Envisioning Structural System Behavior: From da Vinci to the Finite Element Montage

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INTRODUCTION

The conventions of graphical representation of architectural form and space are well established and understood by practitioners and students alike: sectional, elevational, axonometric and perspectival drawings, sketches, photographs, and now, in addition, computer generated images and animations are all used to convey in a two-dimensional medium the three-dimensional reality of the architectural built world. On the other hand, a much more diagrammatic and abstract set of principles, analytically based, have historically governed the way in which the structure that supports and shapes this architecture is visually portrayed as responding to gravitational and environmental forces. These two contrasting approaches to representation have surely contributed significantly to the widening chasm between what many architects perceive of as "structure" on the one hand and as "architecture" on the other.

Current computer technology, however, has the potential for narrowing that gap. Research both in computer graphics and in structural analysis has separately revolutionized the manner in which architecture and engineering are understood and taught. One need only visit an architecture school or design office to see the possibilities that computers offer for special effects, for layering of images, text, animations and sound, and for experiencing the three-dimensional virtual built world. In the field of structural engineering, finite element analysis programs now allow engineers to design irregular, large scale structures accurately and relatively easily. More importantly in this context, these programs offer the opportunity for the visualization of structural behavior that goes far beyond the limitations of previous methods of representation. Nevertheless, these relatively new representations remain mutually exclusive; architectural form and space are presented without regard to structural behavior and structural behavior is presented without an architectural context.

The representational technique described in the second part of this article, coined the Finite Element Montage, is introduced as an attempt to bridge the gap between these two worlds. It involves the combination of finite element analysis, three-dimensional modeling, two-dimensional editing, and multi-media authoring software to produce representations of structural behavior integrated with images of architectural form and space. The idea is to promote conceptualization of structural behavior parallel and with respect to a simultaneous reading of architectural context. In describing the concerns that led to the development of the Finite Element Montage method in its present form, it will be found to be useful and, we believe, historically interesting and revealing to conduct in the first part of this paper a brief survey of traditional and commonly used methods of structural behavior representation and to discuss their particular strengths and deficiencies.

The text of this paper is intended to be complemented by many drawing and photographic illustrations; their large number, unfortunately, does not lend itself to the space limitations prescibed for this publication. Moreover, the essential color requirements of the Finite Element Montage images make their reproduction here impossible. To gain a full appreciation of the method being proposed, therefore, it will be essential for readers to attend the illustrated presentation of this material at the conference.

A BRIEF HISTORICAL SURVEY

We can only speculate as to the precise origin of structural representation. The modern connotation of the term "structure" as being the elements or system within a building that resist only loads and that is distinct from the architectural enclosure system had little meaning before the Renaissance. Before scientific inquiry into the nature of statics within buildings there was little need to discriminate between "structural" and "architectural" systems; the elements responsible for supporting the building against loads, were, by enlarged, integrally a part of the form and space of the building.

Force Vector Diagrams

It has been argued that the emergence of Leonardo da Vinci's force vector diagrams marks the point in time at which the study of statics and physics began to have influence on the design of structure.[1] Beginning with proportioned line diagrams representing ropes under a given load situation, the diagrams became abstract visualizations of forces underlying the numerical truth of equations of equilibrium that explain structural behavior. Over time these diagrams evolved into quite sophisticated graphical statical analysis techniques that proved not only remarkably accurate but that also, importantly, retained an integral visual link to the building's architectural form.[2] Today, more abstract numerical computer analysis techniques have largely superseded these manual graphical methods for complex structures; nevertheless, the basic force vector diagram remains as a widely used and understood method of representation of the fundamental statics and equilibrium of structures.

Human Analogy Method

Perhaps an even older and more compelling way of representing structural behavior is in making analogies of structural response and the human body's reaction to load. From the image of the Caryatids to the demonstration of the basic forces in the Firth of Forth Bridge,[3] to the humorous drawings of Forrest Wilson,[4] human beings have been portrayed resisting the loads on buildings or other structures. Instinctively, we understand these representations of structural tensions, compressions, and bending as though we were the figures in the images themselves.

Physical Modeling

Physical modeling has long been an effective means for studying the effects of load on structure. Historically, full scale models have often been produced to test new system configurations or spans not previously attempted, while reduced scale models have served to study similar building system innovations too costly or unfeasible to experiment with full scale.[5] The advantage of physical modeling in an architectural context is obvious: the spaces and forms created by the structural system model mimic directly those of the real building. With the advent of computer structural modeling, physical modeling for understanding structural behavior has greatly diminished in importance in the real-life practice of building. As an educational tool, however, the method continues to be used effectively to demonstrate fundamental structural behavior to architecture students. Physical modeling of real structural forms using cheap and flexible Styrofoam, balsa wood and cardboard materials allows structural behavior to be represented by exaggerating the often imperceptible deformations of structures into a strong visual image.[6,7] This image, however, tends to have a rather ambiguous and greatly simplified relationship to the architectural context due to the necessities of choosing a material flexible enough and of connecting the pieces together in such a fashion that the desired amount of expressive deformation can take place.

Deformed/Deflected Shapes

Derived from the physical modeling method and with a similarly strong and accessible visual message is the structural behavior representational technique of drawing an exaggerated deformed/deflected shape of the structure under imaginary loading, used extensively in Salvadori and Heller's influential text *Structure in Architecture*.[8] Since the flexible material constraint of the physical model does not exist in the case of a drawn deflected shape, architectural form and space can become a strong and integral part of the representation. Much more common today, however, are linear abstractions of structural form shown in deflected shape. This tendency is a result of the now commonplace finite element analysis method of modeling structure by means of connecting points in space with linear elements, leading to a "wire-frame" representation.

Load Path Diagrams

Load path diagrams are another tool for visualizing the behavior of structure. These representations are intended to reveal the direction of forces as they "move" through structural systems. Images are drawn based on the results of analyses and use lines or arrows of varying size or thickness to indicate variations of load intensity, or "track" applied load as it makes its way through the system to the supports. While seductively simple and visually very accessible (based perhaps on personal experimentation and association with water and sand play during early childhood) the load path diagram representational technique is fundamentally misleading, for applied loads do not "travel" through a structure. Instead, a structure *carries* load by means of equilibrium of applied and reactive forces in each of the structural elements of the system. What the load path diagram is actually indirectly representing is the equilibrium hierarchy of the elements involved in supporting particular loads.

Mathematical Graphing

Abstract mathematical graphing is one of the most frequently encountered of all techniques currently used to represent structural behavior. This is hardly surprising given that the developments in understanding and predicting structural behavior have been accomplished largely by numerically oriented scientists and engineers. Bending moment, shear force, and axial force diagrams are all, of course, nothing other than scaled graphical plots that visually describe the magnitudes of these actions along the lengths of members. Generally, these plots are drawn in relation to two-dimensional symbolic loading diagrams for individual structural elements pulled out of their three-dimensional architectural context of form and space. On the other hand, the plots do present a very strong visual image of unseen intensity variations of forces within the members, and have themselves been interpreted back into structural form by inspired designers such as Nervi and Calatrava.

Photoelastic and Other Stress Mapping Methods

Photoelastic model representation is yet another way that has been used to "see" into a structural system that is being subjected to load. It uses the relationship between the state of stress in a transparent material and the way that that material transmits polarized light. During the first half of this century, the method underwent several stages of development, from two-dimensional cross sectional studies to complete system three-dimensional modeling. Analysis of interference patterns and colors created by polarized light reveal levels of intensity of strain that can represent force distribution within very complex and statically indeterminate structural systems.[9,10] The patterns are visually very appealing and can be interpreted both qualitatively relatively easily to recognize parts of the structure subjected to bending action or direct axial force and with rather more effort and experience quantitatively to obtain actual magnitudes of stress. An additional advantage of the photoelastic means of representation is that it reveals simultaneously overall system behavior and individual member response; i.e., one can "zoom in" to a particular area of the structure for more detailed information if desired.

The advent of computer numerical modeling and analysis of structures has superseded physical photoelastic model making and interpretation; the visual advantages and appeal of the method's mapping of stresses, however, has been carried forth, first in isostatic diagrams that plotted contours of principal stresses and, more recently, in the familiar richly colored patterns of membrane finite element mappings.

A NEW DIRECTION: THE FINITE ELEMENT MONTAGE

The Concepts

The Finite Element Montage representational method was developed by the present authors in light of the strengths and weaknesses of the techniques just reviewed. Five basic concepts were concluded to be of primary importance in effectively communicating structural system behavior:

First, *the representation of structural system response to loading should occur within the context of architectural form and space.* Traditionally, architectural form and space is represented through drawing, be it a two-dimensional projection (plan, section, and elevation) that gives a clear understanding of spacial relationships in the plane of the cut and beyond, or a three-dimensional axonometric or perspective that deals more with the perception of a space or form. Photography, in addition, is a useful tool for the representation of built works because it has the capacity to reveal color and texture, lighting and shadows, and human scale and interaction. More recently, three dimensional computer models have become increasingly used due to their versatility and limitless potential for perceptual and conceptual representations. As will be seen at the conference presentation, all of these media are adopted in the Finite Element Montage technique in order to present structural behavior within its architectural context. A clearer understanding of structural behavior can be given to architects by speaking to them in the languages of architecture, and revealing behavior within a representation of architecture.

Second, *a strong and visually striking and accessible presentation format is required.* The importance of presenting structural behavior in an attractive and graphically direct way was deemed to be of primary importance given the strongly visual orientation of the intended audience. As we have described, many of the methods of representation that are currently in use have been developed with a mathematical and scientific prejudice; force vector diagrams as well as shear force and bending moment plots may as a result seem somewhat abstract and removed from direct relationships to the architectural forms being studied. Human analogy, deformed shapes, load paths, and stress contour mappings, on the other hand, seem to offer both more visually striking and more accessible behavioral information and inspired many of the aspects of the Finite Element Montage.

Third, *the method should have the ability to reveal several different facets of behavior*, such as force and stress distribution as well as structure deformation and deflection. The representation of different facets of behavior is important to the complete understanding of any structural system. Deflected shapes, through exaggeration, allow one to visualize points of maximum rigidity and weakness within a system., as well as the effects of support conditions and connections. Displaying stress distributions within individual elements or within layers allows one to study tension and compression in axial members and points of maximum, minimum, and gradations of stress within plate or shell structures. And understanding a structural system's behavior is incomplete without examining its response to different loading conditions. All of these facets of system behavior are included in the multi-media framework developed for the Finite Element Montage method.

Fourth, *the method should have the capacity to simultaneously consider detailed localized member response as well as its participation in overall system behavior.* Understanding both the local and global structural behavior is analogous to the study of many different aspects of an architectural work. Architects understand the relationship of a simple diagram to the completed form of a building as well as how small details affect or are affected by the system in which they belong. Similarly, understanding the forces within a beam, for example, is equally as important as understanding that beam's role in a complex roof structure. "Zooming" capability, therefore, was considered to be of fundamental importance to the new representational technique.

Finally, *the use of multiple images in representing structural behavior was deemed essential.* It may be observed that while a structural system's response to load is often a complex, three-dimensional phenomenon, typically only one or two images of its behavior are presented (e.g., for a typical cross section). However, just as viewing one picture of a building can lead to oversimplification or misreading of its architecture, so, too, can a limited exposure of structural behavior cause its misrepresentation. Clear understanding of three dimensional form and space in architecture comes typically only from a series of images, the assimilation and mental collaging of which creates conceptual three-dimensional relationships in the mind of the viewer. In the Finite Element Montage multi-media framework, multiple images are used to demonstrate the different facets of a building's structural response from many different perspectives and in different media, leading to a better overall conceptual understanding of its behavior.

A Precedent

The format of Heino Engel's 1967 book, *Structural Systems,*[11] addressed many of these objectives and provided a useful and inspiring precedent for the development of the present method. His displays of many different drawings, models, and system variations utilizing several different behavioral representation techniques, enabled a more complete than usual understanding of overall system behavior within the context of architectural form and space characteristics. Engel's text, however, relies on technology and representational methods that are now decades old.

The Product

As mentioned earlier, developments in computer technology have produced revolutionary new methods of analysis and graphic representation that provide the next step in the evolution of envisioning structural behavior. Finite element structural analysis methods now allow us to "see" the "unseen" behavior of systems very quickly and without tedious computation. Their richly color-coded graphic outputs of hidden forces, stresses and deflections offer an appealing and readily accessible presentation of structural behavior. Computer graphics and imaging are also changing the way in which we study and represent architectural ideas. Images are easily manipulated, changed, overlapped and enhanced, resulting in completely new presentation techniques as well as original readings of form and space. Most recently, the enabling of the exchange and integration of the electronic products of different computer programs and platforms has allowed for the combination and further manipulation of electronic files. New capabilities call for new ways of approaching representation. The Finite Element Montage technique for envisioning structural behavior acknowledges and utilizes the most effective precedents while incorporating the latest in computer technology; its fundamental innovation is the juxtaposition of "structural behavior" images produced by a finite element analysis program with corresponding "architectural" drawings and photographs of a building. This overlapping of images enables the simultaneous conceptualization of structural behavior and architectural form and space.

Construction of a Finite Element Montage representation begins with the building of a complete finite element model of the structural system, joining connection "nodes" with either line or membrane finite elements depending on the type of structure being modeled, assigning geometric and elastic properties to these elements, applying loads, and "running" the numerical analysis program (in our case ROBOT V6[12]). The graphical output generated by the analysis will include deflected shapes of the structure and force and stress mappings color-coded according to levels of intensity. This output, however, will typically be in the form of "wire-frame" structures created by linear finite elements and be mysteriously "floating" on a black or white background devoid of any architectural context. The association of structural behavior to architectural context is remote and difficult to make.

Using the electronic .DXF graphical output file of this model analysis, the deflected shape and force intensity mappings can be transferred over to an image and text manipulation program (such as PhotoShop[13]) for overlaying onto electronically scanned drawings and photos of the building. At this point, the 3-D orthogonal grid-based finite element model output must be scaled, distorted, twisted and tweaked such that corresponding elements will match in the perspectival views of the 2-D photos and drawings (sectional, elevational, and plan overlays tend to be much simpler). The results of one finite element model analysis, however, can be used repeatedly to match different photo viewpoints on both the exterior and interior of the building since the model is constructed three-dimensionally.

The advantages of the Finite Element Montage method of representing structural behavior and associating it with architectural design intentions of form and space can only be suggested here in print, but will be readily apparent in the illustrated examples to be presented in person at the Conference, including the the Waterloo Train Station by Grimshaw and Partners, the Sainsbury Centre for the Visual Arts by Norman Foster Associates, and the Mount Rokko Church by Tadao Ando.

CONCLUSION

In this paper we have briefly reviewed many of today's most commonly used methods of structural system behavior representation and have identified their particular strengths and weaknesses. Based on these conclusions, and on recent developments in computational and graphical imaging technology, a new technique for envisioning structural response to loading, called the Finite Element Montage, has been described and will be presented visually at the conference session. The advantages of the method are several: a) it directly connects visual images of structural behavior with those of architectural context; b) it builds upon and combines the stronger visual aspects of the preceding methods such as stress mapping, deformed/deflected shape, and human analogy; c) it offers the opportunity to consider several different facets of structural behavior—deflection, force and stress distribution—in order to gain a complete understanding of the system's behavior; d) it allows for detailed individual member response to be considered as part of overall system behavior (this can be readily taken advantage of using the inherent ability of computer graphics software to "zoom" in and out of the images); and, e) it provides the opportunity, in a multi-media package currently under development, for the multi-directional / multi-image viewing considered necessary to gain a full appreciation and understanding of overall structural system response and of architectural concepts and realities. Considering all of these attributes, it is hoped that the Finite Element Montage representational technique will assist in providing for the re-establishment of concurrent understandings of structural behavior and architectural design issues among practitioners and students alike.

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