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Breaking (A)way: The Role of Productive Failures in a New Structural Design Pedagogy

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Abstract

At its most basic level, structural design is about creating strategies for elegantly and efficiently combining a range of materials and shapes to graceful resist the different stresses created by "spanning and stacking" elements. Unfortunately, instead of focusing on the potential richness of design that can emerge from this complex array of qualitative and quantitative choices, many structural design courses rely on the traditional engineering--based teaching methods that favor abstract representations of physical behavior, calculation---based analysis, and assessments of student performance based on the accuracy of those calculations. In these courses, because learning assessment is based on a student's understanding of quantitative information, it follows that the course content itself must be filled primarily with mathematical analysis and sizing exercises. Instead of teaching a diversity of problem--solving methods aimed at developing the ability to assess and improve a structure's design and performance, right and wrong answers become the ultimate measure of understanding and "failures" are to be avoided.

Disciplines

Architecture

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AVERSITY TO FAILURE

At its most basic level, structural design is about creating strategies for elegantly and efficiently combining a range of materials and shapes to graceful resist the different stresses created by "spanning and stacking" elements. Unfortunately, instead of focusing on the potential richness of design that can emerge from this complex array of qualitative and quantitative choices, many structural design courses rely on the traditional engineering-based teaching methods that favor abstract representations of physical behavior, calculation-based analysis, and assessments of student performance based on the accuracy of those calculations. In these courses, because learning assessment is based on a student's understanding of quantitative information, it follows that the course content itself must be filled primarily with mathematical analysis and sizing exercises. Instead of teaching a diversity of problem-solving methods aimed at developing the ability to assess and improve a structure's design and performance, right and wrong answers become the ultimate measure of understanding and "failures" are to be avoided.

This is understandable to a certain extent, of course, because meeting the fundamental responsibilities of protecting the health, safety, and welfare of building occupants depends heavily on an assured and stable structure. If structural design is presented as a search answers that are either right or wrong, then students may mistakenly develop an adversity to risk and experimentation. If young architects are taught to be afraid of exploring options in structural design, lest they inadvertently "fail", they may cease to see this topic as a realm for innovation and experimentation—a habit that will leave them unprepared to deal with the inter-active and synergetic nature of critical design practice.

This paper will argue that structural design is, at its essence, a design course—it should promote the search for several right answers instead of one. In order to promote the integration of progressive and innovative structural solutions into the architectural profession, the methods of presenting, processing, and integrating this information to architectural students must be done using a more effective pedagogical model, one that actively promotes the productive value of learning by through failure and reiteration.

PEDAGOGICAL COMPLEXITIES

The challenges of teaching structural design are relatively unique in an architectural curriculum. At its heart, it is still a design course focused on problem solving, but it relies upon detailed knowledge of math, physics, material science, and construction methodologies to assess the behavior and effectiveness of the different formal strategies suggested. Effectively presenting both factual and abstract ideas alongside their qualitative and quantitative assessment strategies is extremely difficult because this information is usually processed with two different and divergent learning methods by students: the sensing/active factually-based problem solvers on one hand, and the intuitive/reflective learners that try to find fundamental understanding through abstract concepts. Teaching approaches differ as well. Most math and science courses are usually taught deductively (going from fundamentals to application), but the opposite approach, induction, is much better suited to promote the types of inquiries and discoveries needed in the problem-based design curricula of architecture. The ultimate challenge is that students and teachers both have preferences for presenting and receiving information and when their preferences aren't met, the effectiveness of comprehension is diminished and motivation for learning is dramatically reduced[1].

Adding to this difficulty is the relatively abstract nature of the terminology and diagrams associated with its traditional manner of instruction. Mathematical diagrams and two-dimensional representations are poor methods for promoting visualization skills of complex structural behavior. The capacity to imagine the consequences of structural behavior in complex systems without any conscious perceptible experience is extremely difficult—if one can't "see" what's going to happen in a structural system, it's more difficult to imagine an apt design response. Therefore, one of the central challenges that needs to be maintained throughout a new structural design pedagogy, is how to impart knowledge about these structural behaviors in a manner that enhances the capacity to visualize the potential behavior.

One solution to promote visualization is to engage students in haptic augmented simulations to enhance their conceptual learning by using physical activity as a "cognitive anchor to comprehend abstract concepts in learning situations."[2] Integrating physical exercises enhances the relationship between the body and the physical world, in an attempt to develop embodied cognition, which studies have shown help students to better visualize abstract behaviors based on their perceptual experiences.[3] Embodied cognition can also be enhanced if failures are intentionally introduced into the learning methodology. Simply put, one of the answers for increasing the efficacy of learning and design aptitude of students was to encourage the making and breaking of structures.

RESTRUCTURING STRUCTURES

When the opportunity presented itself two years ago to modify the undergraduate structural sequence at Iowa State University, all aspects of the course were modified: the type of learning environments, course content, and teaching methodologies to better address these inherent challenges. The resulting sequential multi-semester course module, titled Structural Technology in Practice (STP), combines a studio-like lab and lecture class format, integrates haptic learning methodologies with project-based design exercises, and expects multi-modal representations of learning including the integration of learning from their failures.

The "lecture-lab" class environment provides an opportunity to have both active and passive learning portions of the class and a diversity of activities and representations of learning to occur. The first portion of the class is a lecture that presents the information that students need to solve a set of design "problems" for the lab portion of the class that immediately follows. They are encouraged to solve the design problems through a range of strategies, but often times this involves the construction and testing of a structural prototype (Figure 1). The structural performance of the design is evaluated in student-created laboratory reports that include descriptions of their designs alongside technical diagrams, calculations (when possible), and a summary of "lessons learned" about the topic—obviously this approach helps balance the sensing and intuitive learning styles and promotes a multimodal means of representation[4].

Figure 1: Students describing anticipated structural behavior before testing.

Processing abstract information while physically manipulating objects is a proven method for enhancing comprehension, so throughout the entire STP sequence, the use of haptic learning techniques, including the first hand participation in testing their creations to the point of failure, has been a matter of central pedagogical importance in both theory and practice.[5] In nearly every lab, students have built, tested, bent, and often broken their structures in an attempt to better understand the inherent physical behaviors of how the structures work. Choosing what to make, and how to break, became a central pedagogical concern.

LEARNING FROM FAILURES

Failures can occur, and be perceived, on many different levels of scale and performance. We are surrounded by designed objects and spaces and consciously or not, are constantly engaged in a system of testing, evaluating, and recording the results of our tests. Does this object or space do what it is supposed to do? How does the form, material, scale or ergonomics relate to its effectiveness? We catalog the results of these tests in our mind and eventually start to develop a hypothesis about how we would expect certain things to work and develop a capacity to visualize potential failures before they occur. Simply by means of intuitive life experiences, certain failures can be anticipated. (e.g., the chair seems too low, the object seems to be too sharp to touch, the log seems too thin to support my weight). In these cases, the failures have a sense of clarity because they seem to immediately suggest a set of improvements that could be made.

This skill is one that is developed either actively by physically causing and experiencing the failure oneself, or passively, by learning from a failures of others. Certain experiences can immediately embed a cognitive lesson, such as touching a hot pan, while others require multiple trials and interactions (e.g., repeatedly touching the pan over time to determine how long it needs to cool) in order to determine a set of anticipated behaviors. Because this is a learned skill of perception, it logically follows that there is a great opportunity to improve learning, retention, and conception of structural performance by intentionally integrating failures into a structural pedagogy.

These intuitive learning opportunities were already embedded in the course's design with the incorporation of haptic learning methods, but it was understood that not all types of failures would be particularly instructive. For instance, a two-legged chair falling over or a ten-pound weight falling through a piece of paper doesn't significantly add to one's basic intuitive understanding of basic physical behavior. Interestingly, we quickly realize that it is the *failures* we encounter, particularly in circumstances that where we didn't initially suspect failure to occur become more memorable because they reveal more.[6] It is the failures that occur in situations that are relatively unexpected (seeing a four-legged chair fall over) can become the most useful learning opportunities (Figure 2).

Figure 2: A cardboard platform structure suddenly fails under loading. The student standing in the center of the span, at the point of collapse, clearly understands the relationship between load location and structural span.

METHODOLOGICAL LIMITS

Most building failures still regularly occur throughout the profession and the highest percentage of failures are directly attributable to errors in judgment and deficient knowledge of the design team[7]. Because of this, it is important to state that a methodology of making and breaking structures is ultimately only parts of a larger set of teaching tools that are needed to develop a greater level of knowledge (including the more traditional diagrams, calculations, and readings that are incorporated throughout the sequence).

Additionally, there are certain practical limits on the effectiveness of this methodology and the potential extent of possible integration.

First, there were obvious circumstances of scale, cost, complexity, and time would severely limit our ability to prototype and test all structural topics. It was understood and explained to students that there were limits to the methodology. For instance, building a truss out of wood sticks and testing it would certainly be able to reveal certain information about truss behavior, but actual steel trusses might behave profoundly different under similar loading conditions. The second main limitation was related to the gap of knowledge about structural behaviors that inherently limited the usefulness of the testing—at times students simply don't know enough about the structural topic to be able to build an accurate enough representation to make the failure test useful.

However, the first lab in the sequence, The Anthropomorphic Body Structure seemed to not only assuage these concerns but it pointed to the profound benefits that could be gained by this approach.

STRUCTURALLY SUPPORTING STUDENTS

In this lab, students use their bodies to create different structures, one that reached out and one that reached up, in order to explore the basic structural principles related to the relationship between form and forces. The learning objective was to help students conceptually connect abstract terminology of structural behavior (e.g., forces, loads, stresses, and states of equilibrium) with the various physical actions undertaken in each scenario—it wasn't intended to have the students create "structural failures" with their bodies, but as the lab progressed and the students reached higher and farther, it became an inevitable, and productive central lesson (Figure 3).

By being able to successfully complete these modest challenges initially, students realized that they *already* understood some aspects of structural behavior and that they regularly create effective, responsive, structural forms, even subconsciously in their daily routines. As a lesson, this wasn't enough for some students. In a fascinating example of how students teach the teacher, many students found the process of simply standing, reaching, and holding objects is so common place and uninformative that without prompting, they began to create structural scenarios that pushed the physical limits of their bodies and in some cases resulted in a modest types of failure (e.g., losing their grip, having to "fall out" of a pose, etc.).

Students discovered that their body structures failed in a relatively predictable range of ways. Some student structures failed because they couldn't develop a state of equilibrium (they would either fall over if they reached to far or didn't have a wide stance to support a load). Others failed eventually due to a feeling of fatigue caused by having too much stress in the system (typically the groups that built human pyramid-like towers or held a weight out a shoulder length for a certain period of time), or failures that occurred at the point of "connection" (typically when their structural form generated too much tension stress to maintain a grip between team members).

Figure 3: A pose demonstrating translational and rotational structural equilibrium. The structural form was developed intuitively by the students and it eventually failed due to stress at the connection of hands.

As a result of this lab, it was understood that constructing and testing structural prototypes in order to see what failures occurred would be particularly useful in a structural pedagogy for nearly all subsequent labs. Not only did these failures present an opportunity for students to visualize behaviors and stresses that are traditionally "hidden" by the static nature of internal load resistance in structural systems, but the students seemed to embrace the methodology with an enthusiasm.

UNEXPECTED LESSONS

I hear and I forget; I see and I remember; I do and I understand. –Confucius

One of the interesting paradoxes is that successful design strives to understand how/why something fails in order to reveal strategies for its improvement—but the causes are not always obvious and we often ironically fail to discern the proper lessons. Rarely does a part simply break in two. More often the causes are obscured by the interconnected set of variables inherent in the process of design and construction.[8]

Because of this paradox, as the sequence progressed to more complex structural systems, the lessons created by making and breaking their models varied in their efficacy.

Certain initial labs that dealt with stability in frames could very clearly demonstrate compliance or failure. In these labs, students built a series of increasingly complex three-dimensional representations of pinned frames and were asked to stabilize the structure using a variety of bracing methods (moment connections, shear walls, cross bracing, etc.). But the interesting lesson from these labs was that the students didn't need to be told IF it failed, they often were able to discern that themselves simply with the touch of a finger, as much as they needed to be told how to fix the failure that was occurring.

Other labs very clearly demonstrate the types of internal behaviors presented to students in lectures but reveal other lessons that may not have been as obvious. For instance, in the Beam Bending Lab students quickly understand the importance of not only beam depth, but the cross-sectional distribution of area in resisting loads. The interesting beam failures occur when students build overly deep beams with large amounts of area at the flanges but forget to stiffen the web—obviously under a particular amount of loading these beams experience web buckling. This is an important lesson certainly, but a lesson that is difficult to impart using only words and diagrams.[9]

Certain labs reveal important lessons about the various behaviors and relative efficiencies of different materials and their manner of construction. During the Slab Lab students are asked to construct a variety of slabs (both one-way and two-way) using paper, cardboard, and plaster. These slabs are ostensibly to be analyzed by comparing the weight of the structure to the weight of the load capacity, but the nature of the material itself and the relative limits on its construction usually becomes the cause of the failures and discussion. Inevitably certain groups aren't able to test their cast model because it breaks during the construction process—they explain that they are disappointed because making the plaster model was very messy, expensive, and the form-work was time consuming (all important lessons on the limits of casting structures) (Figure 4).

Figure 4: An unreinforced slab predictably shatters under loading.

Interestingly, one particular lab, the Thin Shell Shelter, was designed specifically with profound construction and structural behavioral challenges as a way of trying to provoke a series of useful failures but ended up being memorable for the lack of failures it produced (Figure 5). The lab asked students to cover a series of internal volumes with thin shell structures made using Heinz Isler's hanging fabric design methodology in which they coated the fabric with a viscous material that would eventually harden, and then flipped the structures over to become fully compressive shells. There were certain complications with the construction methods for some students, but for the most part, the structures not only were able to be constructed accurately, they performed so well structurally that their bearing capacities far exceeded the testing requirements.

Figure 5: Testing of lightweight thin shell structures. This structure carries a load more than 100 times its dead load weight.

Figure 6: The box truss failure developed gradually under loading and failed progressively to the point of eventual collapse.

One of the more useful results of the methodology is when a very specific type of internal behavior in a structural component because obvious to a student during testing. As an example, in the cumulative module of the sequence, students were asked to construct wood trusses that spanned four feet and held fifty pounds (a daunting challenge). In one particular case, a group built a relatively stout box framed truss system that included an intentional amount of structural redundancy in the number and size of members. Under the loading conditions, certain diagonal truss components began to bow outward under the stress—these were identified by the students as compressive members that were trying to resist buckling. Eventually when these members failed under additional loading, new components (the redundant members) began to buckle and the failure of the system was prolonged. This demonstration of a slowly progressive failure served as a great example not only of the value of this teaching methodology, but also of its relative efficacy across the sequence. In their lab report, the students called it, "a spectacular failure!" (Figure 6).

REPRESENTING AND RECOGNIZING FAILURES

"The horror of that moment," the King went on, "I shall never, never forget."
"You will though," the Queen said, "if you don't make a memorandum of it."—Lewis Carroll, Through the Looking Glass, 1871

As the sequence progressed to more complex structural systems and behaviors students no longer needed to be encouraged to embrace the importance of learning from their failures. Instead the challenge was getting them to record and accurately analyze the manner of failure that occurred. Learning from one's failures is, in fact, a common struggle. Typically the results of our daily perceptual tests of our environment go unrecorded and unless the type of failure observed or experienced was quite memorable, the exact circumstances of the cause and the appropriate lessons to learn from the failure are hard to discern retroactively. Further, unless there is a common range of words and symbols used to record and analyze the failure, effectively communicating the nature of these failures to others is marginalized.

This challenge was a great opportunity to introduce the usefulness of the relatively abstract range of terms and diagrams typically associated with traditional structural coursework. In more advanced structural design lessons, there comes a time when the calculations and diagrams that describe structural behavior must be understood qualitatively and quantitatively. The conventional representations and terminologies are actually quite useful as they describe a series of inter-related, tested, and measured variables that allow for experienced and knowledgeable designers to quickly assess the pros and cons of their design choices. Developing the capacity to have students engage in this level of co-variant reasoning cannot happen unless students feel equipped to understand the concepts behind the formulas and have had experiencing developing their own versions of these types of representations.

Initially this required their understanding of the basic terms that describe structural behavior (strength, stiffness, stability, serviceability, and shape) and how these terms could be utilized to describe the nature of the failure that had occurred. Using photographs from their labs, students often create force vector free-body diagrams to describe certain failures, show problems of equilibrium in loading diagrams, or represent failures by comparing a series of photos in sequence to demonstrate a change in behavior or deformation.

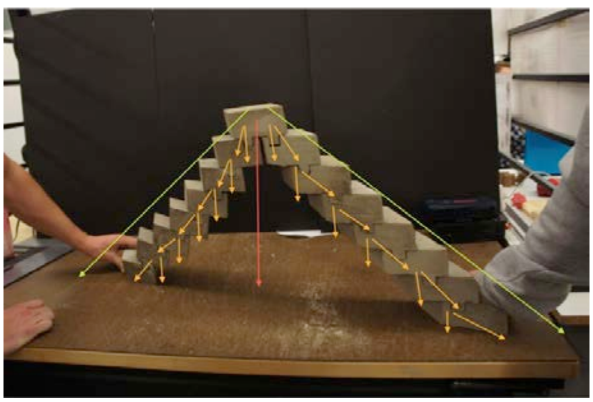

Figure 7: A skew arch created from modular pieces. The lab report included information about how the construction process of forming the components was related to the overall transfer of forces. Failure eventually occurred at the connection between pieces.

An important way of institutionalizing this requirement to observe and record their behaviors took the form of lab reports. These structural lab reports are required to address the key learning objectives and questions put forth in the lab handout, and nearly always include: descriptions and representations of the group's hypothesis (including early sketches), testing process (including weights and measures as needed), test results (mode of failure), a comparative analysis of results, and a conclusion of what was learned. These early lab reports are relatively open-ended in terms of the type of representations that are required. This flexibility gives students the leeway to experiment with different ways of best representing what they learned. However, there are certain requirements about representational styles that help introduce students to more conventional structural design graphic standards.

SUMMARY LESSONS:

Structural design courses should be taught to architects in a manner that helps them to develop an intuitive understanding about the relationship between forces, structural behavior, and the array of potentially responsive architectural forms. Breaking away from this traditional pedagogical approach requires certain important modifications to the traditional classroom settings and teaching methodologies. Creating interactive learning environments allows students to develop a range of problem-solving strategies and representational techniques. These changes increase their conceptual understanding, retention and enthusiasm for the topic.

The intentional inclusion of activities that promote the value of learning through failure and reiteration are central to this methodology. Accepting certain types of failures as a central and desired component of a structural design teaching methodology may seem counter-intuitive, but this promotes an interactive, design-based attitude towards structural design that encourages promote the integration of progressive and innovative structural solutions into the architectural profession. Embracing the design potential that can emerge from a staggering array of qualitative and quantitative choices involved in structural design takes a certain level of expertise and experience—skills that are honed from a well-practiced capacity to learn productively from failures.

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