# Learning in Digital Space: Dynamic Visualization of Structural Behavior as a Teaching Strategy

**Shahin Vassigh**
State University New York , Buffalo

**Abstract**
This article explores the problems with the existing models employed as a basis for teaching structures effectively in architecture programs. As a solution, it outlines the development of a multi-media educational software package as an alternative to the less effective traditional approach. The software described utilizes a wide range of high-quality graphics, computer-generated models, animations, Virtual reality models and audio to demonstrate the principles and applications of structural analysis. The development of the educational software aims to provide structural analysis instruction that is better suited to the skills, disposition, and learning needs of architecture students.

## 1 Introduction

The teaching of structures (the analysis, behavior and design of structural systems) within academic architecture programs faces a fundamental problem - understanding structures is central to the education of the architect, but the content "content" (theory and pedagogy) and "delivery systems" (teaching methods) currently in use are distinctly inappropriate for the vast majority of architecture students. Architecture faculty and students struggle with the traditional engineering-based approach to structures instruction, which is increasingly proving to be ineffective in the classroom.

The structures pedagogy used in most architecture programs presents a few significant problems. First, the curriculum, teaching methods, concepts, and instructional tools are borrowed in a wholesale manner from engineering programs, with little modification. Instruction is therefore quantitative, communicating even basic concepts using a high-level mathematics nomenclature. This is problematical as architecture students have neither the background, disposition, nor time to master the mathematics skills required to understand or utilize a system based on highly mathematical models. They, therefore quickly become uninterested, frustrated, or even intimidated by the structures curriculum. In an article written in 1994, Gary black and Stephen Duff wrote the following on the state of structures pedagogy in architecture programs:

> *"Unfortunately, present programs in structures are usually derivatives of traditional teaching methods and conception that originated in civil engineering schools. As such, they are not conceived, developed or taught as programs aimed at architects and architectural needs. More often than not, they are watered down civil engineering program, too weak to satisfy technical requirements and ill conceived for other objectives." (Black, 1994)*

Although a number of architecture educators have attempted to overcome this problem, the statement above remains largely true today. Other than a few structures texts, most of the existing teaching material is either geared towards the descriptive and qualitative methods which are insufficient for the architectural needs, or they remain highly quantitative and difficult to comprehend for the majority of architecture students.

The second problem with the current structures pedagogy is that the applied-engineering approach to teaching structures uses an abstractionist and reductionist methodology that seeks to develop a quantitative explanation for all physical events. Although abstraction and reduction are necessary steps in defining analytical solutions to structural problems, understanding structural behavior through component analysis and abstract behavioral formulas creates serious impediments for developing a comprehensive understanding of this subject. Particularly for architecture students, instruction which is void of continuous reference to a building context or a structural system remains mostly ineffective.

Lastly, structures instruction is rarely, if ever, fully integrated into the broader architecture curriculum. Typically, structures courses are separated completely from the remainder of the program. The subject arena of structural problem solving (particularly creative structural design and application) is often excluded most architecture design studio courses. Architecture design studios allow architecture students to interact one-on-one with faculty to solve design problems and are the central means by which architecture students learn to apply concepts learned elsewhere in the program. Design studios provide the means for highly directed, interactive instruction and the opportunity for students to integrate, demonstrate, and apply the cumulative concepts and issues they study throughout their learning tenure. By excluding, or not specifically addressing issues of structure within the design studio, students are poorly served in that a primary opportunity to reinforce structures concepts is lost, the central importance of structure as a design element (and opportunity) is overlooked, and new opportunities for students to develop creative and expressive design through structural innovation are missed.

This paper discusses the nature of the problems inherent in current teaching approaches to structures and outlines the framework for the development of an alternative pedagogy and instructional delivery system based on the use of digital technology. This alternative seeks to integrate the quantitative engineering methods with the qualitative approaches using a range of digital visualization devices to better meet the architecture students' needs and measurably improve the understanding and application of basic and advanced structural engineering principles.

## 2 Architecture and the difficulty with the traditional engineering model

The scientific revolution is marked by the progression from Aristotle’s worldview, which was based on an entirely non-mathematical system and observation of common phenomenon to the Newtonian universe of quantitative methods. Newton’s natural philosophy began an era of explaining all natural phenomenon through observation, deduction followed by mathematical theorizing. Newton wrote:

> *“Natural philosophy consists in the discovering the frame and operations of nature, reducing them, as far as they may be, to general rules or laws- establishing these rules by observation and experiments, and thence deducing the causes and effects of things…” (Bechler 1991)*

Modern mechanical engineering science is founded on the Newtonian principles, which were formulated from Newton’s studies of planetary motion. Although these principles have been modified by scientists like D’Alembert and Lagrange and Hamilton, their validity has been unchallenged and *newtoninan mechanics* remains the foundation for our understanding of the physical sciences. (Johnson 1997)

Not surprisingly, the Newtonian mechanics uses a methodology which is based on abstraction. The process of analyzing an engineering problem is based on progression through a logical sequence that requires abstraction and reduction in each step of the process. The analytical method of understanding structures using the engineering model mandates a process which consecutively dismantles a structure into sub-components, focusing on a particular element, detaching it from all other connected structural members, and then reducing it to a notation system of structural symbols, mathematical formulae and annotations. In short this process is called drawing the free body diagram of the structural member. The textbook definition of the free body diagram is the following:

> *“Problems in engineering mechanics are concerned with the external effects of a system of forces on a physical body. The approach usually followed in solving an engineering mechanics problem requires identification of all external forces acting on the “ body of interest”. A carefully prepared drawing that shows the “body of interest” separated from all other interacting bodies and with all external forces applied is known as a free body diagram.” (Riley 1993)*

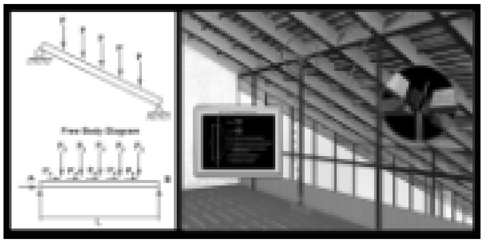

**Fig. 1a-1b**

This process disconnects all the conceptual and visual relations between a structural member and the building structure. In most cases, a complete context is never presented either prior to, or, after the analysis. The engineering-based model also seldom engages the overall structural system to clarify the relationship between small-scale components and large-scale structure. This can be further clarified by using an example. Figures 1a and 2a show the standard diagrams used for analyzing beams and columns in almost all engineering and architecture texts. Fig. 1a shows the beam and its free body diagram. The beam diagram includes the loading pattern represented by arrows and the connection condition to the adjacent element, which are represented by the two symbols at the beam-ends. Similarly, figure 2a shows a column and its corresponding free body diagram.

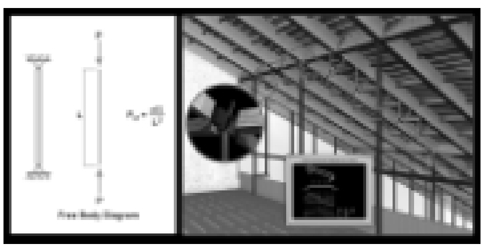

**Fig. 2a-2b**

Although these diagrams constitute valuable engineering tools, they are completely abstract and are void of context. Missing from this picture is the information conveyed in figures 1b and 2b demonstrating the actual support condition, the source producing the load, and the relation of the beam and column under analysis in relation to the grand scheme of the structural system.

Teaching structures based on abstract and quantitative analysis of individual elements in isolation does not promote a comprehensive understanding of structural behavior. Furthermore, this limited approach could directly impact the quality of the architectural design and the student's performance in the design studio. As stated by Gary Black and Stephen Duff:

Figure 2a-2b

> *"It is an understanding of the global behavior, more than anything else that enables the designer to integrate the structure and space. Understanding the global behavior is the crucial link between a qualitative understanding of structural systems and a qualitative understanding of structural details that makes engineering come alive and that gives an architect the ability to wield structures creatively as he or she would color." (Black, 1994)*

By overlooking the broad picture of structural behavior, the architecture educator completely loses the opportunity to address structural issues as an innovative and creative activity in a design project. Equally problematical, instead of being a set of interesting challenges, structural considerations merely becomes a burden that the student must bear in order to get his/her project to be functional.

### 3 Project description

If architecture students are to learn to apply sophisticated structural analysis and design in an effective manner, then the abstraction and reduction embedded in the engineering based model must be resolved. Also the teaching methods must respond to the needs, capabilities, and the perspectives of the architecture student. This section describes alternative structures pedagogy and tool constructed on a conceptual approach and grounded in architectural design to eliminate abstraction. Coupled with a visual and interactive approach to instruction, it offers improved core course instruction and can facilitate a much stronger understanding of basic and advanced structural principle.

Under a grant funded by the by the U.S. Department of Education *Fund for the Improvement of Postsecondary Education* (FIPSE), an interdisciplinary, multi-institutional team from University at Buffalo, University of Oregon, University of Utah and Virginia Polytechnic Institute State University, are collaborating to compete the development, testing and evaluation of a *Structures Instructional Software Package (ISIP).* A teaching tool that utilizes a wide range of digital and graphic technologies including detailed and realistic three-dimensional computer generated models and animation to teach basic structural principles. The visual approach used in the development of this tool also provides an intuitive understanding supported by experiencing structural behavior and engaging the students with the consequences of architectural form selection. Although the work and methods for developing the software are new, they build on the work of significant authors and educators such as Mario Salvadori, Heino Engel, Daniel Schodek, Ronald Shaeffer and Waclaw Zalewski and Edward Allen. The development of the software is based on six principles listed below:

- structures instruction should facilitate comprehension of fundamental principles of the ***practical*** aspects of structural design as well as the ***creative possibilities*** of applied structure within the built environment;
- instruction in structures should always be grounded and referenced to complete buildings and/or structural systems which connects principles of sub-component analysis to broader issues of building design;
- the instruction of structures for architecture students, should be *visually* grounded, using real-world classroom activities and the communication of basic theory and principles should focus on reinforcing and demonstrating principles of *application*;
- educational and instructional tools should make the instructor more effective in the classroom, permit the student to be a more effective and efficient learner, and foster productive student-faculty interaction; and;
- structures instruction should be addressed to increase student interest in structural design, particularly as a life long learning skill. Since architecture is a continuous learning process, creating an interest in structures can inspire a student to explore structures as a practicing professional in a confidently intelligent manner.

The Structures Instruction Software uses a wide range of digital and graphic technology, including computer generated models, interactive images, full motion video, and audio to improve the content and delivery of structural concepts. This software system attempts to overcome the limitations of two-dimensional, abstracted representations of structural dynamics and provides the means to study structure within a simulated building context. The full version of the program divides the study of structures into four concept areas. These include:

1. ***The Architects:*** contains biographies, excerpts from written works, and drawings from both architects and engineers. It also includes a searchable, interactive database of their most significant works, presented using computer-generated models, photographs, movies, and interactive files. The key learning element of this section is that each building and structural system presented is actively linked through a series of "hot spots." Hence, the user can click on any portion of the building and view information from any of the other concept areas regarding that specific building element, such as, the structural member type, its behavior, member connections at that location, and analytical data and formulae.
2. ***Basic Concepts***: explores general structural analysis and design concepts, definitions, and working principles. Introductory concepts such as statics principles and strength of materials are all available within this option.
3. ***Structural Systems***: is a searchable database of structural subsystems (trusses, cables,

arches, beams & columns, etc.)which includes construction details, models of structural behavior under various loading conditions, and analytical procedures for structural investigation and analysis.

4. ***Technical Reference Library:*** includes a technical reference of analytical formulae, member properties, and selected national building code guidelines for specific materials.

Each concept area is not a separate study module, but a point from which to initiate different aspects of structural performance and analysis. For example, a user will typically begin by examining the works of the Architects, settling on a single architect, and selecting a single work (building). Clicking on any part of the building structure reveals the Basic Concepts of its structural design. Through the use of linked menus and hypertext, all concept areas are linked and accessible from within each other, but the student can also move from the more specific to the more general.

A complete building always provides the visual axis, which grounds the investigation. Successive layers of information (mathematical formulas, analytical results, graphic representations of behavior, etc.) can be accessed and overlain onto the buildings, issues, and sub-systems currently being studied. Rather than abstract representations, three-dimensional graphics are used and most are animated to simulate behavior under conditions of structural stress. Using specific examples, the following three sections discuss how the software can assist in eliminating abstraction by utilizing various visualization devices.

## 4 Removing abstraction by providing context

A significant portion of architectural education is based on study of precedents and examination of the work of various architects and landmark buildings. Although many faculty teaching structures use analysis of existing buildings as a venue for discussion of the subject, the effectiveness of their effort is frequently limited by the constraints of the traditional delivery system of the content. Most often, this important avenue of study cannot progress beyond a standard analysis that includes a few static images or graphic representation of the building (or building components) followed by diagrams and mathematical annotations. Alternatively, using Structures Instructional software can offer a few advantages and enhance the effectiveness and possible variables of this practice.

The example shown in figure 3 represents one of the options for investigating the subject of "beams and columns" within the Software. In this scenario, the user selects Operation Centre for the British Rail at Waterloo designed by Nicholas Grimshaw from the Architect concept area. Based on this selection, a computer a model of the building showing the most significant architectural features as well as the structural system of the building. Next, text and audio covey information about the function of the building and offer the choice of structural material as well as the choice of the structural system. The student can then navigate through the structure of the building by pointing to various structural elements. Clicking on any beam or column or beam to column connection within the space will open a window with graphic analysis of the specific member, followed by an animation demonstrating the behavior of the member under loading. All successive layers of information (like mathematical analysis and numerical calculations) can be accessed and overlain onto the buildings.

By using a computer-generated model, the building becomes an interactive device rather than a static image or a flattened background for the study. By providing the possibility of moving through the building and exposing structural elements by deliberate selection, the user engages the entire building as a continuous context. Rather than abstract representation of structural members, the component analysis occurs within the building context.

Computer models permit focusing on details as well as the entire structure instantaneously, removing abstraction by clearly connecting the detail to whole and vice versa. Using digital modeling also permits many layers of information to be presented simultaneously and further allowing the user to study a particular element in a smaller window, while the larger context is still in view.

## 5 Visualizing structural behavior using conceptual load distribution paths

Many structural engineering computer programs designed for performing analytical calculations have some visualization capability for showing structural response under the load application. Although architecture students could potentially benefit from the use of these programs, their use requires an extensive knowledge of structural concepts, careful engineering modeling skills, and proper assumptions and procedures for load application to the models. Although today these programs have become user-friendlier, they are exclusively tailored for the use of engineers and are notably difficult for architecture students to utilize. Even when architecture students have learned to use these programs, they usually engage them at an elementary level. Thus, the modeling significant work of architecture, if not impossible by the level their expertise, will no be feasible by the limited time devoted to the subject.

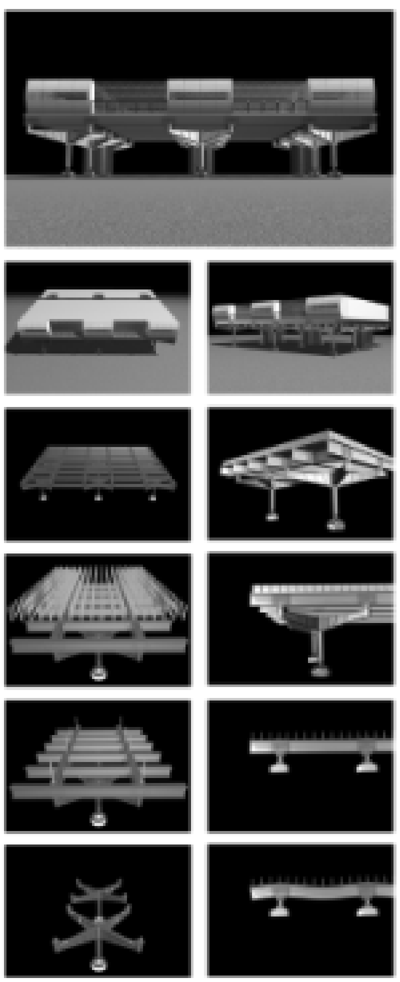

**Fig 3**

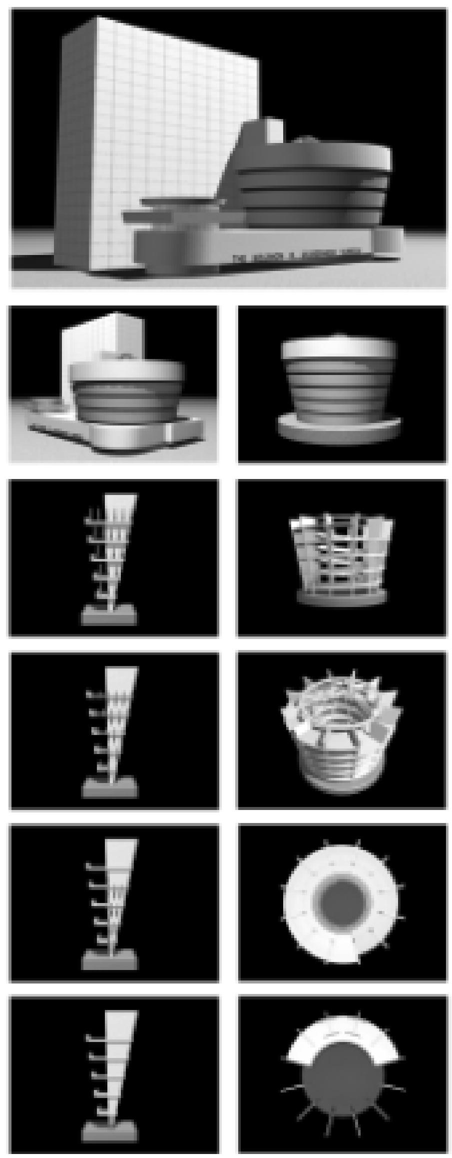

**Fig 4**

Given the importance that visualization contributes to the understanding of structural behavior, the Structures Instruction Software uses computer-generated models to show the load collection mechanism and load distribution path across the entire structural system. Figure 4 is a series of images from a computer model of the Guggenheim Museum designed by Frank Lloyd Wright. The model details the major structural system of the building, which is composed of a spiral reinforced concrete ramp and a series of fin shaped columns arranged in a circular plan. The ramp and the fin shaped columns mutually support one another. The ramp rests on the columns with a significant part cantilevered from the columns. The columns gain their stability and resist tipping inward by the compression ring and the hoop action of the spiral floor slab. Figure 4 also shows consecutive frames of the animation demonstrating the load travel path from the cantilevered floor slab to the finned columns and to the foundation and how the arch action of the ramp keeps the column stable.

Just like the computer-generated models discussed in the previous section, these models also include the major structural systems, structural connections, as well as important architectural features of the building such as facade panels, fenestration, and interior spaces. However modeling the loading patterns, the load collection and the hierarchy of load movement through the structure are all based on conceptual predications and are not based on numerical analysis. These models are prepared by superimposing a series of arrows on structural load bearing systems. Using the animation feature of the modeling program, the arrows are animated showing load travel path through the body of each structural component and eventually to the foundation system. The animations are then rendered and saved into a Quick Time movie format with a slider bar that allows students to control the speed of animation.

## 6 Visualizing structural behavior using dynamic models

Typically, studying the variation of forces and moments in a structural member is a critical component of teaching structures. In most structures courses, this is achieved through numerical exercises, which involve longhand calculations of the internal forces and moments, followed by plotting shear and moment diagrams that indicate the critical stress areas and values. The final stage of this exercise is the design of the structural member. In structural engineering terms, this means selecting the most economical member to perform safely under the applied loads.

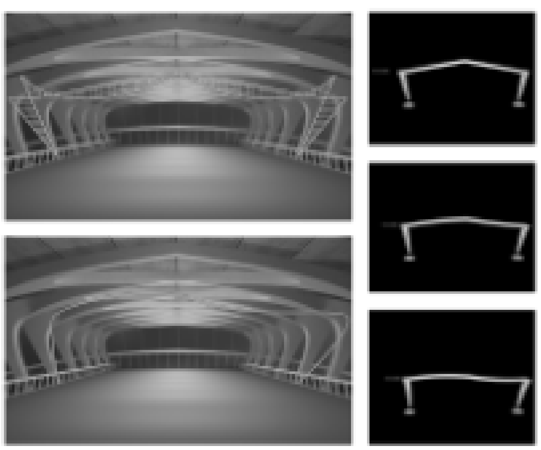

**Fig. 5a-5b**

Although this is a very important exercise in analyzing structural behavior, most often it does not go beyond a quantitative exercise and does not foster an intuitive understanding of structures. However, this exercise could be significantly improved if the relationship of the moment diagram and deflection mechanism of a structure or structural member were to be explored simultaneously.

The Structures Instructional Software provides an option to view the deflection mechanism and dynamic behavior of structures under the application of loads. Visualizing the structural deformation at key locations such as mid-spans, connections to other members, and anchorage to the foundation can add a great value to the students' understanding of the behavior. What makes this an even more effective device is the capacity of the tool to superimpose the moment diagram directly on the model, which instantly brings forth the immediate relationship of the moment diagram and the deflection mechanism.

Fig. 5a is a model of the concrete frame of the Lyon Airport Railroad Station designed by Santiago Calatrava. The consecutive frames of the animation demonstrate how the frame deforms and responds to the lateral loads. By exaggerating the frame behavior, it becomes clearly visible that the frame corners go through large displacement, and the center span of the frame (beam member) remains stationary. Superimposed on the model is the moment diagram, which reflects the consequence of the deformation in terms of moment and stress generation. The shape of the moment diagram indicates large amount of moment generated at the corners (thus producing large stresses) while there is practically no moment at the center span of the beam.

Another important concept to communicate in this example is the choice of the structurally expressive form of the frame by the architect. Looking at Figs. 5a and 5b, this form can be considered as a direct response to the deflection mechanism and the moment diagram. Calatrava's forms the frame with significant mass at the corners where the moment is maximum, sculpts the center to minimize mass at the center, responding to minimal moment, and stresses at that location.

Such examples based on a strong visualization approach provide an intuitive understanding supported by experiencing the structural behavior. In addition, such an approach engages the students with other issues, such as the utility of the moment diagrams and the clarity of the structural form. This can change the students' conception of drawing moment diagrams from a useless, laborious effort to a potential form of expression in the process of architectural design.

## 7 Closing Remarks

The problems with the current approach to teaching structures are rooted in the use of an engineering based model, which is founded on abstraction and reduction. Although abstraction and reduction are necessary steps to manage and simplify complicated structural problems and find analytical solutions, this method of inquiry removes the overall context and impedes gaining a comprehensive understanding of the subject.

Also architects think, learn, and approach the design of the built environment differently than engineers. Unfortunately, the standard engineering-based approach employed to teach structures does not address the thinking, strengths, and weaknesses of architecture students. Clearly, most architecture students do not have a strong mathematical background, but they do possess a strong facility for and training in three-dimensional visualization and can quickly absorb information through this medium. Therefore, any approach, which is used to teach architecture students effectively and to promote an intuitive understanding of the subject, needs to be sensitive to these issues. The project described above builds on some of these issues. The central underlying principle for the development of the project is to provide a visual and direct means of communicating concepts and grounding them in the real-world context. It is anticipated that by using powerful graphics, animation, and other means of visual communication, an intuitive base for the understanding of the structural concepts can be well established and strengthened.

There are also other anticipated improvements in the students' learning by means of using this approach to structures education. For example, unlimited access to the software (CD-ROM or over the Internet) makes independent learning practical and allows students to progress at differing rates. The generic lecture approach to learning, which necessitates that all students earn at the same rate, could be replaced by individualized learning patterns that are more compatible with teaching in this design studio format. Students can access the subject under investigation in the form exactly as it is delivered in class, have the ability to repeat information, and use multiple views and magnifications to investigate the subject more thoroughly. By selecting a different path within the software, it is also possible to avoid repetition and study the same subject in a completely different context. This structured self-exploratory system allows the students to explore concepts from introductory and advanced principles at their own pace. Long hours of lecturing can be reduced and supplanted with self-directed learning, freeing up the instructor's time to interact individually with small groups and to participate more actively in the design studio.

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