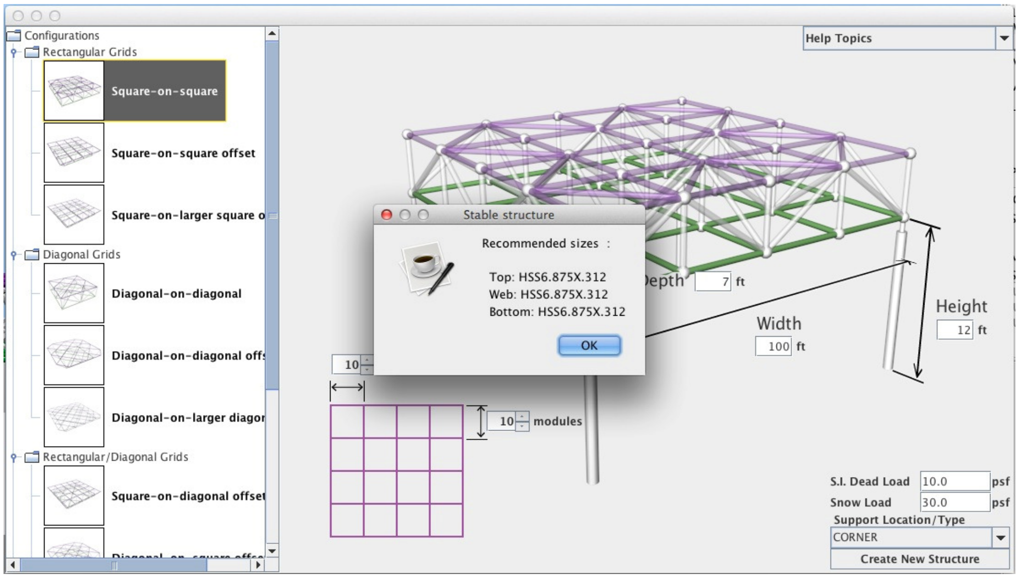


Figure 3. Dialog box showing the suggested approximate member sizes for each layer (SAFAS module 2)

interface is developed so that the various operations will be easy to execute and have a complete set of tools for model manipulations. All the spatial structures used in this module are made of double layer grids. It consists of two modes: the Pre-Analysis Mode (in which the user defines the structure and the applied loads), and the Post-Analysis Mode (in which the user investigates the effects of the loads on the structure).

Pre-Analysis Mode

Spatial Structures Configurations

The users start the model creation with a rectangular flat double-layer grid spatial structure. They can select the structure's base unit pattern from a list of eleven different configurations in four groups based on the pattern of the top and bottom layer grids (see Figure 2):

Group A (Rectangular Grids): Square-on-Square (configuration 1); Square-on-Square Offset (configuration 2); and Square-on-Larger Square Offset (configuration 3).

Group B (Diagonal Grids): Diagonal-on-Diagonal (configuration 4); Diagonal-on-Diagonal Offset (configuration 5); and Diagonal-on-Larger Diagonal Offset (configuration 6).

Group C (Rectangular/Diagonal Grids): Square-on-Diagonal Offset (configuration 7); Diagonal-on-Square Offset (configuration 8), and Diagonal-on-Larger Square Offset (configuration 9).

Group D (Three-Way Grids): Triangle-on-Triangle (configuration 10); and Triangle-on-Triangle Offset (configuration 11). At this stage, the user can define the overall dimensions, the number of base unit repetitions in two dimensions, the layer depth, and the column configuration to create a new model.

Load Definition and Support Type/Location Selection

The users can define the gravity loads (superimposed dead and snow loads) acting on the structure. They can also select different columns support types and locations: straight columns, pyramid columns, and tree columns, which can be placed along the edges or at the corners (connected to the bottom layer nodes); see Figure 2.

The SAFAS computes the applied loads on the structure as nodal forces based on the nodal tributary areas and the load intensity already defined by the user.

Member Sizing

An algorithm based on the modified "slab-analogy method [12]" was developed and implemented in the SAFAS, which provides suggestions for the approximate sizes of the top, bottom, and diagonal (bracing) layers. One member size is used for each layer based on the largest estimated force. Once the user defines the overall dimensions, number of modules, location, and type of supports, a dialog box opens and provides the recommended sizes (See Figure 3).

The users can accept the suggested member sizes or select individual or a group of members and assign new member sizes provided in a database. All the structural elements modeled are standard round, hollow structural steel shapes (HSS) with different diameters and wall thicknesses.

Morphing

The users can modify the structural geometry in three dimensions by using the morph utility. The software includes two morphing options: vault and dome.

These terms refer to the different proxy shapes used for what is called the 'deformer': a vault is a cylinder and a

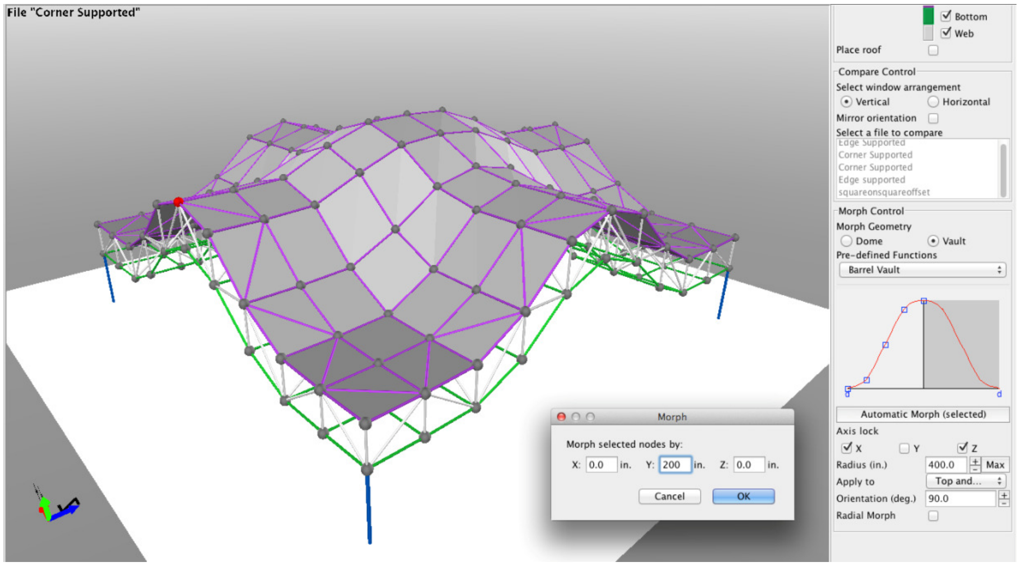


Figure 4. Morphing toolbox of the SAFAS module 2

dome is a sphere. A radius is selected which defines the members to be affected by the deformation. A radius field is used to set the distance from the deformer shape's center to the edge of the area to be morphed. In addition, the effect of a morphing manipulation may vary by several functions from the center to the periphery (linear, exponential, and user-defined).

Two morphing options are available:

(1) *Manual (Direct-Manipulation) Morph:* Using this option, the user can change the structural configuration by selecting nodes and freely dragging/moving them in the three orthogonal directions using the mouse.

(2) *Auto (Numeric-Entry) Morph:* In this option, the user can define the amount of joint movements in the X,Y, and Z directions and the structure is automatically displaced based on the entered values. Figure 4 shows the morphing toolbox of the SAFAS with numeric entry morph dialogue open.

Analyze

Once the structural model is complete, the user submits it to the analytical engine to conduct the structural analysis. The structural analysis software used is SAP2000 [13], which resides on a remote server. To provide system security, the user is required to provide a username and password to have access to the structural analysis software. The simulation service is managed by a queue and each user's results are saved on both the client and the server computers.

Post-Analysis Mode

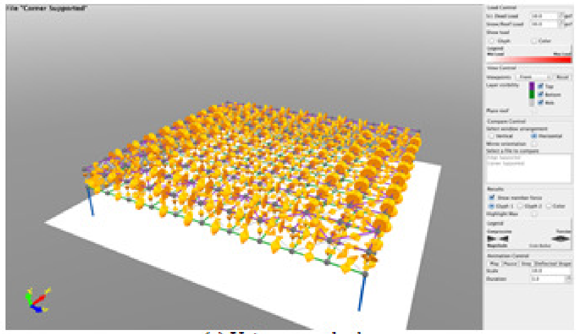
Upon the completion of the structural analysis, the users can observe the distribution of internal forces using several visualization options including glyphs and color map options. They can also determine the values at specific members or nodes by placing the cursor over the particular element. For example, placing the cursor on a node, a user can check the nodal deflection when subjected to the applied loads. Figure 5 shows the variations of the internal forces in a structure using the three glyph options. These options include: (a) *Cone Glyph*, which represents the magnitude of the internal forces by their size and relative distance of the cones from each other; (b) *Cylinder Glyph*, which the magnitude of the member forces is represented by the radius of the cylinder; and (c) *Color Coding*, for which red is used to indicate members in compression and blue for tension. Various shades of these two colors are used to identify the different force levels. The red and blue color codes are also used for the cylinder glyphs to represent compressive and tensile forces, respectively.

Compare

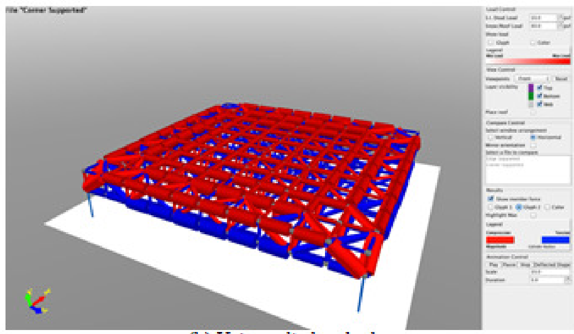
The compare utility is part of the post-analysis mode, which shows the results of the analysis of two structures simultaneously in split windows (horizontally or vertically). This helps the user see directly how changes made to the structural configuration, its properties or applied loads affect the structure's performance in terms of internal member forces and nodal deflections. In addition, the virtual cameras can be coupled between compare windows - the windows can be synchronized so that the models maintain alignment even when the user navigates in either view (Mirror Orientation option). Figure 6 is a screenshot showing the compare windows.

III. TUTORIALS

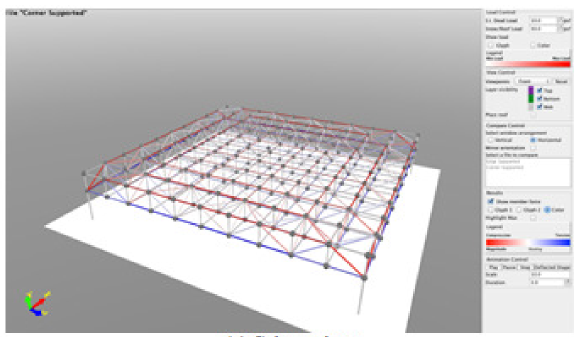
The website includes several video tutorials with audio that show how to use the SAFAS features. An overview tutorial provides information about how to operate the software in pre- and post-analysis modes. Other, more specific tutorials show users example uses of the program's various analytical features. Currently, these tutorials address several topics such as effects of the



(a) Using cone glyphs



(b) Using cylinder glyphs



(c) Color coding

Figure 5. Glyph and color options to visually demonstrate the member forces in the structure (SAFAS module 2)

location and number of supports, and the span/depth ratios on the behavior of the flat and barrel vault double-layer grid spatial structures.

IV. Evaluation

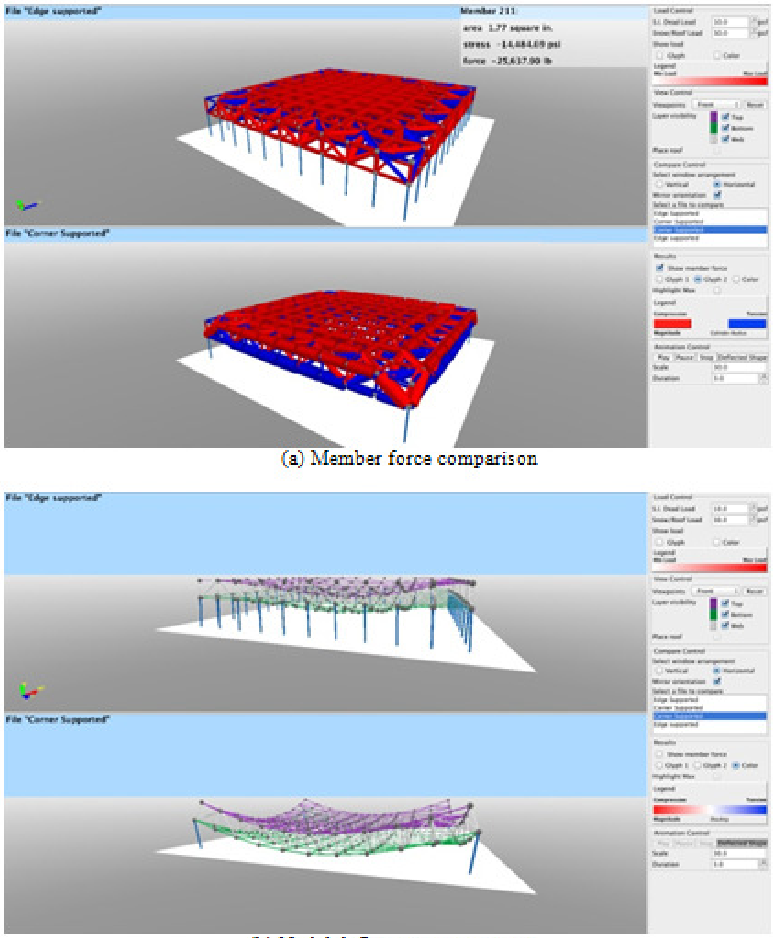
To assess the efficacy of the SAFAS educational tools, we evaluated their use with 35 architecture students in an undergraduate building structures course at a large, public university in the eastern U.S. We developed the SAFAS to create structures, solve problems, and answer questions. The assignments were designed so that, through their completion, students would learn important structural concepts, such as the effects of the *number* of supports on structural behavior (Assignment 1), the effects of support *number and location* on structural behavior (Assignment 2), and the effects of *span-to-depth* ratio on structural behavior (Assignment 3).

The three assignments required students to design flat and barrel vault double-layer grid spatial structures and analyze the effects of various column locations and numbers, and module depths on the forces and deformations within the structure. Based on the results, students were asked to interpret their findings and answer questions.

Thus, the assignments served the educational objectives of (a) teaching students structural concepts, and (b) how to use the SAFAS tools. Students completed the assignments on their own without help from other students or their instructor to allow us to evaluate whether the SAFAS could be used by undergraduate students in this manner with only a brief introduction to the SAFAS provided by the course instructor.

Learning Assessment

To determine whether the students already understood the concepts to be learned in the assignments prior to beginning the assignments, students completed a 12-item multiple-choice pre-test that we developed to assess the



(a) Member force comparison

(b) Nodal deflection comparison

Figure 6. Screenshots of the compare split windows

concepts in the assignments. Students answered correctly an average of 3.1 (*SD* = 1.3) questions on the pre-test. Because students would have been able to answer an average of 2.7 questions correctly by answering randomly (some questions had four responses options and others had five), we concluded that students knew very little about the concepts assessed on the pre-test. To assess whether students had learned these concepts after using the SAFAS, we asked the same pre-test questions as part of the assignments. Students answered correctly an average of 8.3 questions (*SD* = 1.5) on these 12 items on the assignments, which based on statistical analysis, were significantly more questions than they answered correctly on the pre-test (t = 21.82, df = 34, $p < 0.001$). These findings indicate that students learned these concepts by using the SAFAS educational tools.

Students' Beliefs

After using the SAFAS to complete the three assignments, students were asked to complete an online questionnaire that included closed- and open-ended items about the specific components of the SAFAS, as well as their beliefs about their use of the SAFAS. For the closed-ended items, students were asked to report their beliefs on a 5-point Likert-format scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

The results shown in Table 1 indicate that students learned new knowledge and skills, found the material to be interesting, believed that they could complete the assignments successfully, were confident in their ability to use the SAFAS in the future, and believed that the SAFAS could be useful to them in the future. When asked in an open-ended item what knowledge and skills they learned, students reported that they not only learned how to use the SAFAS, but also learned specific concepts related to structural design. The concepts students reported learning related directly to the purposes of the assignments, including understanding the effects of number and location of supports on structural behavior and the effects of span-to-depth ratio on structural behavior. The fact that students were confident in their ability to use the SAFAS for the three current assignments and in the future is important because when students' are more confident in their ability to complete a task, they are more likely to choose to do the task, put forth more effort in the task, and persist at the task [14]. Thus, we have evidence that the three assignments were sufficient to teach students how to use the SAFAS and about structural concepts, as well as to motivate students to use it in the future based on their reported interest and confidence, and their beliefs about the usefulness of the SAFAS.

TABLE I.
STUDENTS' OVERALL BELIEFS ABOUT USING THE SAFAS

Questionnaire Items	*M*	*SD*
I learned new knowledge and skills from using SAFAS.	3.89	0.80
The material that I learned from using SAFAS was interesting.	3.86	0.85
As I was working on the three SAFAS assignments, I felt confident that I could complete them successfully.	3.57	0.78
I am confident in my ability to use SAFAS in the future if I wanted to do so.	3.94	0.84
SAFAS could be useful to me in the future.	3.97	0.99

Note: Response options ranged from 1 (strongly disagree) to 5 (strongly agree).

To examine in more detail which aspects of the SAFAS tools were most useful to students, we asked them specific questions about their beliefs about the tutorials, the Knowledgebase Module, and the Structure and Form Experimentation Module. When asked how useful each of the tutorials was on a 5-point scale, students' responses ranged from 3.16 (SD = 1.19) to 3.82 (SD = 0.82), indicating that students found the tutorials to be useful. When asked about how helpful the materials presented in each section of the Knowledgebase were, students reported that they were generally helpful, with means ranging from 3.29 (SD = 1.01) to 3.81 (SD = 0.87).

TABLE II.
STUDENTS BELIEFS ABOUT THE STRUCTURE AND FORM EXPERIMENTATION MODULE

Questionnaire Items	*M*	*SD*
It was easy for me to visualize the various configurations of spatial structures presented when I created a new model.	4.09	0.82
It was easy for me to note the differences between the various configurations.	3.70	0.81
The 'Compare' window was useful to me to better understand differences between the performances of structures under loads.	4.29	1.05
The 'color coding' of the structure helped me to understand the action of loads and distribution of forces within the structure.	4.57	0.66
The 'Highlight Max' option helped me to understand structural behavior.	4.82	0.39
Selecting members and assigning sizes to the structure was easy.	4.03	0.99
Morphing the structural form was easy.	3.54	1.01
It was easy to understand the different morphing options.	3.94	0.80
Placing columns was easy to do.	4.57	0.70
The 'Compare' window was easy to use.	4.17	1.01

Note: Response options ranged from 1 (strongly disagree) to 5 (strongly agree).

Students' responses to closed-ended questions about the Structure and Form Experimentation Module indicated that the module was fairly easy to use and that its features made it easy for students to visualize and understand the various spatial structure configurations (see Table 2 for the questions and mean responses). Responses to these items were consistent with responses to the open-ended item that asked: "What did you like most about using SAFAS?" Of the 33 students that answered the question, 24 (72.7%) reported that they liked that SAFAS made it easy to visualize structural behavior. Nine students (27.3%) reported that they liked that it was easy to analyze a structure using the SAFAS, and nine students (27.3%) replied that it was easy to manipulate a structure using the SAFAS. Seven students (21.2%) reported that they liked it because it was user friendly, and four students (12.1%) replied that they liked it because it identified the maximum forces in a structure. Given that one of the primary purposes of the SAFAS is to provide a visualization of structural behavior that has been analyzed after manipulation, these findings indicate that it is meeting the primary purposes that it was intended to serve.

V. SUMMARY AND CONCLUSION

This paper provided the details of a web-based educational system for architects and architecture students to better comprehend the relationships between structure and form, especially the effects of variations of form on structural behavior. Results of the evaluation of undergraduate architecture students' performance demonstrated that the developed educational materials were effective in helping students gain a better understanding about spatial structures and to comprehend the relationships between structure and form. Students reported that by using the educational tools, they became confident in their use of the SAFAS program, they were interested in it, and found it useful. Students also reported that it helped them to visualize structural behavior, which is one of the primary uses of the SAFAS program. These findings indicate that the SAFAS and the associated educational tools could be used in undergraduate architecture and structures courses to foster a better understanding of various structural concepts. Given that the SAFAS can be used by students without instruction other than that provided online at the SAFAS website, we predict that the SAFAS will also be useful to professionals in the fields of architecture and engineering.

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