

STRUCTURAL PERFORMANCE MODELING IN ARCHITECTURAL DESIGN EDUCATION

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Abstract: In architectural education the process of design has evolved with the development of CAD technology. In many design schools throughout the world, the computer has extended its role beyond that of a drafting machine to become a tool for performance modeling. Applications currently used by students test lighting, thermal conditions, and structural validity, to name a few. However the goals in education are not identical to those in practice, and digital modeling can support learning in many ways that are not particularly useful or appropriate in professional practice.

In the design of structures there are three fundamental levels of understanding: *behavior, form, and performance*. Each has its place in design education and uses digital modeling in different forms. This paper describes various pedagogical models that incorporate computer aided drawing and performance modeling in the teaching of structures. Examples of student exercises and projects are discussed.

1. Beginnings: Computer Aided Structural Modeling in Education

Modeling plays an important role in design and is a key element of the design process. The introduction of digital modeling in architecture has had a powerful influence on the manipulation of form, so much so that many designers equate the transformation in design thinking to that which was attributed to the invention of tracing paper or even further back, to the discovery of perspective drawing. Each tool was a means towards better visualization and provided the designer with a new way to envision space and three-dimensional form.

In architectural education digital modeling has penetrated many areas of study in addition to design. One of the first was probably building technology, namely structures. Civil engineers adopted structural modeling as a primary design tool years before architects adopted CAD for production

use and later, 3D modeling. Early structural modeling programs such as STRUDL and SAP were introduced in engineering schools in the eighties. The early versions of these applications were not visually oriented. They were primarily programmable calculators designed to solve simultaneous equations in matrix format in order to determine member forces and stresses in a loaded structure. Hence the input and output was numerical. Using the method of finite element analysis enabled engineers to analyze even more complex structures such as shells, warped surfaces, stressed skins and membranes.

With the advent of the graphic user interface and the development of improved vector imaging, the presentation of structural behavior and performance in graphic form (as opposed to lists of coordinates and computed numerical values) gave designers a tool with which to visualize the effects of load and stress on a structural framework. This new ability to demonstrate behavior (e.g. the representation of deflected members) was recognized by educators as a potentially powerful teaching tool. A significant article published in the architectural journal JAE in 1994 described a new approach in structural education that employed digital modeling for observing structural behavior (Black and Duff, 1994). In the article the authors outlined an approach for teaching structures in architecture that incorporated digital modeling and finite element analysis. Their methodology was based on twelve tenets that ranged from defining the scope of engineering content appropriate for the education of architects to reaffirming the use of labs in teaching structures. Fundamental to their approach, however, was an integrated studio-based curriculum that incorporated both digital performance and physical form models in exploring structural concepts, and verifying structural behavior.

This methodology went against conventional wisdom that had more or less excluded the use of advanced structural modeling in architectural education on the assumption that architecture students did not have the structural background or knowledge to be able to correctly model structures (input) or comprehend the results of the analysis (output). Those opposed to using the computer saw it, as a "black box" that would provide numbers and 'results' that could not be verified by the non-professional.

Digital computer analysis can and should be supplemented by other methods of evaluating structural behavior, such as by approximate hand calculation or physical modeling. A good structural designer will know before performing a detailed computer analysis what the outcome is likely to be. By analogy, one might say that the computer is more like a device that sharpens one's eyesight as opposed to enabling a totally blind person to see. An informed intuition for structure should always accompany the precision of a digital analysis. It is also essential to see the computer not simply as a tool for making analysis easier (or possible, as in the case of indeterminate

structures) but rather as a new instrument for discovery. The example of Galileo using the first telescope not simply as an aid to navigation but as a tool for planetary discovery is quoted by Black and Duff (1994). In this sense the computer might be used as a device to reveal new information and thus encourage the exploration of structure in new ways. For the computer does possess enormous potential to enhance our understanding of the behavior of both simple and complex structural systems.

2. Types of Digital Models: Form, Behavior, and Performance

In design education, three forms of structural modeling can be identified. First, computer modeling in architecture can be used to evaluate and study the *form* of structure. An architect requires visual representations; both representative and abstract, in order to make decisions about the formal characteristics of a building structure, especially where the skeleton of a building is revealed and tectonics play a more significant role. This is a more qualitative aspect of the design process and computer modeling has introduced many sophisticated techniques that enable designers to visualize form more easily and see the implications of structure on other aspects of the building design.

Second, the computer can be used as a tool for revealing the structural *behavior* of systems, subsystems or individual elements. In this role a digital structural model is especially useful as a teaching tool to explain concepts and foster an understanding of the basic structural principles. The graphic display capabilities of today's modeling programs (with both static and animated representation) provide many options for depicting the behavior of structures under loading and thereby providing a visualization of the otherwise unseen structural response.

A third use of modeling is for the verification of design proposals. Most often the term structural modeling refers to the use of structural analysis software to predict the effects of load on elements of a building structure so that member types and sectional properties can be determined. In this role the computer is used to test the *performance* of a structure by calculating the structural model's response to applied loads. This is a quantitative analysis and is the traditional function of computing that the engineer employs to size members, predict deformations, and check overall stability.

In the text that follows each of these applications is described and illustrated with studio exercises that demonstrate various approaches in using modeling software to understand, evaluate, and employ structures in building design.

3. Visualizing Structural Behavior

Architecture students traditionally encounter difficulty with aspects of structure that involve the calculation of forces and mathematical modeling. In particular, the construction of internal shear and bending moment diagrams is an especially abstract exercise for non-engineering students. Yet the insight that can be gained from these graph representations of structural member forces makes them an invaluable aid to understanding structural behavior.

The introduction of computer analysis has simplified the process for architecture students. Digital structural models that can be 'tested' are easy to create using current software. Once the basic parameters of a structural model (joint type, reaction type, member section, load representation and placement, and overall geometrical configuration) are known, it is a straightforward process to model and test a structure using any of the new graphically oriented structural applications. Using a program such as *MultiFrame*® for example, a basic truss can be modeled in minutes and, with loads identified and placed, an analysis will instantly produce performance measurements in the form of member forces/stresses, reactions, and accurate deflection profiles indicating the predicted movement of the structure in an exaggerated, and thus, visually enhanced plot. If desired, these shear and moment diagrams can be displayed for any member in the structure. Varying a single parameter (eliminating half the loads, for example) will produce new results that can be compared to the first and so on, leading to insights into the behavior of the structure and the potential for improvement. The model is interactive and the designer can test any number of assumptions about the geometry of the truss, the effect of pin versus rigid joints, the efficiency of the member sections, or the effect of alternative materials.

The interactive nature in using structural analysis software in this way offers many interesting pedagogical applications. Black and Duff (1994) have introduced a series of exercises in structural behavior that is reminiscent of *reverse engineering*. In a lab class, Black provides his students with a partial analysis of a simple structure in the form of load, shear, moment and deflected shape diagrams. From this output information students are asked to work backwards to 'discover' the configuration and support conditions of the original (and unknown) structure. (Figure 1) It is a challenging puzzle that induces students to consider the relationships between load, shear, moment, member deflection, and the types of connections or supports involved. The computer model can quickly test hypotheses in an informed trial and error process. The author has also used the exercise with excellent results.

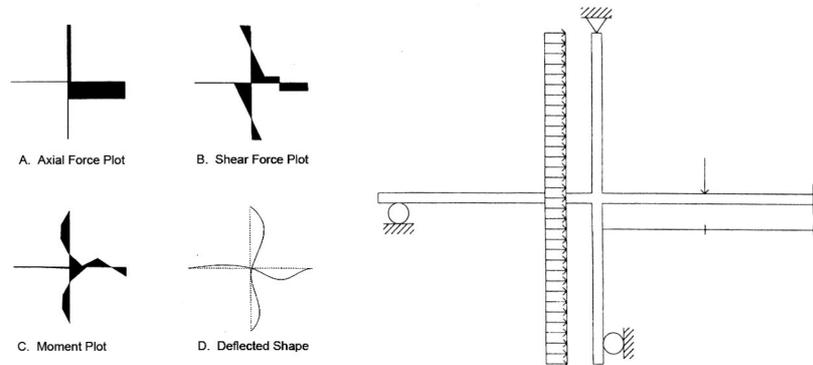


Figure 1. Example of a “reverse engineering” exercise. (Black and Duff, 1994)

For some structural behavior investigations an ordinary CAD drawing program is all that is needed. Take for example graphic statics. This is a vector drawing analysis technique developed in the 19th century to predict the behavior of many types of structures including trusses, arches, frames and beams. It was devised with the drafting table in mind. However, since the method only requires the accurate positioning of vector lines, any application that enables line drawing can be used to construct a graphical analysis of a proposed member such as an arch. The analysis will reveal the magnitude and direction of forces in the structure and lead to its design. This process can also be inverted into what Edward Allen, a leading proponent of graphic statics refers to as 'form finding' (Allen, E. and Zalewski, W., 1998). On the computer, a graphic analysis diagram can be easily modified to account for changes in loading and geometry.

A way to make the above interactions even more dramatic as a visualization is to employ some form of animation. Using *Flash* for example, the effect of force on a structural form can be made into an animated clip enabling the displacement of the structure to be viewed as a continuous motion. This can be very helpful in describing lateral force effects such as those due to wind or seismic loading. Using *Java* programming language, interactive programs known as 'applets' can be created to produce interactive loading diagrams (Luebkehan, C.H., 1996). In 'Pencil Tower Loading' a multi-story tower is illustrated with wind forces acting on one side. Shear, moment and deflection diagrams are shown alongside the tower. There are three 'controls' that the user can interact with: building height, building width, and wind load. Increasing or decreasing the

magnitude of either of these controls instantaneously modifies the diagrams giving a visual and numerical measurement of the behavior of the tower.

4. Visualizing Structural Form

Computer modeling can be used to create a detailed, realistic image of a proposed design. This type of rendered 3D image has advanced to the point that one can barely tell the difference between the real and the imagined project. Walk-throughs enable a designer (or client) to experience views of an un-built work and decide if further improvement or change is needed before construction begins. These forms of rendered 3D models can be used to illustrate aspects of structure for the purpose of studying the relationship of scale, detailing, material selection and many other structural characteristics in relation to space, lighting, building envelope, and other systems.

In studying the formal relationships of buildings: abstract, diagrammatic views are helpful in visualizing the principle formal characteristics of architecture. A building case study analysis will generally attempt to deconstruct the finished project in order to discover important structural relationships that may be obscured by the complexity of the totality of the work. The pattern of the structural supports and framing, the alignment or placement of structure in relation to the spaces of the building, and the relationship of the building's exterior envelope and the structure are revealed more clearly in an edited image. For this kind of analysis the computer is a powerful tool. Two common features of most 3D modeling software that are especially useful for depicting hidden relationships are *layers* and *transparency*.

The concept of layers is fundamental to CAD software and needs little explanation. Different types of information are grouped and drawn in a layer, which can be turned on or off. This enables a designer to examine various systems of a building in isolation or in relationship to any other system or group of elements. In design education this can be a valuable tool for revealing the sometimes hidden formal organizations and strategies that are fundamental to the best architecture. Pattern, proportion, thematic variation, hierarchical strategies, zoning, even the concept of 'layering' can all be isolated and made more visible and comprehensible. By reducing the amount of information and eliminating unrelated and visually obstructing portions of a building, the structural design can be revealed as a form itself.

In a building with a repetitive structure it is common to study a single unit or bay. The CAD model can easily isolate a bay and focus on its primary design characteristics. In a student analysis of the Tung Chung MTR Station, a built project of Rocco Yim Associates in Hong Kong, a series of layers is used to illustrate the different components of the structure and

envelop assemblies (Figure 3). Seen in succession, the 3D images re-create the sequence of construction illustrating how the building is built. Each drawing adds the next layer of assembly: primary structural frame, curtain wall frame, glazing and skylight, and finally cladding and sheathing elements.

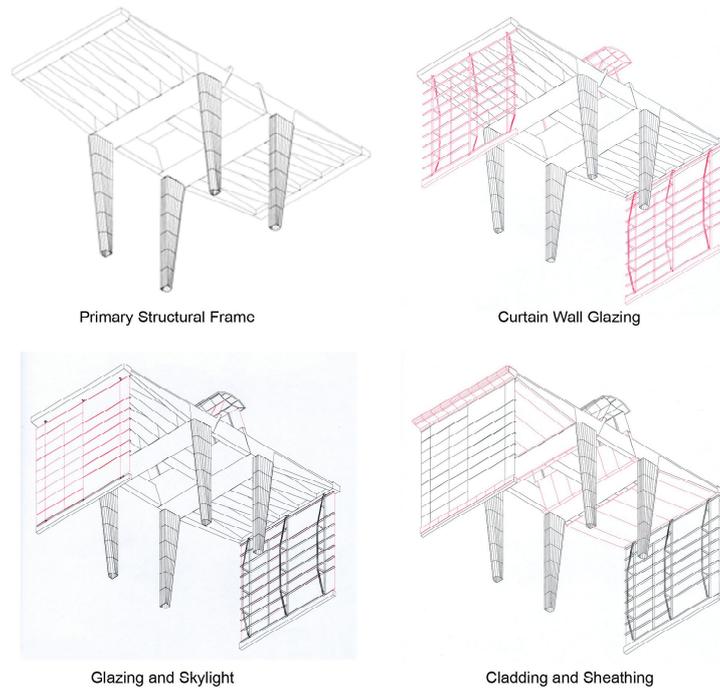


Figure 2. Analysis of a bay of the Tung Chung MTR Station. Student Project by Chiu Chun Kit and Lee Shuk Fun.

For the same case study, an investigation of the frame uses a structural analysis application (*Multiframe 2D*) to determine the effect of the position of the columns on the bending moment distribution of the frame. As the loadings used in the analysis do not attempt to reflect the actual loads that might act on the structure, the results are qualitative in nature. Nonetheless, the graphic visualizations of deflected shape and moment distribution offer insights into the behavior of the structure and its implication on the form of the double-cantilevered frame structure. (Figure 3)

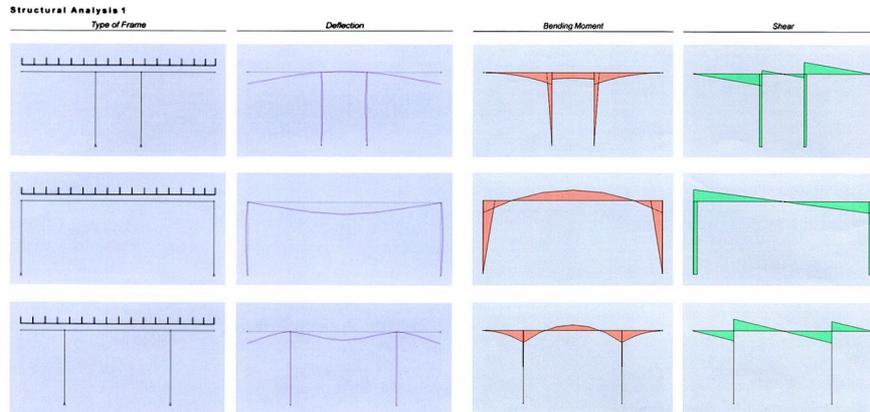


Figure 3. Structural behavior analysis of Tung Chung MTR Station. Student Project by Chiu Chun Kit and Lee Shuk Fun

A rendered model is sometimes preferable to a line image for highlighting particular features. In a case study of the Centre Pompidou in Paris, a key work of the mid-seventies, the configuration of the floor framing is accentuated with a solid model rendering. (Figure 4) The relationship of the floor framing to the long span trusses is isolated and the layers of floor construction are peeled away. The contrast of the dark floor components against the light-toned structural frame reveals clearly the hierarchy of structure. An additional advantage of the digital model is the ability to zoom in to a critical element or connection. A close-up view of the model shows the floor framing and its relationship to the principal trusses, the cast steel gerberette end supports, and the connections of the truss members. (Figure 5) Using the same model, arrows are inserted to indicate the load paths and explain the built-up, hierarchical layering of the framing system. (Figure 6)

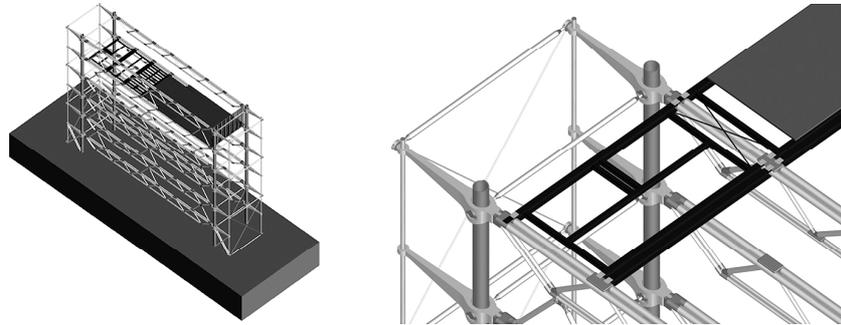


Figure 4. A structural bay and detail of Centre Pompidou by Piano and Rogers. Student case study project by Abdulilah Saad, Andaleeb Taher, Fatma Al-Sahlawi and Talal Al-Ansari

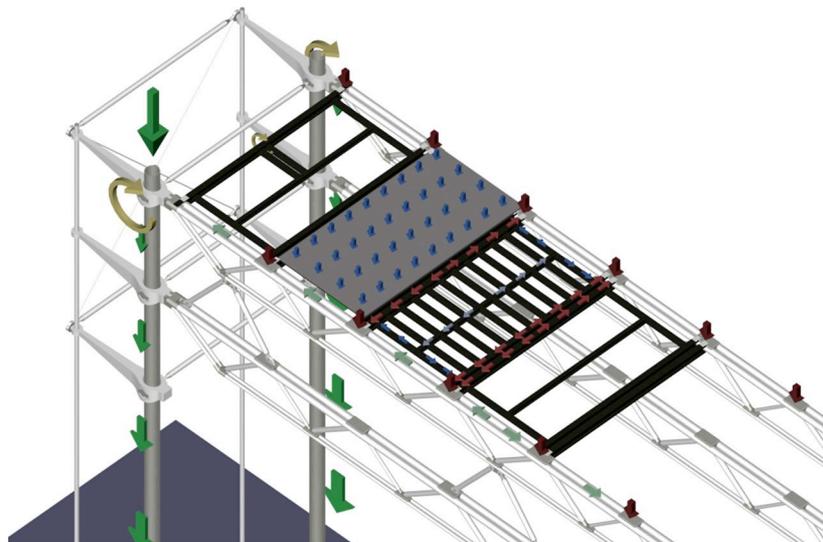


Figure 5. Load trace diagram on Centre Pompidou. Student case study project by Abdulilah Saad, Andaleeb Taher, Fatma Al-Sahlawi and Talal Al-Ansari

In a case study analysis of the Exchange House, a building designed by SOM for the Docklands Development in London, transparency is used in addition to layers to illustrate the position of the four main structural arches and the framing structure that is carried by them. The first view identifies the primary structure of the four parabolic arches enmeshed within the floor

plates of the building. The second view adds the layer of the columns, beams, and hangars that comprise the secondary orthogonal framing system. (Figure 6)

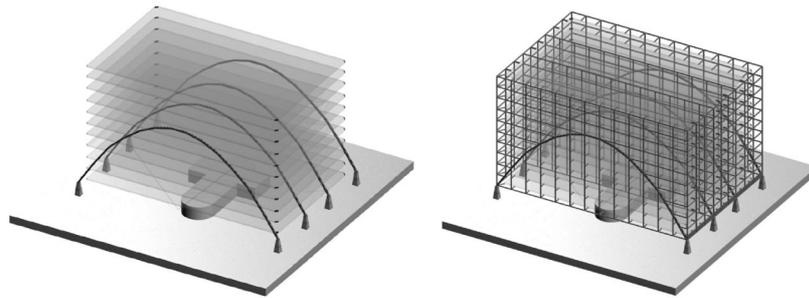


Figure 6. Two views of Exchange House, Skidmore, Owings and Merrill. Student Case Study Project by Mona Ganjineh, Leila Motahedan, Tarik Nour, and Mohamad Rushdie

5. Digital Models in Studio Design Projects

In architectural education a design project is an exercise in synthesizing form to accommodate certain functional and contextual conditions. The parameters of the project help to determine the focus of the design investigation. For example, a design exercise might focus primarily on structure and space, limiting the consideration of site, program, and other issues normally considered in a real world design project. Pedagogically this enables a design student to explore particular issues (e.g. structure and space) in depth in a relatively short time.

Wall-Plate-Frame is the name given to a series of exercises that explore three short span, structural system types and the space defining characteristics of each. In each exercise, 3D models in FormZ provide the means to create a range of analytical diagrams. One of the key features of a solid modeling program is control of the opacity (and its opposite: transparency) of the solid elements. Using this tool allows one to reverse solid and void representation in a design: interior spaces (voids) are rendered as solid masses, giving them tangible form and allowing them to be read through the structural matrix of solids. Secondary infill elements (habitable poche) can be introduced as a separate layer of solids and seen as an intermediary between primary spaces and structural solids. (Figure 7)

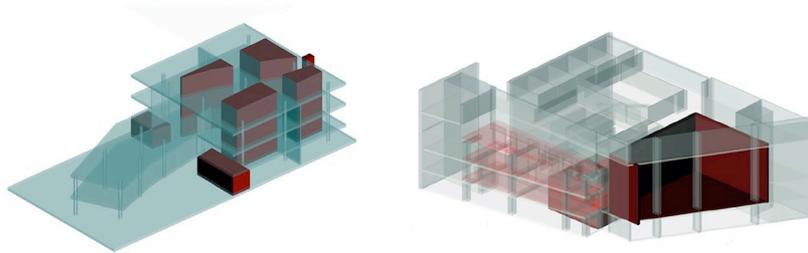


Figure 7. Two student design projects that use transparent structure to reveal the placement of non-structural solids (left) and principal spaces (right). Ahmed Al-Daqa and Waleed Hashim.

By simply switching layers on and off, the digital model can combine many different systems for comparison and study. (Figure 8)

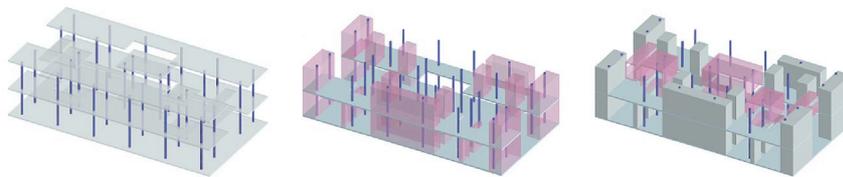


Figure 8. Three views of a Plate System Project: Structure, Structure + Infill, and Structure + Infill + Spaces. Project by Fatma Al-Sahlawi.

5. Creating Structural Form with Digital Modeling

New possibilities for creating structural form are emerging with the use of digital modeling. Although structural analysis applications are making it easier to verify performance, they are designed to aid in the synthesis of form. Created primarily to compute large structural frames with Cartesian geometries, they are less adaptable to the new wave of non-Euclidian *smooth* architectures. The structural forms that can support and provide armature for these curved and non-linear shapes are usually derived from architectural digital models whose coordinates are then imported into a structural application in which a finite element mesh is created to analysis the structure. Interestingly, the software most often used to model these forms is borrowed from related fields such as industrial design.

Product designers of objects ranging from toothbrushes to jet airliners have had to grapple with smooth, curved shapes whether because of ergonomics, physics, or just plain style. Their embrace of 3D modeling software preceded that of architects out of necessity. But now, as the current trend towards non-rectilinear shape grows, more architects are adopting various modeling software common to graphic artists, ship designers, and toolmakers to experiment with and to use in shaping complex form.

The role of the structural designer in this has become increasingly more challenging. Although a 3D model of an architectural form might exist, there must still be a design for the structure to accommodate the shape. That structure may be simply a three dimensional grid frame composed of linear elements whose overall shape follows the contour of the building. This describes the approach of Oosterhuis (2003), a leading designer on the forefront of what he calls an “E-motive architecture”. The genesis of the design is formally driven and the designer is confident that a suitable structural assembly can be devised.

This is not the same as an architectural form that is derived from structural invention. In that camp we would find a long line of engineer architects from the early masters like Nervi, Torroja, and Freyssinet, to present-day innovators such as Frei Otto and Calatrava. Most did not use the computer, relying instead on physical models to test performance. While the basic forms were not limited to rectilinear geometry, a mathematical relationship between shape and structural behavior was a guiding principle that might be seen as a kind of bridge between formal expression and computer analysis.

One technique that is currently being employed to define non-orthogonal shapes with a relationship to structural form is *parametric modeling*. Kolarevic (2003) explains how a parametric design is described not by its shape but rather by a set of values or parameters that can be varied in such a way as to produce complex, formally unconventional shapes. Using the example of Waterloo Station by Nicholas Grimshaw Architects, Kolarevic indicates that although parametrics are useful in generating a 3-D model of a complex building form, the success of the method requires that a well-conceived concept of structure that addresses basic tectonic issues must first be envisioned. For example, in Waterloo Station the scheme of a three-hinged trussed arch, asymmetrical about its axis, and varying in span, satisfies the site condition of a tapering rail terminal with differing height requirements from side to side. Based on this sectional concept, a parametric model could be defined to account for the incremental adjustments that would occur along the axis of the shed, resulting in 36 topologically identical trussed arches that vary from a maximum span of 48 m to a minimum of 35 m. (Figure 9)

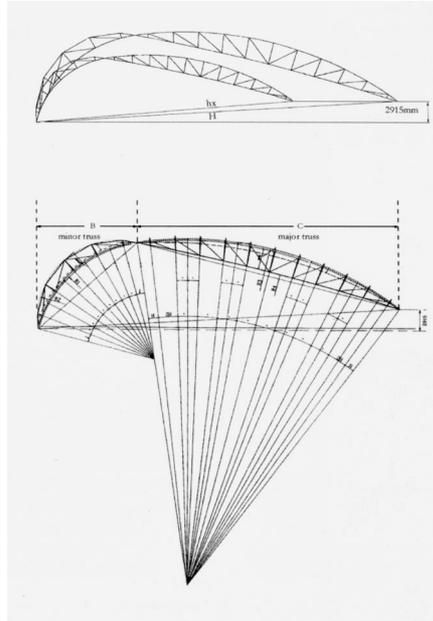


Figure 9. Waterloo Station, Nicholas Grimshaw Architects.

6. Summary

It may be obvious that applications of computer modeling in architectural education are numerous and diverse. For example, in the design of structures there are now many specialized applications that test performance through modeling and quantitative analysis. These applications are finding use in the teaching of structural behavior and in some instances, are being used in the design process. Yet the most benefit of digital modeling in architectural education today seems to be in enhanced visualization, that is, using the unique capabilities of the computer to make the manipulation of form easier and to construct new types of analytical views that reveal aspects of form (structural patterns in relation to other building systems, for example) that were previously too difficult produce. In the future CAD will play a decisive role in shifting our attitudes towards form. It will provide tools to increase our ability to create complex form and work with it in three dimensions. It should also continue to provide us with better techniques for investigating structure through the visualization of behavior and form.

References

- ALLEN, E. AND ZALEWSKI, W., 1998. *Shaping Structures: Statics*, John Wiley, New York.
- BLACK, G., AND DUFF, S., 1994. A Model for Teaching Structure: Finite Element Analysis in Architectural Education, *Journal of Architectural Education*, 48 (1): 38-55.
- KOLAREVIC, B., 2003. *Architecture in the Digital Age: Design and Manufacturing*. Spon Press, New York.
- LONNMAN, B., 2000. Structural Models in Design Education: Visualizing Form and Behavior, *Architectural Theory Review*, 5/2: 27-43.
- LUEBKEMAN, C. H., 1997. JAVA Applets: Web-based Interactive Visualization Tools to Enhance the Effectiveness of Teaching/Learning of Architectonics, *In: Architecture: Material and Imagined, Proceedings of the 85th ACSA Annual Meeting and Technology Conference*, ACSA, Washington, DC.
- OOSTERHUIS, K., 2003. *Hyperbodies: Toward an E-motive Architecture*, Birkhauser, Basel.
- PHIRI, M., 1999. *Information Technology in Construction Design*, Thomas Telford, London.