Empirical Exercise in Structural Design: 
Force, Form, Material and Connection 

Christopher D. Trumble 
School of Architecture, University of Arizona,  
1040 North Olive Road, Tucson, AZ 85721, US  
E-mail: ctrumble@u.arizona.edu

This article presents an educational exercise designed for architecture students to study static structural behavior and develop an understanding necessary and appropriate for their role in structural design. The exercise examines structure about the conceptual criteria of force, form, material and connection. The symbiotic relationships between these criteria serve as a means to explore, evaluate and understand the various components of structural design. The exercise employs an empirical methodology, the most ancient form of structural analysis, as it requires students to conceive of a structural design in response to specific conditions, develop drawings that examine the criteria of force, form, material and connection, fabricate, physically test and reflect upon its performance. This sequence is repeated three times and the stages are ordered about the objectives of concept, specificity and efficiency. The conditions are abstract, specific and require the resolution of two linear concentrated loads evenly spaced over a three-foot span.  

Keywords: education, empiricism, pedagogy, laboratory, structural behavior, structural design.

1 Context and Premise

Architects are charged with the responsibility of conceiving, developing and delivering building designs. This process involves many seemingly divergent conditions, interests, and specialties rendering the effective role of the architect as chief coordinator and collaborator with entities ranging from owners and engineers to contractors. To effectively perform in this capacity architects must have an understanding, knowledge and abilities related to each respective ingredient. 

Structural design in architecture can be considered the process and product resulting from the collaboration of architect and structural engineer. In partnership they work to develop building designs that are not just structurally feasible but that satisfy the objectives of safety, economy, integration and expression. 

The conceptual design of structures is the common ground between architects and structural engineers. The architect conceptualizes through a lens of integration and human experience. The structural engineer conceptualizes through a lens of qualitative and quantitative structural performance. 

Traditional structures curricula for architecture students employ lectures, reading and computational exercises to cultivate a knowledge and understanding of structural theory and methods of analysis; on occasion a peripheral laboratory project is employed for the purposes of didactic demonstration, verification and the brief opportunity for abstract application. 

The pedagogical strategy of the exercise presented in this article inverts the proportional importance of the modes of learning by centralizing the laboratory project and thereby elevating it to the primary learning vehicle. Lectures and computational exercises in turn serve in a supporting and complimentary capacity.
Entitled force, form, material and connection (ffmc), the exercise presented in this article is an introductory exercise in a series of empirical laboratory exercises that constitute the architectural structures curriculum of the School of Architecture at the University of Arizona. It is designed for undergraduate students in the first year of the professional phase of the Bachelor of Architecture degree program. The exercise is intended to cultivate an introductory yet comprehensive understanding and knowledge of static structural principles, behavior, systems and components. It is also intended to cultivate a qualitative approach to conceptual and technical structural design, under the premise that structural engineering is not simply an applied science (Billington 1985) but inherently creative and able to be qualitatively incorporated into architectural design.

2 Pedagogy

The pedagogy of this exercise is comprised of five fundamental propositions related to: empiricism, deliberate practice, collaborative learning, scale and evaluation.

2.1 Empirical learning

Empiricism is “the view that all concepts originate in experience, that all concepts are about or applicable to things that can be experienced, or that all rationally acceptable beliefs or propositions are justifiable or knowable only through experience” (Fumerton, Quinton 2010). Comprehensive sensory experience cultivates an understanding and knowledge that is more genuine, profound and enduring than didactic abstract methods. The ffmc exercise is empirical in nature; it requires students to experience a comprehensive structural design process from the analysis of generative conditions, design conception, design development, fabrication to evaluation through physical destructive testing.

2.2 Deliberate practice

Deliberate practice is characterized as activities that “allow for repeated experiences in which the individual can attend to the critical aspects of the situation and incrementally improve her or his performance in response to knowledge of results”. Deliberate practice is distinct from work, which is motivated by external rewards, and play where the objective is enjoyment (Ericsson 1993). The ffmc exercise employs this proposition by requiring students to perform a simple well-defined task multiple times with the expectation of repeated failure giving rise to subsequent improvement.

2.3 Collaborative learning

Collaborative learning is an educational methodology where students work in small groups to construct knowledge; where knowledge is considered to be a consensus constructed through individual contributions and group discussion (Bruffee 1993). The ffmc exercise implements collaborative learning by beginning each of the three project stages with individual responsibilities; each student is required to develop an independent design strategy, and subsequently collaborates with her or his teammates to negotiate and develop the team’s solution for that stage.

2.4 Scale

The square-cube law defines the variable rates of increase of volume and surface area in relation to the proportional increase of an object’s size (Galilei 1914). The effective value in an engineering context is that structural design is size specific; increasing or decreasing the scale of a structure changes the magnitudes of force, performance of structural form and renders material a mere surrogate. In consideration of the square-cube law this exercise is executed in full scale. Therefore, the structural performance is accurately rendered in regards to the criteria of force, form, material and connection.
2.5 Evaluation

The evaluation of student performance correlates directly to the objectives: cultivating (i) an understanding and knowledge of static structural principles, behavior, systems and components and (ii) a qualitative approach to conceptual and technical structural design. Structural efficiency, determined by strength-weight ratio, is a conceptual objective considered relative to the inherent potential of a given design strategy. If quantitative structural efficiency were the stated objective students would select off-the-shelf designs and fail to conceptually explore and develop, falling into a state of verification rather than exploration.

3 Conceptual Criteria

“There can be no difference anywhere that doesn’t make a difference elsewhere.” (James 1991)

This exercise examines structure about the conceptual criteria of force, form, material and connection. The symbiotic relationships between these criteria serve as a means to explore, evaluate and understand the comprehensive design of static structural elements and systems. These concepts have been selected because they comprise an accessible structural vocabulary and all structures can be distilled and understood through them. The implications of these concepts reach beyond the realm of structures into other areas of architectural design and therefore provide the foundation for design integration by encouraging students to develop an understanding of these common criteria in seemingly divergent yet related areas of architectural design.

3.1 Force and form

Structural design can be considered the generation, resolution and management of forces through geometric form. Like water, force is dependent upon a vessel for embodiment and in a structural sense that vessel is form. The inseparable force-form relationship is demonstrated most fundamentally through the comparison of an ideal tensile form to an ideal compressive form for the resolution of an applied load of a given magnitude. The tensile form requires a concentration of material about the center of the cross-section. The compressive form, to resist buckling tendencies, requires a distribution of material about the perimeter of the cross-section.

3.2 Material

If form is the embodiment of force, material can be considered the embodiment of form. Structural materiality can be discerned through the comparison of the forms of standardized wood and steel beams. The cross sectional form of a steel wide flange beam illustrates an efficient geometric distribution of material. The flanges accommodate tensile and compressive stresses in response to flexure, while the horizontal shear stresses are concentrated about the web. The specificity of this cross section is required by the great weight and density of steel but is afforded by the great tensile and compressive capacities of the material. A common wood beam is subject to the same types and distribution of stresses yet maintains a homogenous rectangular cross-section. This is due to the inherent properties of wood, an organic material, comprised of linear cellulose fibers that exhibit greater strength when forces are applied parallel to its grain. The stronger axis is dependent upon the weaker axis for lateral stability and therefore warrants a more uniform cross-section.

3.3 Connection

Connection in structures is considered the transfer of force between members.
Connections are the most common point of structural failure as stresses are concentrated in relatively small amounts of material. Structural connections are generally classified into three types: the rigid connection which resists moment, the pin connection that is moment free yet resists lateral translation and the roller connection which is also moment free but allows lateral translation. Connection cannot be considered in isolation. The type of connection has great implications as it defines the character of stress induced in the members it adjoins. For example, a beam that is supported with rigid connections performs differently than one with roller connections, a difference expressible in form. A triangular frame is inherently stable when its members are joined with pin connections, while a rectangular frame joined with pin connections is not.

4 Exercise Definition

The ffmc exercise is defined in terms of technical objectives and conditions, primary activities and creative sensibilities.

4.1 Technical objectives and conditions

The fundamental technical challenge of the ffmc exercise is to design a structural system that receives two linear concentrated loads, evenly spaced over a three-foot span, and resolves them at either two or four bearing surfaces [figure 1].

The students are assigned one of two options; option 1 permits only the use of the top bearing surfaces (R1) located one-half inch below the elevation of the load application, option 2 permits only the use of the lower horizontal and vertical bearing surfaces (R2). The load applicator consists of two cylinders, eight inches in length and is nested around a hydraulic piston and is therefore dependent upon the structural design for lateral stability. The bearing surfaces are four inches in width.

4.2 Activities and stages

Students, in teams of three, alternate between individual and collaborative assignments. Each student is required to develop a comprehensive design for the structural system, illustrating it in plan, section and details indicating form and force diagrams in all projections. Secondly, the team collaborates to develop a single design for fabrication. Thirdly, the entire class, consisting of both options, congregates for the collective destructive testing and discussion of the projects. Afterward each individual student analyzes their team’s structural design and develops a revised proposal. This procedure constitutes one two-week stage in the six-week three-stage sequence. Each stage has a focus. The first, entitled concept, is intended to establish a primary strategy for resolving the loads. The second, entitled specificity, is intended to examine the components of their structural design, enhancing their specificity relative to the overall concept; this is often a matter of maximizing connections and minimizing members as connections prove to be the most vulnerable aspects of a structural design. The third stage, entitled efficiency, is an opportunity for students to maximize their strength-to-weight ratio, focus on expression and implement refined strategies toward that objective.
4.3 Creative sensibilities

Creativity and innovation are fostered in the negotiation of constraints and opportunities. The physical conditions of the load frame are conceived to provide dimensional constraints that limit the effectiveness of an obvious design strategy, they also provide opportunities when appropriately challenged and interpreted. For example the option 1 conditions provide one-half inch, vertically, between the elevation of the bearing surfaces and the reception of the load applicator. If respected, in the context of a truss, a straight compression chord would be effectively limited in cross-section to one-half inch. If the compression chord is run to the exterior of the eight-inch load applicator the cross-section can be increased considerably. The creative exploitation of this condition enhances quantitative structural performance and introduces an eccentrically loaded compressive member that is form-biased, has legible deformation tendencies and achieves structural expression.

5 Student Work

The concepts and designs of the student projects are invariably diverse and regular collective review provides students the opportunity to observe virtually every static structural principle and phenomenon. The following projects represent a small fraction of the 20-24 projects developed during a single course of the exercise.

5.1 Project one

This option 1 project utilizes the upper bearing surfaces [figure 2]. Concept: simple truss; compression chord rendered in steel tube and faceted in plan to maximize lateral stability by supporting load applicator over its full breadth, tensile chord rendered in cable, compressive web rendered in pyramidal geometry. Specificity: pyramidal web is detached from the compression chord in order to distill compressive forces by eliminating flexure; compression chord is curved around the load applicator to accommodate its displacement downward resulting in a biased form with predictable deformation constrained internally by cables. Efficiency: truss depth is increased to maximize the efficiency of the tension and compression chords; compression chords are rendered as lenticular trusses with member hierarchy calibrated to stress concentration and anticipated deformation.

Figure 2. Evolution of project one.

5.2 Project two

This option 2 project utilizes the lower horizontal and vertical bearing surfaces [figure 3]. Concept: two mutually supporting cantilevered beams connected by a central pin introducing arch action. Specificity: member form rendered specific to variation in magnitude of flexural stresses, central pin
location adjusted and diameter increased, bearing connections rendered specific as pins. Efficiency: introduction of a composite flitch system with sheet steel laminated between layers of plywood, plywood is removed in areas subject primarily to horizontal shear.

Figure 3. Evolution of project two.

6 Conclusions

The effectiveness of this educational experience is evidenced by student enthusiasm, effort, development and their interest in and ability to meaningfully integrate structure into architectural design projects. Upon completion of this exercise students have expressed a perception of structural design as a creative endeavor with multiple possible solutions yet they appreciate the rules and constraints provided by quantitative physical principles and phenomena. Students have also expressed an appreciation for the opportunity to work directly with materials, experiencing their physical properties and understanding the limits and possibilities of various fabrication techniques. From the instructor’s perspective, one of the most revealing products of the exercise is the varied profundity of student understanding; a student adept at rote abstract memorization does not necessarily exhibit a comparable understanding in application.

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References

Journal Papers

Books