Intuition: The Missing Link Between Design and Technology Courses

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INTRODUCTION

Imagine, for a moment that a rope has been strung around a perfect sphere the diameter of the earth. The rope is just taught, just touching the surface. In this configuration, it will have a length of approximately 24,000 miles. Now imagine cutting the rope and splicing in a six foot length, so that a new rope is formed which is six feet longer than the original. How far does the new rope move away from the earth's surface? Guess. Just use your intuition. Does it move a millionth of an inch, a thousandth of an inch, a hundredth of an inch, one inch, a foot, two feet? Before continuing, close your eyes and imagine the answer for yourself.

If you are like most people with whom I have performed this thought experiment your guess will lie somewhere between a millionth of an inch and a thousandth of an inch. The correct answer, however, is approximately one foot. Next, imagine a disk the size of a U.S. twenty five cent piece. Once again a rope or string has been drawn taught to the circumference and once again I would like you to imagine splicing in a six foot length of string. Similarly, I would ask you to guess how far you think the new string will move away from its original position in touch with the edge of the disk. Again the answer is the same...about a foot.

The reason is - as I splice the circumference of one circle into another (a six foot length of rope corresponds to a circle with a diameter of about 2 feet), the new diameter will be the direct summation of the original ones. Therefore, if I splice a six foot length of rope into ANY circle, the new resulting circle will be two feet in diameter larger than it was originally.[1]

This is not the point of the thought experiment, however. The important lesson is this. There is a particular way of understanding circles -- a way which transcends the simple equation that relates circumference to diameter, (but which is consistent with it) which allows a person to visualize the act of splicing in a length of circumference and permits them to accurately predict the new diameter. They can successfully formulate an answer within the twinkling of an eye without lengthy calculation. If we didn't know the "trick" ourselves, and if we observed someone performing this experiment and witnessed them coming up with the correct answer over and over again, we might say the person possessed an "intuitive" understanding of circles, one which somehow allows them to "see" or to "feel" the correct answer without performing an analysis. Moreover, by intuition, we would not mean some weak blind feeling, but rather a highly developed sense which is right every time.

THE IMPORTANCE OF INTUITION

Intuition is a fundamental ingredient in the practice of architecture and is relied on over and over again in the act of designing. The building should be sited just so because... it feels right in this position. The pool should be placed in this location because... it seems like the right place for it. The proportions of the windows and the details of the sill should be like this because... it makes sense with the rest of the building. Some of the most important decisions that are made during the design of a building are made on the basis of intuition. Furthermore, only those intuitions which are readily available to the designer are included in this process. If a designer doesn't have an intuition about a particular option, they will either reject it outright or, more typically, never even consider it. In certain cases, they will defer to a specialist and grudgingly rely on the outside expert opinion.

Architectural design studios encourage this intuitive approach. Critiques of student work is almost entirely based on a juror's own intuition about a particular matter. "I don't think the entrance really works because...my intuition tells me that it doesn't really work."

Technical subjects, on the other hand, generally depart from the intuitive approach. You never hear an instructor say that a moment diagram will look like such and such because their intuition tells them so. They never say that a particular structural system will be the most appropriate solution because intuitively speaking it makes the most sense. On the contrary, intuition appears to be barred from entering the scientific realm of technical related courses where numbers and calculations rule. One could quite correctly ask the question, why? But more significantly one could ask the question at what cost? If the architectural design process depends heavily on a designer's first-hand intuition, and if they do not posses intuition about technical matters, is it any great mystery why it is so difficult to meaningfully integrate technical concerns with design?

TOWARD AN INTUITIVE UNDERSTANDING OF STRUCTURES

Intuition is only gained through direct experience. A student will not acquire it from a lecture, and they will not develop it from reading a book. Intuition cannot be "taught" -- passed along like information. However, it is possible to set up learning situations in which students will begin to develop their structural intuition. These situations require that the student be treated more like an apprentice, where they can experiment, fail, succeed, fail, experiment... all under an umbrella of instruction that seeks to give them a *basic* set of tools which they can continue to use to gain mastery of the material.

Prior to and concurrent with my teaching career I have had the opportunity to design a number of buildings in which I took the role of architectural designer and structural engineer. In many of these projects the structure was specifically used to drive the architectural form, affording me the chance to begin formulating a design process that integrates structure and architecture, and also begin to appreciate what architects need to know about structures.

Based on these experiences, I propose that architects need to be able to do the following:

1. Conceive a structural form that is consistent with (and helpful to) the architecture and which really works as a structure.
2. Perform simple static analyses (thumb-nail calculations) which will allow them to check and evaluate their ideas.
3. Visualize the basic force flow, deformations, and overall behavior of a complex structural system.
4. Apply code requirements and accepted engineering design procedures and understand their underlying intentions.

In addition, they need to know what level of analysis is required at a given design stage, and they need to be able to access the relevant information quickly. To achieve this, the information must be accessible at the level of intuition. The architect needs to be able to "know" that the design will check out when all of the engineering calculations are completed.

To acquire such an understanding, students must perform something on the order of *hundreds* of analyses of real building structures. It is essential that they observe the structural behavior (flow of forces and deformations) of a wide range of buildings subjected to gravity, wind, and seismic forces. Further, they need to be able to interact with and manipulate the buildings' structure to see how changes effect the structural performance. Only in this way will a student begin to develop their intuition, and a sense for how some new arrangement of structure will perform. The buildings experimented with can be existing ones or products of student design work, but in all cases it is necessary that the analysis take into account the behavior of entire systems.

In order for students to comprehend and interpret a buildings' structural behavior they must be given a basic set of analytical tools. These tools should be the **minimum** necessary to get them started. Instruction should error on the side of less theoretical material rather than more. As a student's intuition becomes more developed they will begin to ask questions of a more theoretical nature -- and if the instructor can hold off answering these deeper theoretical questions until that time, the discussion will be much richer and have much more impact on a students' overall understanding than any independent lecture on structural theory.

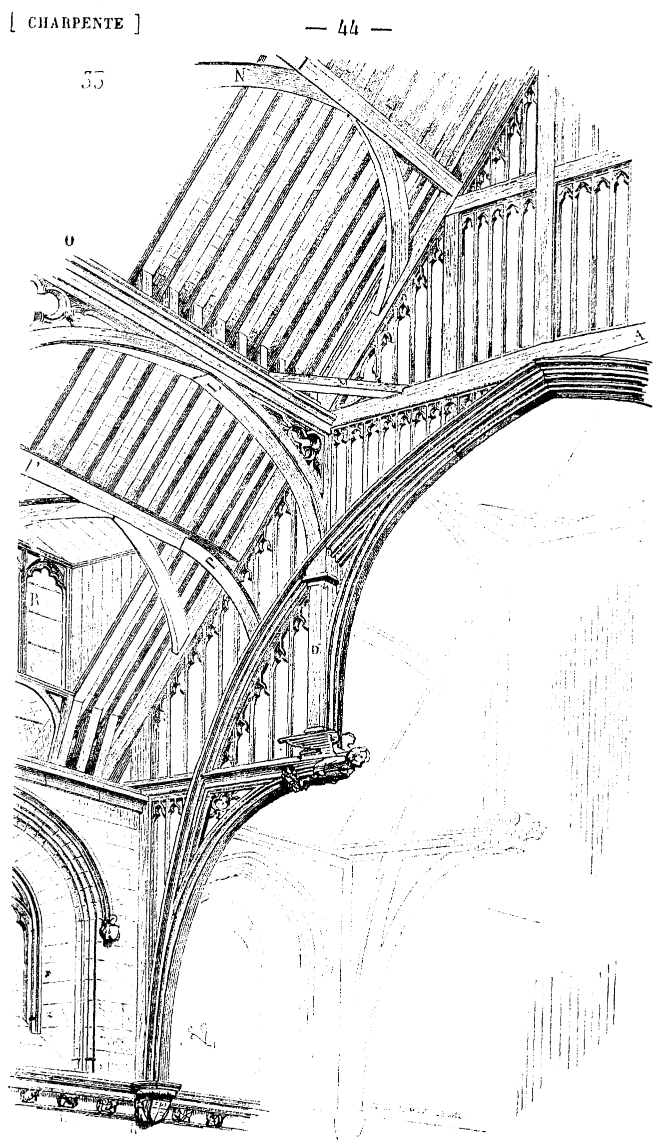

Fig. 1. Westminster Hall. Roof and truss design showing roof framing (drawing by Viollet-le-Duc, Dictionnaire raisonne, c. 1850, III).

FINITE ELEMENT ANALYSIS AS A TOOL FOR DEVELOPING STRUCTURAL INTUITION

Computer aided finite element analysis (FEA) is well suited to the task of helping a student acquire structural intuition. It allows the student to study the global and detail structural behavior of whole structural systems. It permits them to make minor or radical changes to the structure, facilitating a series of "what-if" games. For most structures, the analyses are fast, taking less than five minutes per cycle, thus permitting a student to look at ten or twenty alternatives in a single hour. Additionally, because the output is graphical a student can begin to "feel" the flow of forces and understand the relationships between force and deformation -- between deformation and force.

As an example, the following exercise is used to illustrate some of the potential of using FEA in a course of instruction. The structure shown in figure 1 is a drawing of the Westminster Hall roof framing by Viollet-le-Duc. Figure 2 depicts an elevation of the same structure -- a complex roof truss designed and built by Hugh Herland in 1395 and employing both a great arch rib and a hammer beam system. The structural behavior of this truss has been a subject of debate among architectural historians and engineers for a number of years.[2] In this exercise, students are allowed to study these drawings (and a physical model of the truss made by a previous student)[3] for a period of just five minutes. They are not permitted to make any sketches, they are only allowed to examine it visually. Then the model and drawings are put away and the students are asked to draw an elevation of the truss from memory. They are allowed five minutes to complete this task. The average submission is completely wrong, representing a very "loose" description of the overall form, but totally unworkable as a structure.

Following this, the students are put in front of a computer which contains a finite element model of the same truss.

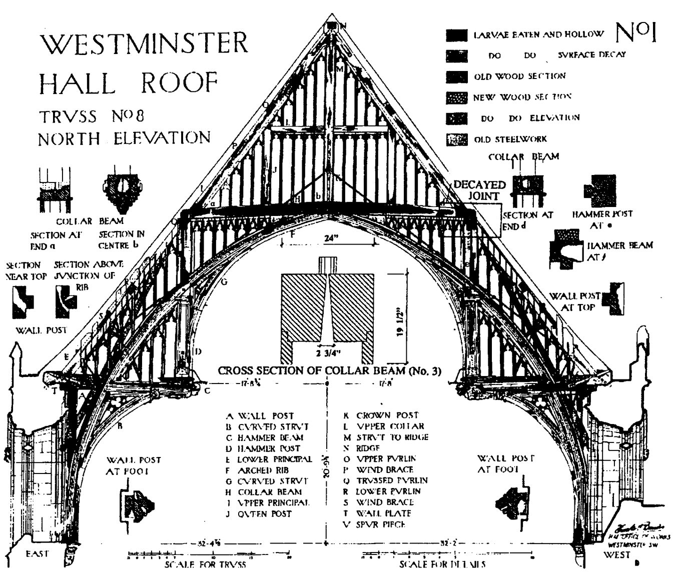

Fig. 2. Westminster Hall. Elevation of truss framing (drawing published in Baines' Report, 1914, Plate 3).

Once again, they are given just five minutes to "play" with the truss, to try to understand how it works structurally. Most students will quickly pull up graphical images of the deflected shape, the axial force diagram, and the moment diagram; knowing from experience that these descriptions of the structural behavior will give the most insights in the shortest time frame. These are shown in figures 3, 4, and 5.

After students have had a chance to experiment with the structure and have completed this step, they are once again asked to draw the truss from memory. However, this time they are told to visualize the flow of forces and the deformations of the real structure as they make the drawing. The student sketches in every case, are much improved, matching the real structural form almost perfectly.

This exercise doesn't give a student any new or particu

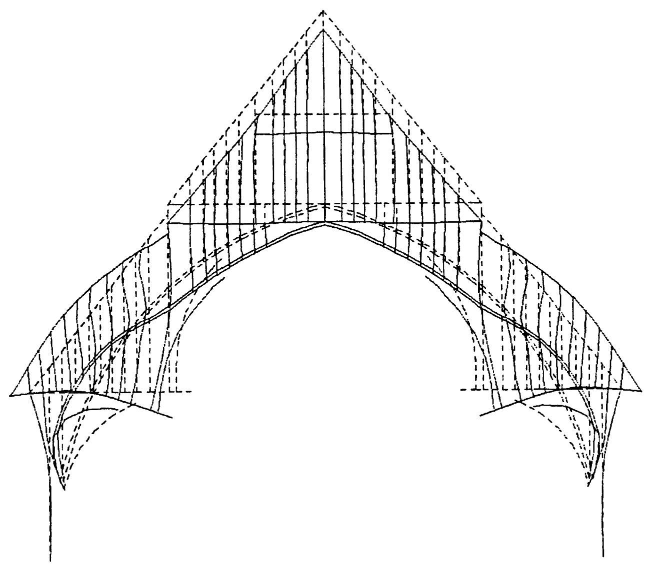

Fig. 3. Finite element output showing the deformed shape when the structure is subjected to symmetrically applied vertical loads.

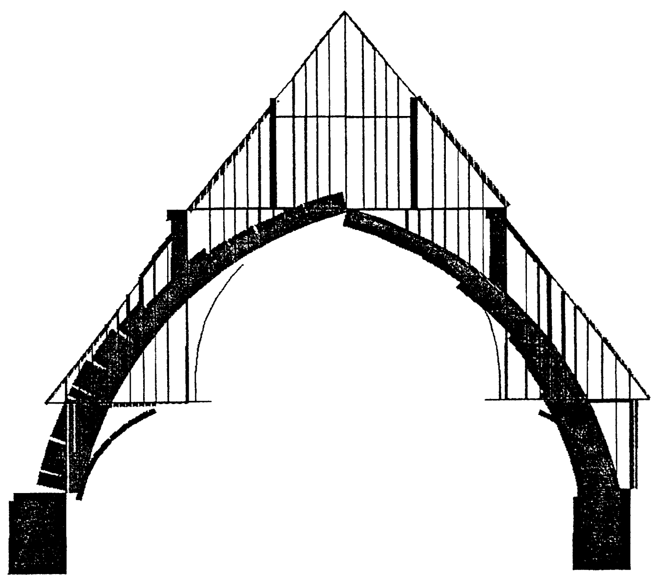

Fig. 4. Finite element output showing the internal axial forces resulting from a symmetrically applied vertical load.

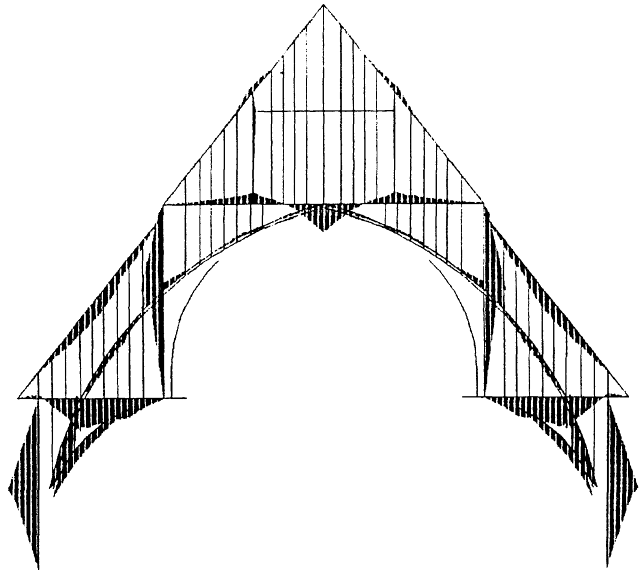

Fig. 5. Finite element output showing the internal axial forces resulting from a symetrically applied vertical load.

larly useful *information*, unless they happen to be interested in the trusses at Westminster. What it does, is begin to develop their *intuition* regarding the relationship between form and structure and the flow of forces, and it begins to develop it in a way that merely talking about it can never achieve.

Once a student becomes familiar with FEA they can use it to investigate the behavior of existing structures or use it as part of an overall integrated design process to design structures for their own projects.

CONCLUSION

Developing a students intuition with regard to structures is paramount if integrating the material in any real way with design is an issue. Faculty interested in setting up an effective learning environment which can begin to cultivate a students intuition will need to find answers to the following questions: 1) what, specifically should architecture students know about the subject, 2) how should students understand the information so that it is most useful to them when they need it, 3) what is a proper design process which will allow the material to be integrated with and influence the design instead of being tacked on at the end as the necessary stuff that holds the building up, and 4) what technologies and teaching methods will enable a student to gain an intuitive grasp of the subject.

It is the authors contention that instruction should focus on the behavior of real buildings and that much of the "theoretical" material currently taught should be abandoned in favor of a more practical approach. Additionally, instruction should seek to develop students' intuition (rather than giving them information) so that the material is readily accessible to the designer during the design process. An integrated design process, which brings structural issues to bear on design decisions, should be explicitly taught, and new technologies which can aid in the learning process, such as FEA, should be introduced at all class levels from introductory courses through to graduate design studios.

NOTES

1. I discovered this "property" of circles one evening in the fall of 1991 while helping my daughter with her high school geometry.
2. See the writings of R. Mark and L.T. Courtenay in the United States, and engineers J. Heyman and R. Mainstone in Great Britain, among others.
3. The model was built by Toby Morris as part of his work for the class, "Structure, Space, and Construction in Great Historical Buildings," given by the author, Stephen Tobriner, and Stephen Duff and which uses finite element analysis to study the performance of historical buildings and bridges.