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(In)Determinacy: Material and Joint Constraints to Unleash Tectonic Thinking

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ABSTRACT: *Tectonics has been defined as the art of joinings. The focus on expressive potential of joints differentiates tectonic material systems, those built from multiple visible components, from atectonic material systems, those bonded or made solid by and, in some cases, indistinguishable from the joints. Kenneth Frampton's account of the history of modern architecture through construction reinterpreted Gottfried Semper's Four Elements as two categories of building crafts: the tectonics of the frame, that is the "lightweight linear components…assembled to encompass a spatial matrix" associated with tension; and the stereotomics of the earthwork, produced through "the piling up of the heavyweight elements" and associated with compression. That places wood and some metal assemblies in the first category, and cast-in-place concrete and masonry in the latter. Although joints are central to tectonic thinking, the implication of different structural methods of joining, and their primarily shear and friction forces, are mostly absent in the discourse. This paper argues that structural determinacy is an important differentiator between tectonic and atectonic expression by eliminating rigid joints. To test this idea, the constraint of determinacy was introduced through material choice in a design project for a Structural Systems course. Constraints are essential in any pedagogy to focus learning and avoid cognitive overload. For example, in previous years the course introduced constraints of program and site to focus structural decisions on load path patterns and hierarchy without added complexities of enclosure or type. Students could make material decisions based on conceptual drivers or interests, but the fear of complexity in the assignment resulted in many misguided and self-imposed limits. Students selected certain material and joint types, specifically concrete flat slabs or steel moment frames, believing it would simplify model making and diagramming of lateral systems, i.e. being able to ignore joints and their dynamic movement in detailing and the configuration of systems. The decision was quickly regretted once calculations with indeterminate rigid structures became too complex. This represented a challenge for this one-semester course—the only structures course in the curriculum—which limits content to determinate systems. This necessitated more one-on-one guidance, often with imperfect shortcuts that did not improve learning. To address this issue, a new iteration of the course introduced a new constraint of determinacy, requiring a wood structure where all joints are naturally pinned. The intention was to introduce more complexity in compositional design, physical modeling and details and, in turn, simplify the quantitative analysis. This paper draws on tectonics discourse to explain the pedagogical motivations and methods, analyze student learning outcomes and performance in comparison with previous iterations of the course, and share insights from student reflections. Findings suggest that the physical modeling of joints to simulate pinned behavior increased understanding of the torsional effects of configurations, increased student interest in the pragmatic and aesthetic implications of joint detailing, and in the context of wood, placed new and unprompted attention on the connection to the ground and its expressive potential. Refocusing on pinned joints motivated tectonic thinking, improved learning, and increased the quality of quantitative analysis.*

KEYWORDS: determinacy, structural systems, tectonics, joints, timber

INTRODUCTION

Tectonics, understood as the expressive potential of construction, is unquestionably central to architectural discourse and education. In contrast, knowledge of structural systems is often perceived as the domain of engineering. However, there is an implicit relationship between structural systems and tectonics. But unlike to the craft of construction and inherent logics of materials, which are the foundation of tectonics, the concepts of structural analysis are not explicitly theorized in that body of architecture discourse. Structural systems analysis, as referred to here, is the domain of knowledge that applies scientific and quantitative reasoning from physics and mechanics of materials to understand stability, strength, and serviceability. In other words, it represents the problem-solving approach aligned with engineering structures, as opposed to the space- and form-making approach in architectural structures. Ongoing debate in building technology education question the need for this knowledge domain in the education of an architect, with Ed Allen being one of the most convincing proponents that structures should be taught in design, not quantitively (Allen 2006). Yet, this knowledge is not only still required in professional licensing exams for architects in the United States, but also, as argued in this paper, potentially underutilized as a productive method of modeling, iterating, and evaluating design solutions. Considering the central role of tectonics in architectural education, making the connection between tectonics and structural analysis more explicit may be critical to connect the science of structural systems with the spatial, material aspects of structural design in architecture. The argument made in this paper is that making this connection explicit does not mean to replace but to better integrate quantitative reasoning of structures with the generative process of design. The challenge is to define conceptual connections at different levels of design education. As this paper shows in an introductory level class, these conceptual connections can create productive constraints that can focus learning and improve outcomes.

This paper specifically explores the idea of (in)determinacy—a characteristic defined by the type and arrangement of joints that determines whether a structure can be analyzed with simple equilibrium equations—as a path to more rigorous and liberating tectonic thinking in architectural education. Studying (in)determinacy as a condition created by critical architectural decisions, specifically the type of lateral resistive system, has the goal of foregrounding tectonics in structural design, to bring structural detailing into the fold of a richer tectonics discourse. Specifically, the paper explains why the constraint of determinacy, a purely quantitative concept, aligns with the fundamental role of joints in tectonic expression. Drawing on seminal discourse on tectonics, this paper explains the pedagogical motivations and methods to introduce determinacy as a constraint, present examples of work, examines quantitative results of student learning outcomes in comparison with previous years and finds meaning in the data from student reflections of the project.

1. REVIEWING THE DISCOURSE

1.1 Tectonics and the art of joints

Kenneth Frampton traced the history of the term tectonics in his seminal 1995 book, ascribing it with a foundational role—the emergence of the master builder or *architekton*, (Frampton 1995, 4). In this account, Frampton quoted Adolf Heinrich Borbein who suggested a sense of correctness found in the application of artisanal rules when defining tectonic as “the art of joinings,”. Marco Frascari also arrived at the joint as a means of constructing and construing architecture, that is, an instrument of production and interpretation. In the chapter *The Tell-the-Tale Detail*, Frascari offers a multi-scalar view of architecture where any element that is called a detail “is always a joint”—a small part “in relation to a whole,” and the “minimal units of signification.” (Frascari 1996, 500–501) Louis Kahn, whose spent his entire career pursuing a new order from the logics of material and construction, made the joint the beginning of aesthetic expression, saying “the joint is the beginning of ornament…” and “ornament is the adoration of the joint.” Of course, tectonics is not exclusively or rarely explicitly about structure, and more about its aesthetic language, such as the reinterpretation of the timber frame in the entablature of stone Greek temples. Similarly joints in the enclosure and other non-load bearing systems are equally in the realm of the tectonic. Ironically, it is the architecture of Mies van der Rohe, who advocated for structural honesty and expression in design, that surfaced in the discourse as an example of erasing structural joints in the interest of abstraction. In Farnsworth House columns and beams are connected with spot welds that are temporarily bolted in place, then welded, cut, ground smooth and painted to disappear, leaving no trace of construction.(Cadwell 2007) The beam disappears into the abstracted plane of the roof, leaving no trace of the type or existence of a column-to-beam connection. The mere possibility afforded by the selection of steel explains this atectonic abstraction, which is a sharp contrast with the contingency and difference that is inherent to the joining of other materials.

1.2 Material taxonomies: tectonic and the atectonic

Karl Otfried Müller’s 1830 handbook, which Frampton claimed to be the first to use the term tectonics in architecture, noted the junctional implication, or the role of dry jointing as unique to certain materials, specifically those used by cabinetmakers (Frampton 1995, 4–5). The implication may be that the mechanical attachment of elements controlled by human hands, even with the aid of sophisticated tools, creates the distinction between tectonic material systems, those built from multiple and distinguishable components, from atectonic material systems, those made solid and either bonded with or indistinguishable from the joints. Gottfried Semper’s attempt at defining the origins of architecture in The Four Elements (Semper 1989) was based on a generalization from observing or reconstructing a presumably primitive architecture of a hut, but Frampton’s reinterpretation and validation of the theory provided a contemporary distinction. More specifically, Semper’s taxonomy organized these four elements into different but somewhat universal categories of material crafts found in construction, the mound (earth), hearth (tile), frame (carpentry) and enclosing wall (textiles); whereas Frampton reinterpreted these four elements as two categories of building crafts: the tectonics of the frame, that is the “lightweight linear components…assembled to encompass a spatial matrix” associated with tension; and the stereotomics of the earthwork, produced through “the piling up of the heavyweight elements” and associated with compression. This distinction between tension and compression is the closest connection between tectonics discourse and structural analysis, in that it references magnitude and direction of forces, which can be quantified and analyzed against varying stress capacities of materials. That places wood and some metal assemblies in first category, versus cast-in-place concrete and masonry in the latter. However, the nature of these two fundamental forces of compression and tension mostly refer to the components being joined, but not the nature of joints, or more specifically the connecting elements, which are more likely to involve friction and shear forces. Despite joints being so essential to tectonic thinking and expression, the discourse is less clear about the implication of different structural methods of joining, and thus the resistance forces and movement constraints they introduce remain outside of tectonic discourse. However, within the tension-resisting components in the tectonic tradition, there are important differences between wood and steel. Only wood involves a different material for joining. Steel is connected with steel, whether through bolting or welding. The directionality of wood grain and the low shear resistance means its connections are most often of a different material, mainly steel, sometimes aluminum. Those connections are visible by visual contrast, and decisions have to be made about exposing that difference or somewhat concealing it in recessed knife plates and wood plugs, whether for fire protection, design for deconstruction, or aesthetic (M. Laboy 2021). Furthermore, steel-to-steel connections can be rigid, providing an inherent lateral stability to the frame only resulting in reduced slenderness of members. That is a much more difficult for wood, which is more likely to require other means of providing lateral stability that will be visible in the architecture. Timber construction, which is emerging as a growing alternative to steel and concrete in taller buildings because of advances in performance-based design and the potential to reduce embodied carbon, could refocus architecture on the nature of structural connections and their spatial and aesthetic effects.

1.3 Determinacy as differentiator

In this realm of the seminal definition of tectonics, thinking primarily of wood and steel, it can be said that determinacy emerges as the structural concept that explains this difference. Determinacy is defined as the condition of being determinate, that is, being unequivocally characterized. In different fields from math and game theory to engineering, that could mean having predictable results, a known and unique answer, a winning strategy, or solution. In structures, this refers to conditions of equilibrium to applied loads that have one solution, and where all reaction forces can be found using the three simple equations of static equilibrium:

$$\sum F_x = 0$$ Eq. 1: Sum of forces in the x-axis

$$\sum F_y = 0$$ Eq. 2: Sum of forces in the y-axis

$$\sum M_o = 0$$ Eq. 3: Sum of moment

Determinacy is achieved if the structure or its individual components have three or less unknown reactions. Rigid joints introduce three forms of restraint: movement along the two x and y axis and rotation. Pinned joints introduce two forms of restraint, translatory movement along the two axis. Roller joints introduce a restraint in only one direction. Any of these joints, individually, can be analyzed using three equations of equilibrium. However, architecture rarely involves a single joint. Therefore, assemblies and frames can quickly become indeterminate if a rigid connection is introduced with a member that is connected to another joint of any type (four or more unknown variables).

(In)determinacy is a characteristic specifically related to the joints that define the lateral stability of “stick-built” structures or frames, as opposed to massive structures such as load-bearing walls that can integrate laterally resistance either inherently through mass or as composites through reinforcement. The type of connection, or joint types, introduce forms of restraint to either translatory movement or rotation of the structure and/or its components. This is the result of a strictly architectural decision, mostly connected to spatial concepts, transparency, and legibility. More specifically, the use of rigid, pinned or roller connections determines whether a structure is inherently stable to lateral forces or it needs to be layered with diagonal braces or shear walls.

2. METHODS

2.1 Curriculum and pedagogy

To test this conceptual connection, the constraint of determinacy was introduced through material choice in a design project for a Structural Systems course. This is a required course for the accredited Master in Architecture degree at Northeastern University, and serves mostly undergraduates in the pre-professional degree and graduate students in the 3-year program for students with no prior architecture background. It is the third of a 4-course building technology curriculum sequence that involves three introductory systems courses covering principles of materials, comfort, and structures, and an advanced Integrated Systems course. The introductory level Structural Systems course builds on prior knowledge from physics, calculus, and architectonic systems courses (Fig. 1a). It is designed to explore the intersections of science, systems thinking, and design (Fig. 1b). Centered on experiential and project-based learning instead of traditional exams, the course seeks to connect design decisions with the scientific and quantitative principles and processes that inform them. The phases of the project involve diagraming, model making, and calculation. These phases are supported by a *flipped classroom* video demos, diagramming in field trips, hands-on modeling labs to understand system and connection types using sophisticated teaching tools (“Mola Structural Model: A New Way to Learn About Structures” n.d.), and in-class workshops with Excel.

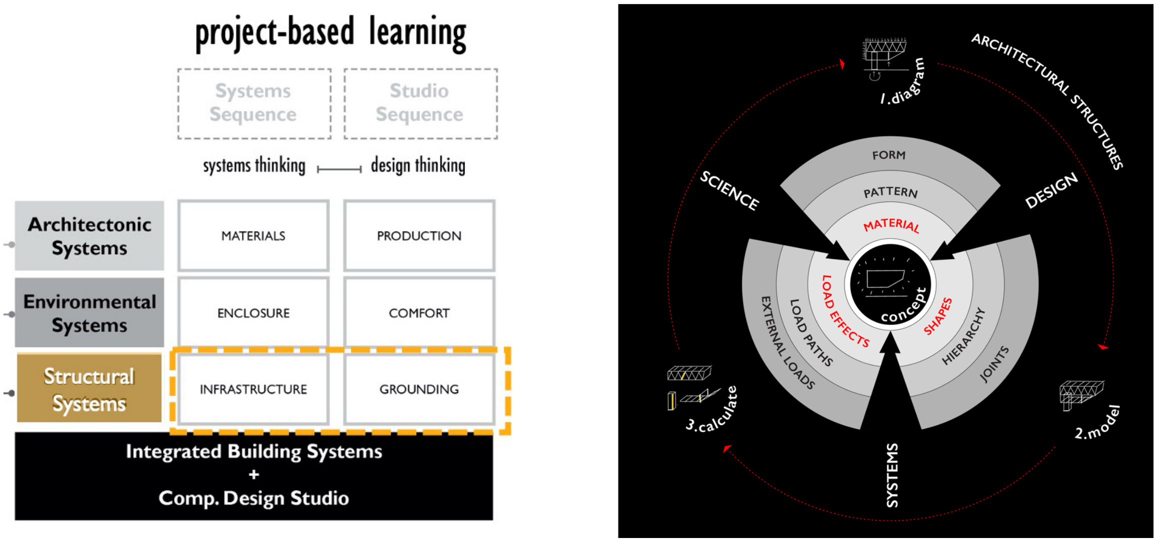
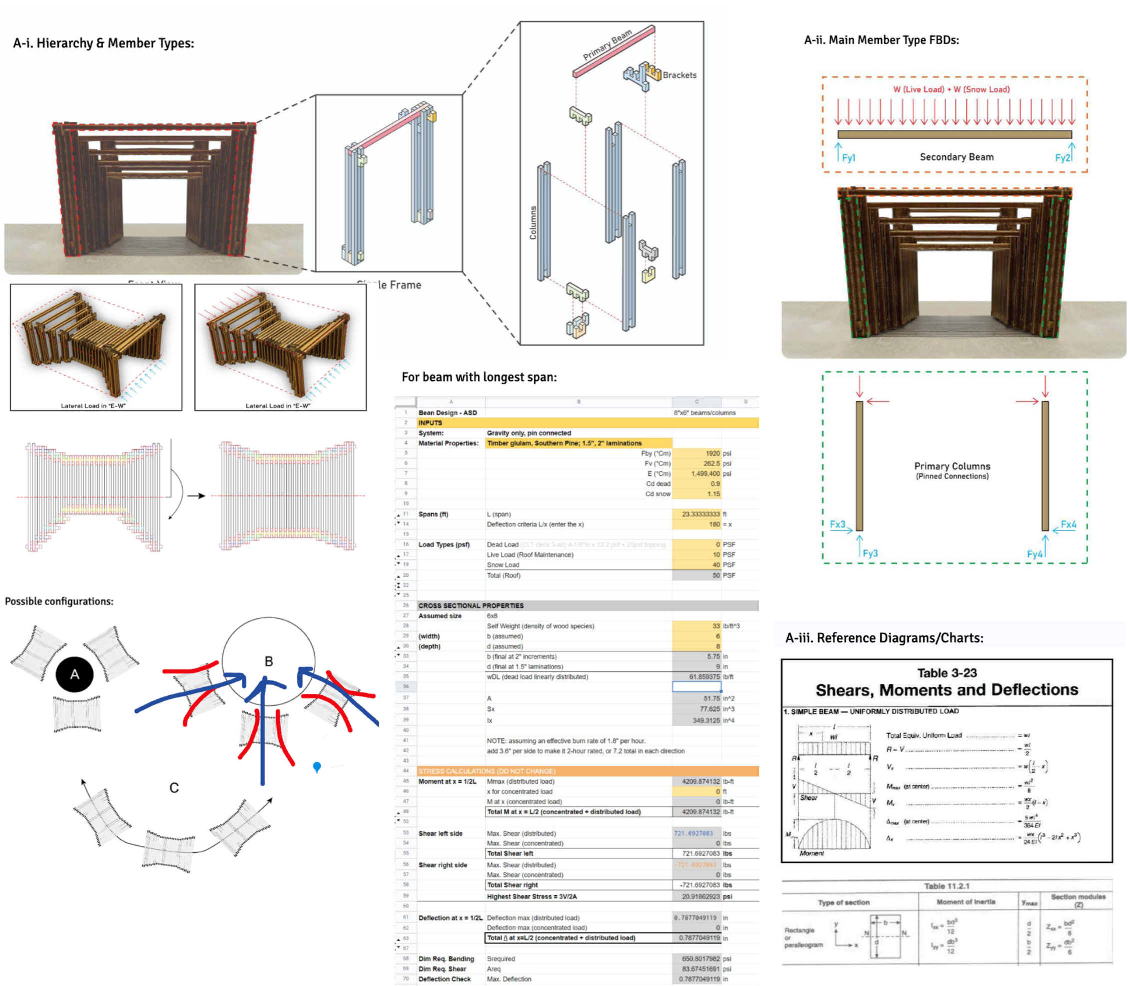


Figure 1: (a) Course in the curriculum sequence (left) and (b) Diagram of course themes organized around three vectors of knowledge (right). Joints are in the outer (first) ring between systems thinking and design, examined through physical modeling that reveals the behaviors of the structural system. This diagram is a revision of an early diagram published after some of the earlier ideas for design-project-based learning were tested (M. M. Laboy 2019). The order and organization of the diagram changed in response to these new constraints, with joints moving to the first ring as an early design decision connected to form and space making.

As a technical course taken alongside different design studios, the design project always had constraints to reduce cognitive load and focus learning. In past years the constraints to program (open market structure or a pavilion with limited use requirements) and site (infill site or with strict dimensional constraints) focused the project on structural decisions without the complexities of enclosure, urbanism or type. Students could make decisions about material based on conceptual drivers or personal interest, but all of them were required to build models that behaved like the structural system based on the construction of joints, and to eventually diagram the load path and calculate the size of one floor and vertical support. Often the students' self-imposed limits were driven by fear of complexity of modeling or diagramming these dynamic lateral systems. Some selected material and joint types, specifically concrete flat slabs or steel moment frames, believing they could ignore the nature of joints in detailing and the compositional resolution of layers of cross-bracing. The decision was quickly regretted in the calculation phase, when indeterminate rigid structures were found to be too complex for their level. This represented a challenge for the faculty in this one-semester course—the only one in the curriculum—because it was not designed to cover indeterminate structures. This necessitated more one-on-one guidance, often with imperfect shortcuts and rules of thumb that did not improve learning. To address this issue, a new iteration of the course in 2022 introduced new and additional constraints. Requiring a wood structure where naturally all joints needed to be pins or rollers (slotted) eliminated rigid connections. This meant that all projects needed to contend with the spatial configuration of lateral systems in diagram and model. This is less about simulating magnitude or testing adequacy, but ensuring students are "looking for geometric stability" (Whitehead 2020, 382). But the result has quantitative implications, as calculations of the gravity system were more likely to be determinate. The intention was to introduce more complexity in compositional design and details and, in turn, simplify the quantitative analysis.

2.2 Project sequence

A 3-phase project sequence moving from diagram to physical model to spreadsheet model had been tried before, and although linear, it was designed for iteration, feedback, and reflection (M. M. Laboy 2022). Students were required to develop a generative cross-section, the architectural drawing with the power to generate both spatial and tectonic ideas. Students deployed this section in a site plan. As shown in one full example on Figure 2, from the section students directly translate into a structural diagram that could be further analyzed as a system of components with individual free body diagrams. In structural analysis the free body diagram reduces a three-dimensional loading condition into a two-dimensional representation of structural elements and forces at the joints, and serves as the foundation for internal moment and shear diagrams. Requiring physical models that were not precious like the lab tools, but true in terms of movement, focused on pattern making, aggregation, behavior and composition. Models are pushed by faculty and students to understand dynamics of deflection, raking, and torsion, and address issues uncovered by the model. In the last phase, spreadsheets allowed students to build their own quantitative models, derived from matching the free body diagram with standard and published shear and moment diagrams that they could use to build an iterative tool with three parts: (a) inputs, i.e. design decisions such as span, spacing, cross-section, and wood species, (b) cells that read the inputs in formulas students entered for equilibrium and stress, and (c) output cells with conditional-formatting that indicated success or failure of the iteration. This allowed quick comparisons between options (strength of wood species, structural sizes, etc) rather than requiring a demonstration of lengthy and tedious manual calculations for one solution.



For beam with longest span:

	A	B	C	D
1	Bean Design - ASD		8"x6" beams/columns	
2	INPUTS			
3	System:	Gravity only, pin connected		
4	Material Properties:	Timber glulam, Southern Pine; 1.5", 2" laminations		
5		Fby (*Cm)	1920	psi
6		Fv (*Cm)	262.5	psi
7		E (*Cm)	1,499,400	psi
8		Cd dead	0.9	
9		Cd snow	1.15	
10				
11	Spans (ft)	L (span)	23.33333333	ft
14		Deflection criteria L/x (enter the x)	180	= x
15				
16	Load Types (psf)	Dead Load (CLT deck 3-alt) 4-1/8"in x 33.2 pcf + 20psf topping	0	PSF
17		Live Load (Roof Maintenance)	10	PSF
19		Snow Load	40	PSF
20		Total (Roof)	50	PSF
22				
25				
26	CROSS SECTIONAL PROPERTIES			
27	Assumed size	6x8		
28		Self Weight (density of wood species)	33	lb/ft^3
29	(width)	b (assumed)	6	
30	(depth)	d (assumed)	8	
33		b (final at 2" increments)	5.75	in
34		d (final at 1.5" laminations)	9	in
35		wDL (dead load linearly distributed)	61.859375	lb/ft
36				
37		A	51.75	in^2
38		Sx	77.625	in^3
39		Ix	349.3125	in^4
40				
41		NOTE: assuming an effective burn rate of 1.8" per hour.		
42		add 3.6" per side to make it 2-hour rated, or 7.2 total in each direction		
43				
44	STRESS CALCULATIONS (DO NOT CHANGE)			
45	Moment at x = 1/2L	Mmax (distributed load)	4209.874132	lb-ft
46		x for concentrated load	0	ft
47		M at x (concentrated load)	0	lb-ft
48		Total M at x = L/2 (concentrated + distributed load)	4209.874132	lb-ft
52				
53	Shear left side	Max. Shear (distributed)	721.6927083	lbs
54		Max. Shear (concentrated)	0	lbs
55		Total Shear left	721.6927083	lbs
56	Shear right side	Max. Shear (distributed)	-721.6927083	lbs
57		Max. Shear (concentrated)	0	lbs
58		Total Shear right	-721.6927083	lbs
59		Highest Shear Stress = 3V/2A	20.91862923	psi
60				
61	Deflection at x = 1/2L	Deflection max (distributed load)	0.7877049119	in
62		Deflection max (concentrated load)	0	in
63		Total Δ at x=L/2 (concentrated + distributed load)	0.7877049119	in
67				
68	Dim Req. Bending	Srequired	650.8017982	psi
69	Dim Req. Shear	Areq	83.67451691	psi
70	Deflection Check	Max. Deflection	0.7877049119	in
71				

Table 3-23

Shears, Moments and Deflections

1. SIMPLE BEAM — UNIFORMLY DISTRIBUTED LOAD

Total Equiv. Uniform Load .... $= wl$

$R = V$ .... $= \frac{wl}{2}$

V_x .... $= w\left(\frac{l}{2} - x\right)$

M_{max} (at center) .... $= \frac{wl^2}{8}$

M_x .... $= \frac{wx}{2}(l - x)$

Δ_{max} (at center) .... $= \frac{5wl^4}{384EI}$

Δ_x .... $= \frac{wx}{24EI}\left(l^3 - 2lx^2 + x^3\right)$

Table 11.2.1

Type of section	Moment of Inertia	y_{max}	Section modulas (Z)
Rectangle or paralleogram	$I_{xx} = \frac{bd^3}{12}$ $I_{yy} = \frac{db^3}{12}$	$\frac{d}{2}$ $\frac{b}{2}$	$Z_{xx} = \frac{bd^2}{6}$ $Z_{yy} = \frac{db^2}{6}$

Figure 2: Images of work by students Qiling Cai and Jean Choi, showing a representation of all phases and most steps of the project sequence. Top (left): Sectional concept of bundled columns and brackets to weave beams through. The components were digitally and physically modeled to be dry joined, simulating pinned behavior. The whole building physical model was used to understand lateral resistance, to diagram hierarchy of components and to develop free body diagrams for preliminary sizing using rules-of-thumb (Allen 2011). Students verified and compared preliminary sizes in spreadsheets they built to take dimensional inputs (span, loads) and modeled standard formulas for shear, moment and deflection, to calculate component sizes (bottom center and right).

2.3 Pedagogical evaluation: sources of evidence

To understand the effectiveness of these new constraints, this study analyzes a few sources of evidence:

- **Student performance in the project** (graded by project, not by individual student): the project with determinacy and material constraints was compared with the average of three previous years without such constraints, separating qualitative (diagrams, physical models) and quantitative phases.
- **Student performance in the course** (individual): the distribution of final course grades. The grades are grouped into high pass, average and low pass to show general shifts and trends. This grade includes individual and collaborative work, therefore can better capture individual outcomes.
- **Instructor's observations of process** from one-on-one and class discussions, and work quality.
- **Individual Student Reflections:** at end of the project, which contextualize and explain the findings

3. RESULTS & DISCUSSION

Table 1 shows the quantitative analysis of student performance. Although grades can be imperfect indicators of learning, the comparison is adequate because the grading criteria for the project and learning goals of the course remained consistent throughout the years, with the only change in 2022 being the added constraint of determinacy and material. Overall there was a significant increase in the mean grade of both the qualitative and quantitative phases of the project; and a significant increase in the percentage of high pass grades (almost double). In general the class shifted in performance by about one letter grade across the board.

Table 1: Student Performance Trends. Source: (Author 2022)

INDICATOR	**Description**	**Previous 3 years***	**2022**	***Trend***
PROJECT MEAN GRADE	*Qualitative Phase*	84%	90%	↑
	Quantitative Phase	80%	85%	↑
COURSE GRADE DISTRIBUTION	*High Pass Grades*	29%	53%	↑
	Average grades	61%	43%	↓
	Below average grades	11%	4%	↓

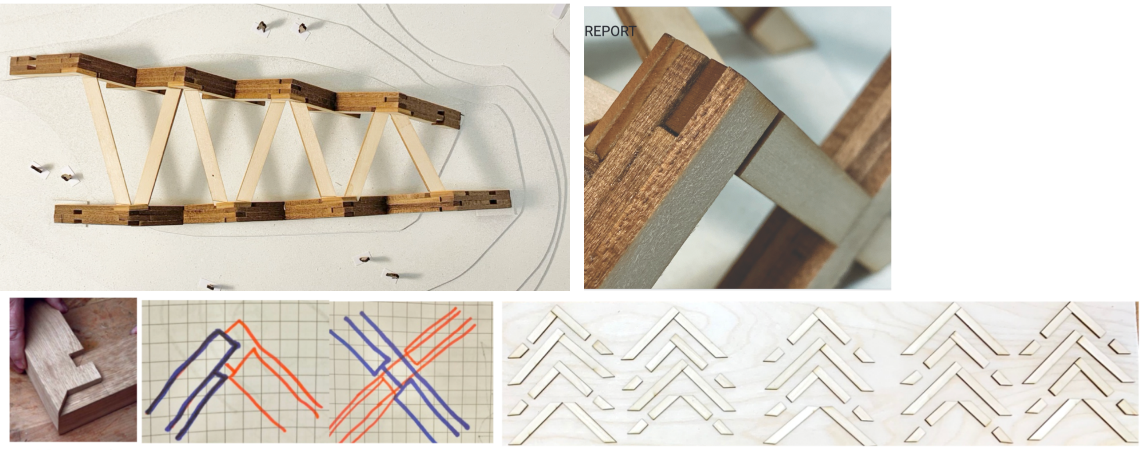
* Weighted Average considers accounts for class size differences.

3.1 Modeling joints

Similar to previous years, the class included field trips to outdoor pavilions with exposed structural components (M. M. Laboy 2022) but this time these happened much earlier, and students spent more time observing and sketching the different types of connections. In the lab, joints were also foregrounded early in the semester. Using the Mola kit (“Mola Structural Model: A New Way to Learn About Structures” n.d.), multiple lab activity were dedicated solely to modeling and observing the behavior of pins, rollers and rigid connections, diagramming conventional symbol as well as allowed movements and restraints, for different systems.

Observations of the student work suggest that the emphasis on joint behavior and movement, when explored with physical modeling of joints to simulate pinned behavior, resulted in better understanding of lateral resistive systems and movement in structures, more interest in form-based resistance, and integration of bracing into overall geometry. Compared to previous years, students seemed less concerned with oversimplifying the structure to have “easier” calculations, because physical modeling and diagramming was emphasized as an experimental and equally important form of validating the system.

During in-progress discussions with students, faculty could observe an increased interest in the detailed design of joints, more genuine questions about means and methods of construction, and attempts at sketching connection types, which were not required but students saw as essential to their understanding of their system, its expressive potential, and its construction, even at a very small scale of the models. The attention to joints and modeling of more behaviorally-accurate representations of pins resulted in more projects exploring bundling, layering and weaving column and beam members, as well as dry jointing, brackets, and triangulation. (Fig. 2 and 3).



1: Precedent of Japanese Joinery

2: Simple Sketch of Design with Layered Connections

3: Design Process/Construction of Primary Structure

Figure 3: Integrated triangulation of primary systems in plan and elevation achieved with oversize layering for dry jointing and stability through mass and geometry. Contending with the requirement of pinned connections in wood, these students were inspired by Japanese joinery to develop a method of connection. Student work by Remi Messier and Michael Rathz.

The modeling at a small scale required creative approaches to pin jointing (flexible hot glue, threading, laser cutting, and 3d printing). One of the students whose work is shown here (figure 3) reflected on how through modeling joints “the importance of lateral support definitely became clearer. The concept of joinery in our project also taught me a lot about how structures can work at joints, where notches, slots, and shelves, etc can bring elements together securely.” In contrast to these observed benefits, the scale required and the almost exclusive focus on behavior was a real impediment to representation of the joint, therefore the impact was limited to the relationship between components being joined and spatial / formal configurations. In future iterations it may be helpful to require models at different scales, one of just the joints at a larger size in parallel with the smaller but full building models.

3.2 Assemblies for determinacy

The requirement for determinacy elicited more nuanced understanding of constructability. This was especially true in projects with column lines that contained more than two supports. In past years students would propose and model continuous beams (indeterminate) in longitudinal (usually primary) directions and would model simple spans in secondary spans (determinate), because they only had to diagram and calculate the size of one beam. The new constraint led to discussions about constructability and efficiency. For example, students asked if introducing joints at the top of columns to make simple beams when beams are intended to be continuous would complicate the connection, by requiring the column to interrupt the beam length or adding more connectors. Some of the solutions discussed included compound beams made of double overhangs supporting simple spans result in less connectors. Similarly, when students needed to find the available (published) shear and moment diagrams for their beam type and load condition (e.g. an overhand beam with a distributed load), which were used for building their spreadsheet models, they had to think creatively about construction in order to redesign the system to better match existing diagrams with known solutions. The inability to find continuous beams of any number of spans encouraged discussions about true methods of compound beam assemblies. This process of breaking one indeterminate system into a few more determinate parts had never been part of student project discussions before, even though such examples were shown in the quantitative analysis part of the class. (Fig. 4) This attempt at editing and simplification in analysis led to debates about transportation of members, site access, and unnecessarily complicated construction process, e.g. placing beams over multiple columns that must be kept plumb. When determinacy was not a constraint, students found a way around these by selecting uncomplicated, albeit secondary members of the system.

Figure 4: Class example of a continuous beam (indeterminate, left) transformed into a 3-part compound beam (determinate, right) that became a more common discussion in projects with the introduction of determinacy as a constraint.

3.3 Ground connections

The constraint of material to wood invited questions from students about the support of the column. When students picked concrete in past years the lack of material differentiation between column and foundation left that detail out of the representation and tectonic expression. Similarly, steel structures were often assumed to be embedded in the ground (somehow the concern for oxidation was never in the mind of students). But with wood, there was a significant preoccupation with and interest on the connection to the ground and its expressive potential. Students intuitively knew that there was something wrong with embedding wood into the ground. More students asked about the connection at the ground and tried to model that separation from grade as part of the logic and expression of the column. (Fig. 5). Many involved interesting approaches to physical modeling to create a pin connection at the base of a model.

Figure 5: Column base elevated above grade, modeled to behave like a pin. Student work by Alice Clements and Shannon Rooney.

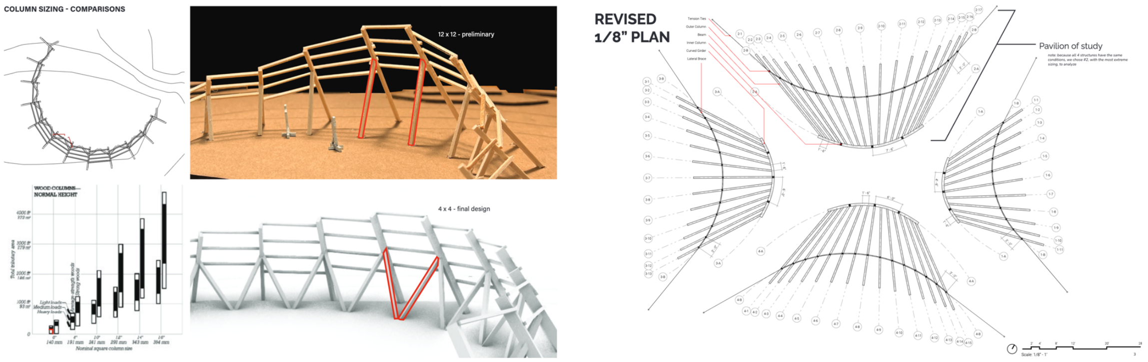


Figure 6: (a) Student work by Katie Dumigan & Ben Harding (left) shows how columns changed from two dimensional to a three-dimensional pattern. (b) Work by Ethan Matthews & Valentina Riera (right) show diagonal braces extending outward from bent girders to lengthen the thresholds from the site into the center of the space in this radial pattern.

3.4 Lateral stability

The new constraint of determinacy and the requirement to more genuinely model pinned connections for wood structures encouraged more students to identify and respond to lateral instabilities. Students could not resort to cantilevered columns (rigid base) that could resist lateral loads in any direction. Now all students had to content with more visible lateral systems that required experimenting with how their spatial configuration cause or prevent torsion. As a result more students integrated these logics into spatial patterns, such as the triangulation of vertical supports to work in three dimensions (Fig. 6a), or leveraging form resistant geometries, e.g. girders curved in plan connected to external braces (Fig. 6b). Even the less ambitious projects that added traditional cross bracing within regular bays without changing geometries revealed their lateral behavior, and had to consider its spatial and aesthetic implications. The contrast is that in previous years the majority of students largely avoided these compositional complexities, and the competency achieved in lateral stability was generally less consistent, especially when calculating the size of columns became more complex by requiring combined axial-bending processes. Although small messy models were less effective at exploring the aesthetic of joints, the modeling of pinned behavior at building scale made torsion very visible, allowing quick experimentation with physical bracing methods, and simplifying the calculations into axial-load only.

3.5 Modeling iterations

The focus on one material and analytical process had a positive impact on learning and increased the students' comfort with and overall quality of quantitative analysis. The constraint of material meant more time to do group activities during class where everyone shared in the general process of building the spreadsheet model and equations, making sense of them collectively, while allowing breaks during class for testing specific aspects of their own design in the model, e.g. selecting a species or changing span length. The slower pace and increased contact time of faculty during the development of the projects, even in the context of a large class (n=68) resulted in much less anecdotal evidence of struggle with calculations, more collaboration between groups, and more creativity in the use of quantitative models to test multiple details of the design. This observation of the faculty was confirmed in the reflections, were most students expressed more confidence in their understanding of the concepts and variables because they could instantly see the impact of manipulating different design inputs with a highly visual and physical tools. The annotations and diagramming over photos of the physical model and the spreadsheet also indicated much more sophisticated understanding of concepts and numbers. This selection of comments from the reflections are most representative of what was seen across all the projects, students for the first time seeing equal value in physical and numerical modeling because of the way they support productive iterations and understanding:

> “By designing and constructing in this way, we were able to physically see where the structure needed extra support…I was more focused on the connections between the members.”
>
> “The physical model allowed us to understand the hierarchy of structural members and helped us understand where further lateral reinforcements were required…. With our spreadsheet, we were much more comfortable understanding numbers... This felt eyeballed in our physical model, but the spreadsheet either confirmed or disproved assumptions.”
>
> “The most effective tool in learning for this exercise was the tactile element of trial and error, both within the spreadsheet model and the physical model. I found it very helpful to be able to push and pull on the model, substitute supports, enter different dimensions and densities, and compare these changes with my anticipations and prior understanding of the structure.”
>
> “The spreadsheets were a really good visual aid… allowed me to instantly see how changing one singular value could change the “ok” or “fail” of any given property that we were checking. It was actually really fascinating and actually fun trying to change the values at certain points… [to] yield ‘ok’ results.”

CONCLUSION

The literature review established that learning about structures is most effective in a project-based pedagogy connected to design. And yet, it is still common to see a disconnect between the structural design projects that involve quantitative analysis for problem solving and those architectural design projects that are more conceptual and qualitative in nature. This paper shows that quantitative analysis can be meaningfully connected to the generative process through constraints that transform quantitative concepts into design opportunities. The study argues for and shows examples of how the constraint of determinacy, that is, structural systems that can be divided into and analyzed using the three equations of equilibrium, can unleash tectonic thinking.

Determinacy can be an important differentiator between tectonic and atectonic expression in architecture, by more intentionally engaging with the both the expressive potential and behavior of joints. This expression potential is of course traditionally associated with the detailing of the individual connections, but it also emerges from geometric configuration of lateral systems into a whole building, especially the placement of and expression of bracing. The use of small-scale physical models that could resemble the behavior of pinned joints (allow rotation but not x- or y- displacement) became a pedagogical and empirical tool to test the stability of configurations of multiple braced frames into whole buildings. One downside of prioritizing geometric stability of the whole building was that the nuanced expression and complexity of the joint does not always scale down to these small models. However, in some cases, as shown in examples, students had the initiative of using the drawing and/or digital model to understand the nature of the joint itself, and to overcome the expressive limitations of the physical model. It is not surprising that architecture students show interest in joinery in a construction class focused on tectonic thinking, but this was completely new for a structures class that still has a significantly more analytical and quantitative approach. Based on these findings, future iterations of the course will further encourage tectonic thinking by including more intentional prompts or requirements for digital and physical modelling of the connections at larger scales, to better connect the tectonic detailing with the tectonic thinking happening at the scale of structural patterns.

The motivation to introduce this conceptual constraint in a pedagogy for structural systems was to make quantitative reasoning a more powerful and generative process, and to anticipate the type of design decisions, such as materials, that could limit tectonic development and thus student learning. The results not only showed a significant improvement in student performance on quantitative reasoning, but just as importantly improved the qualitative performance, i.e. it shows that the intentional use of meaningful constraints imposed in the context of architectural education (less math background, more design) are also opportunities to more intentional connections between building technology and design.

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