Gray-boxing: Integrating Structural Behavior into Architectural Education

Reese Greenlee
Kansas State University

Abstract

The persistent divide between architectural design and structural engineering has led to a lack of intuitive and conceptual structural comprehension in architectural education. Gray-boxing is a pedagogical strategy that selectively exposes knowledge from structural analysis tools to students, allowing them to engage with structural behavior as an integral part of design. Borrowing from gray-box testing in software development, this approach leverages Karamba3D within Rhinoceros 3D and Grasshopper, providing real-time feedback on load paths, material efficiency, and stability while filtering out unnecessary complexity. Through iterative digital and physical experimentation, students develop structural competencies, treating analysis as a design collaborator rather than a technical hurdle. Case studies illustrate how gray-boxing fosters an interdisciplinary learning model, equipping students with critical thinking and adaptability to navigate performance-driven design as a generative and exploratory process.

Introduction

The relationship between architect and engineer has always oscillated within architectural discourse, a tension that Andrew Saint describes as a sibling rivalry. It is a conflict rooted in the division of professional boundaries, the negotiation of collaborative authorship, and the differential valuation of creativity regarding technological and economic imperatives.[1] In the education of both disciplines there is a shared gap—an absence of an embodied, intuitive comprehension of structural space and its possibilities.[2] This paper introduces gray-boxing, a technique borrowed from software development where users have selective knowledge of an application's internal workings, to expose structural analysis software to novice designers. In doing so, it redefines structural tools as co-creators, transforming student engagement with structural concepts from the outset of design ideation.

Gray-boxing leverages Karamba3D within Rhinoceros 3D and Grasshopper, enabling real-time visualization of structural and material behavior. This integration encourages iterative refinement of design concepts, making structural feedback accessible to students and bridging the gap between technical rigor and creative exploration. Gray-boxing facilitates both analytical thinking and tactile learning—an approach inspired by Mario Salvadori's focus on intuitive understanding and Mamoru Kawaguchi’s touch and feel models, where physical interaction enhances comprehension of structural dynamics.[3]

Two key examples of this approach are laboratory exercises in *Structural Systems in Architecture II*, the final structures lecture and laboratory course taken by students in both the Department of Architecture, and the Department of Interior Architecture and Industrial Design. In *The Pushover Game* exercise, students explore torsional irregularities in building structures under lateral loads. By first interacting with dynamic physical models, and then digital simulations, students gain an understanding of structural behavior while reinforcing analytical insights. Similarly, the *Quilt Forms* exercise demonstrates gray-boxing’s capacity to merge creative exploration with structural analysis, as students translate quilt patterns into steel space frames, optimizing material use and structural integrity through digital tools.

Gray-boxing serves as a powerful teaching strategy that enhances student comprehension of building performance across multiple dimensions—structural, material, and experiential. By enabling meaningful access to expert tools, students are empowered to actively apply structural analysis in the design process, bridging the gap between technical assessment and creative decision-making. This approach prepares students to engage with key aspects of architectural performance, from structural systems and material optimization to user experience and spatial impact. As students gain skills in assessing and interpreting structural feedback, they become adept at balancing performance-based requirements with innovative design solutions. Gray-boxing fosters an interdisciplinary mindset, equipping future architects with the resilience and insight needed to address complex, performance-driven challenges in the built environment.

Structured Lineages: A Review of the Historical and Conceptual Framework

The integration of structural knowledge into architectural education has long been a topic of critical reflection, shaped by the relationship between architects and engineers, and consistently criticized for its shortcomings in the education of both professions. The “sibling rivalry”, with an ongoing tension between creative autonomy and technical realization, has been reinforced through the siloing of disciplines by the economic models behind the construction market.[4] In this context, the teaching of structural design is seen as a constraint on architectural education instead of an opportunity for innovation. Even as multi-disciplinary approaches proliferate in architectural discourse, the standard NAAB accredited structures sequence is secondary to the design curriculum, reproducing a fragmented and linear understanding of collaboration between architects and engineers. As much as it misses the core competencies of structural design, it fails to engage with and take advantage of the core features of architectural education: the capacity to foster exploratory, conceptual, and integrative modes of thinking.[5] As a result, architectural students frequently lack the intuitive comprehension of structural behavior necessary to meaningfully engage with and critique the structural aspects of their designs.

This observation is not new: pedagogical approaches such as those of Mario Salvadori and Fred Severud have been emphasizing the importance of developing an intuitive understanding of structures since the 1950s. In *Teaching Structures to Architects* (1958), Salvadori argued for architects to “have a feeling for beams” rather than seek a deep knowledge of the theory and mechanics behind structural analysis.[6] He pointed to an experiential engagement with structures that translated through demonstration models of various structural types. In this way an architect could develop a physical intuition of the behaviors and possibilities of structural systems. In the same mode, Severud, in *Structures: The Feel of Things* (1961), called for a focus on structural fundamentals and empirical results to develop a “sense” for structures, allowing the architect to integrate this insight into the design process.[7] He pointed to an experimental engagement that learned from failure and utilized the human body as a useful structural model. Both emphasized that architects should seek enough structural understanding to advocate effectively for innovative solutions while collaborating with engineers.

Building on these ideas, Dr. Mamoru Kawaguchi utilized and advocated for the use of *Physical models as powerful weapons in structural design* (2004) because they respond directly to being pushed and pulled. Through immediate feedback about the behavior of a structure, “touch and feel” models provide insight into concepts like force flow, and can be used by a structural designer to develop a deeper understanding of a system.[8] This tactile learning method made structural principles visible and experiential.

Despite these historical contributions, and the perennial call to improve structures for architects, contemporary architectural education continues to struggle with integrating structural thinking into the design process. Dr. Sinéad Mac Namara, in *Bringing Engineering into the Studio: Design Assignments for Teaching Structures to Architects* (2012), highlights the disconnect between structural considerations and design in architecture curricula.[9] She argues that when architecture students are held responsible for choosing structural systems, like in a comprehensive design studio, they often lack the conceptual tools to scale structural members accurately or to understand the experiential quality of spaces resulting from their structural material choices. Critically, she identifies that the intuitive understanding of structures motivating this pedagogical research is also lacking in the education of the engineer, a shared blind spot in the possibilities of structural form.

More recently, J.J. Castellón González (2022) has critiqued models for structural education in both disciplines for their failure to establish a pedagogical approach for teaching conceptual structural competencies.[10] Conventional structural education often reproduces the linear model of practice, in which architectural ideas lead and structural input follows as needed. This approach emphasizes analytical precision over conceptual synthesis, resulting in a curriculum that is deductive, passive, and fragmented—it misses the structure for the beams. In response, he calls for educational strategies that activate the intrinsic features of architectural education to foster structural insight as a fundamental aspect of design culture.[11]

This critique of structural education established an approach based on the interplay between physical and digital models, utilizing both material knowledge and parametric tools to develop architectural concepts that integrated structural and spatial considerations. Proven to be effective in filling the knowledge gap between architectural design and structural conception, the results highlight the need for more engagement with common grounds between architects and engineers. In order to do so in architectural education, structural systems should not be viewed as constraints but as co-creators in the design process, interfacing with architectural education's inherent strengths: synthesis, iteration, and a focus on spatial and experiential qualities. Within this pedagogical framework, teaching strategies must cultivate an intuitive grasp of structural behavior while providing enough feedback for students to engage meaningfully with their potential as integral elements of design.

Gray-boxing addresses this need by offering a methodological strategy that integrates structural analysis tools into architectural education in a way that is both accessible and conceptually engaging. By selectively exposing novice users to critical inputs and outputs of structural systems, gray-boxing provides a framework for developing an intuitive understanding of structural behavior and performance. This approach builds on the historical frameworks established by Salvadori and Kawaguchi while addressing the shortcomings identified by Mac Namara and Castellón González, adding to their reimagined role of structures in architectural education as an active, interdisciplinary, and performance-driven design space.

Gray-boxing: Methodology and Tools

Gray-boxing is a pedagogical strategy designed to simplify and integrate advanced structural tools into architectural education, enabling students to engage with the performance of structural systems while also exploring their creative possibilities. Drawing from the principles of "gray-box testing" in software development, a technique where the tester is provided with selective access to internal systems, filtering out unnecessary complexity so they can focus on critical functions and outputs.[12] This approach, which balances the transparency of white-box methods with the functionality-driven focus of black-box methods, is particularly well-suited for architectural education (e.g. scale models). It enables students to engage with structural systems iteratively and intuitively, benefiting from both analytical rigor and creative exploration.

By using digital tools like Karamba3D within Rhinoceros 3D and Grasshopper, gray-boxing transforms structural analysis into a creative collaborator inside of a familiar software. The method emphasizes actionable metrics—from global criteria like stability and deflection to local element criteria like stress utilization and material optimization—framing these as accessible design inputs rather than computational hurdles. The structural systems course sequence at Kansas State University repositions structures in the beginning of the design process and provides real-time visualization of structural behavior, fostering reciprocal feedback between conceptual ideation, formal development, and structural analysis.

Iterative Design and Feedback Loops

Gray-boxing is an iterative design process that encourages students to test, evaluate, and refine their ideas with respect to the structural code requirements for strength and deflection.[13] This cycle begins with conceptual exploration of core structural behaviors using simplified physical models that magnify the response of a structure. By focusing attention on the deflected shape the students can push and pull to understand the critical zones of stress and movement, learning through physical feedback (resistance) and documentation.

This dynamic physical feedback is followed by an analogous digital structural model that reflects a full-scale structure. The students set the boundary conditions as points, draw the elements with centerlines, assign the material properties and connection types, calculate the initial cross-section by rule of thumb, and calculate and apply the loads according to a specific location, topography, and context. The process of building a digital structural model provides good insight into the stability of structures as initial models are often modeled incorrectly, and require a close inspection of its structural instabilities. As students develop a working structural model, they receive immediate feedback, developing an understanding of the nature and magnitude of their structure's behavior.

Once equilibrium is established for an initial model, the design challenge is a combination of deflection and stress criteria with a weight and material use optimization goal. In response to these constraints, students can visualize the structural implications of their decisions in real time, allowing them to refine their designs iteratively and connect formal adjustments with structural performance. This feedback loop cultivates a sense of agency and encourages students to experiment with regular and irregular structural systems, knowing that the tool will guide them toward viable outcomes.

Transforming Structural Tools into Co-Creators

The combination of physical and digital exploration reinforces the complementary roles of each medium. While physical models offer immediacy and tangibility, digital tools provide precision and scalability. Together, they create a pedagogical ecosystem where analysis and creativity inform and enrich one another.

A defining characteristic of gray-boxing is its integration of analytical rigor with tactile intuition, the precise results of the structural model with the exploratory moves of a novice structural designer. This is possible through Karamba3D, a finite element analysis (FEA) tool integrated within Rhinoceros 3D and Grasshopper. Unlike conventional engineering software that requires significant technical expertise, Karamba3D provides an interface that can be packaged within Grasshopper to be both intuitive and adaptable for architecture students. To implement gray-boxing, the tool is configured to expose only essential parameters and workflows—focusing on inputs like structural supports, elements, and loads, and outputs such as stress distribution and deflected shapes. By limiting the complexity of the interface, gray-boxing enables students to interact productively with the tool, fostering confidence in applying structural principles.

Gray-boxing challenges the traditional, hierarchical relationship between design and analysis by embedding structural considerations early in the design process, shifting the perception of structures from rigid constraints to dynamic, creative resources. By repositioning structural systems as integral to creative exploration, and rendering complex tools accessible without diluting their analytical power, gray-boxing empowers students to engage critically with the complex relationship of form, material, and performance in the built environment.

Case Studies: Laboratory Exercises

Laboratory exercises serve as the foundation of *Structural Systems in Architecture II*, bridging theoretical knowledge with hands-on experimentation and digital analysis. By engaging students with short design projects constrained by metrics of structural performance, these exercises illuminate structural principles as both conceptual frameworks and active design collaborators. This pedagogical approach sees structural analysis not as a static validation process but as an integral and dynamic participant in design exploration. The following case studies—The *Pushover Game* and *Quilt Forms* Exercise—demonstrate how this methodology fosters a deeper understanding of the behavior of structural systems.

Case Study 1: The Pushover Game

The *Pushover Game* lab is designed to introduce students to the structural behavior of buildings under lateral loads, with a specific focus on torsional irregularities. The lab investigates how asymmetrical configurations in a building's mass and stiffness distribution can generate hazardous structural responses under wind or seismic forces. The exercise emphasizes the relationship between center of mass (CM) and center of rigidity (CR) as a critical factor in structural performance at the global scale, reinforcing the importance of balanced structural configurations in mitigating torsional effects. By engaging in both physical modeling and digital analysis, students develop a dual intuition—a hands-on understanding of how lateral forces act on irregular structures, paired with analytical insights from computational simulations.

Methodology: The *Pushover Game* is structured as a multi-phase experiment that progresses from hands-on physical investigations to computational analysis. By correlating their empirical findings with computational results, they gain an advanced understanding of how torsional stiffness, mass distribution, and lateral stability inform structural form and performance. The lab unfolds in three parts:

1. Physical Investigations: Quarter Scale Models

Students begin by constructing quarter-scale models of a base structural frame and iteratively removing and reintroducing elements to generate asymmetrical configurations. Through manual loading and observation, they test how different mass and stiffness distributions affect structural response, witnessing firsthand the global rotational behaviors that emerge from torsional irregularities (Figure 1).

2. Computational Analysis: Digital Simulations

After developing an understanding of torsional behavior, students transition to Karamba3D, where they simulate their models under lateral loading conditions. These digital tools allow them to measure deflections, rotations, and stress distributions, providing quantifiable feedback that builds upon their physical observations. The computational analysis phase requires students to optimize their structures by adjusting stiffness distributions—experimenting with the effect of five different geometric configurations on the performance of frame systems (Figure 2).

Fig. 1. Dynamic testing of push and pull physical models.

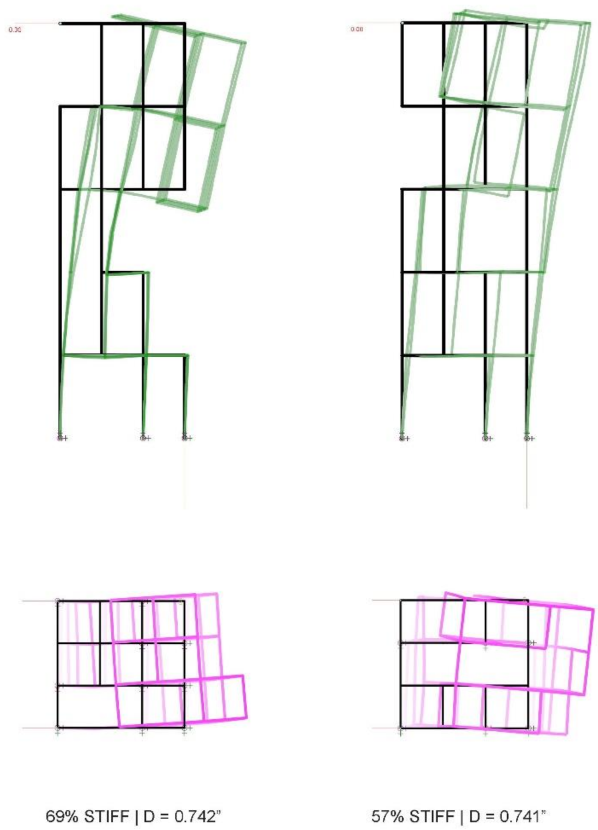

Fig. 2. Digital structural model analogous to the physical model.

3. Wind Load and Bracing Design: Full-Scale Structural Response

The final phase scales up the experiment by applying real-world wind loading scenarios to a high-rise braced-frame model. Using ASCE 7-10 standards, students calculate wind forces for different urban conditions—comparing a suburban office building in Wichita, Kansas and a trauma center in Miami, Florida. This exercise deepens their engagement with structural performance under environmental forces and requires them to design lateral bracing systems to restrict deflection to within acceptable limits (Figure 3).

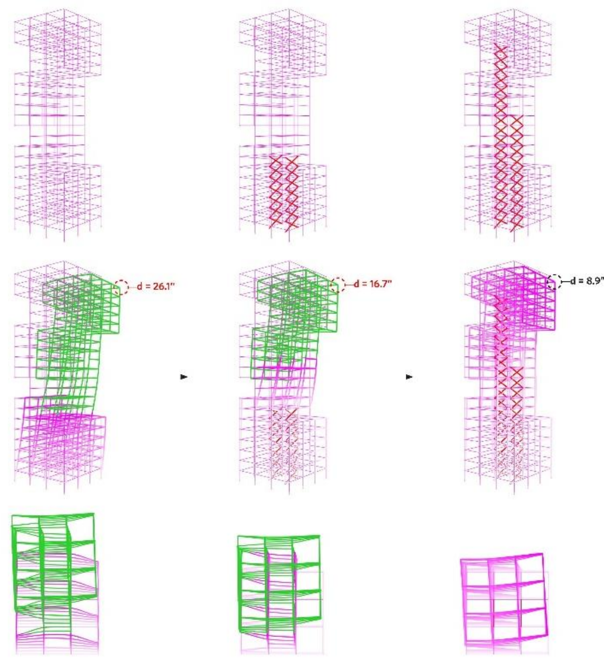

Fig. 3. Design iterations for a brace configuration that is compliant with the ASCE 7-10 deflection criteria.

The *Pushover Game* transforms the conventional teaching of lateral stability from a theoretical, code-driven exercise into an active design investigation. Students develop conceptual clarity on how asymmetrical mass and stiffness distributions generate torsional rotation, gaining an understanding of the relationship between center of mass (CM) and center of rigidity (CR) in seismic and wind-induced deformations. Through hands-on experimentation with physical models, they move beyond formulaic calculations, internalizing the behavior of lateral systems and connecting abstract structural forces to tangible spatial consequences.

By iterating on structural configurations, students engage in strategic decision-making, testing how stiffness redistribution and lateral bracing systems mitigate torsional effects. This adaptive design mindset repositions structural stability as a generative component of architecture, rather than a post-rationalized constraint. Within this framework, gray-boxing ensures that computational tools serve as active design collaborators as opposed to passive validation systems, allowing students to use structural analysis to inform form-making, spatial development, and architectural intent.

Case Study 2: Quilt Forms Exercise

The *Quilt Forms* lab explores the intersection of structural logic and geometric abstraction by translating two-dimensional quilt patterns into three-dimensional steel space frames. This exercise emphasizes the interplay between aesthetics and performance, prompting students to consider how structural geometry informs and is informed by structural performance. By doing so, students investigate its effect on structural efficiency while negotiating aesthetic, spatial, and performance-based considerations like stress utilization, deflection criteria, and weight.

Methodology: The lab is structured around a sequential design process that transitions from geometric interpretation to structural optimization:

1. Geometric Abstraction and Spatial Context

Students begin by selecting a quilt pattern from a historical archive, tracing its underlying geometry in Rhinoceros 3D. They identify a site-specific interior space, measuring and documenting the spatial conditions to inform the scale and placement of the structure.

Through spatial projection and scaling, students determine how the pattern adapts from a two-dimensional pattern into a three-dimensional configuration (Figure 4).

2. Modeling Transformations

Using wireframe sketches, students experiment with depth, modularity, and structural logic, exploring how the quilt pattern translates into a space frame topology.

The wireframe model is then developed into a Finite Element Model (FEM) in Grasshopper/Karamba3D, incorporating ASTM A53 Grade A steel pipe profiles.

3. Structural Analysis and Iteration

Initial digital simulations assess material efficiency, stress distribution, and deflection constraints.

Students refine their designs by iteratively adjusting support conditions, form, frame depth, and element thickness to achieve material minimization while maintaining structural integrity (Figure 5).

The final space frame is structurally optimized to minimize weight, and documented in technical drawings and performance visualizations.

4. Final Documentation and Presentation

Each team produces a comprehensive design sheet, detailing their geometric transformation, structural efficiency metrics, and final installation proposal (Figure 6).

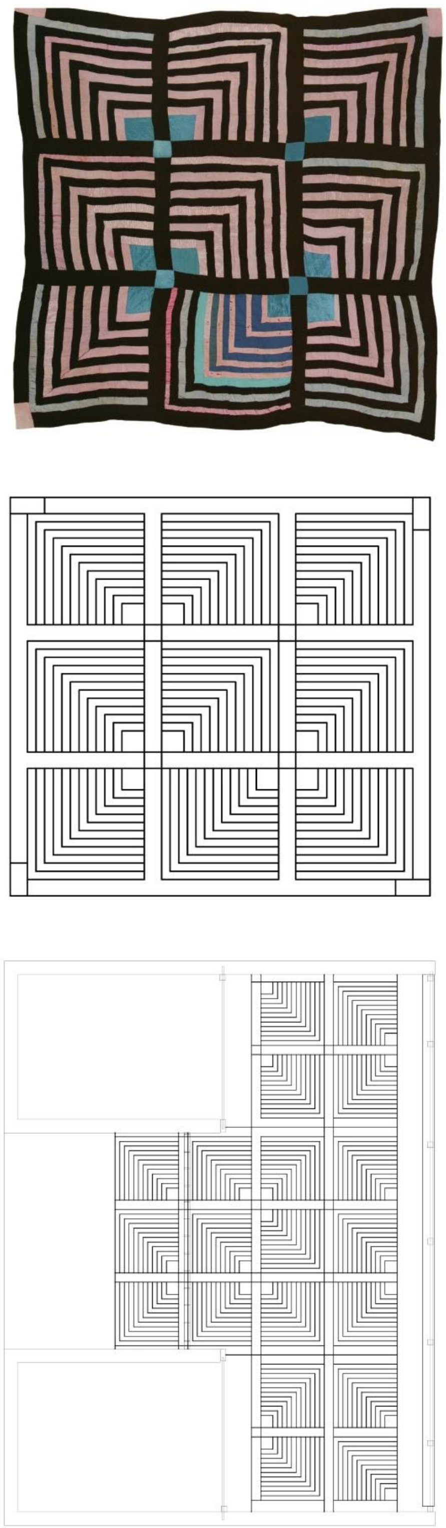

Fig. 4. *The reference quilt, underlying geometry of the quilt, and the spatial application of the installation in plan.*

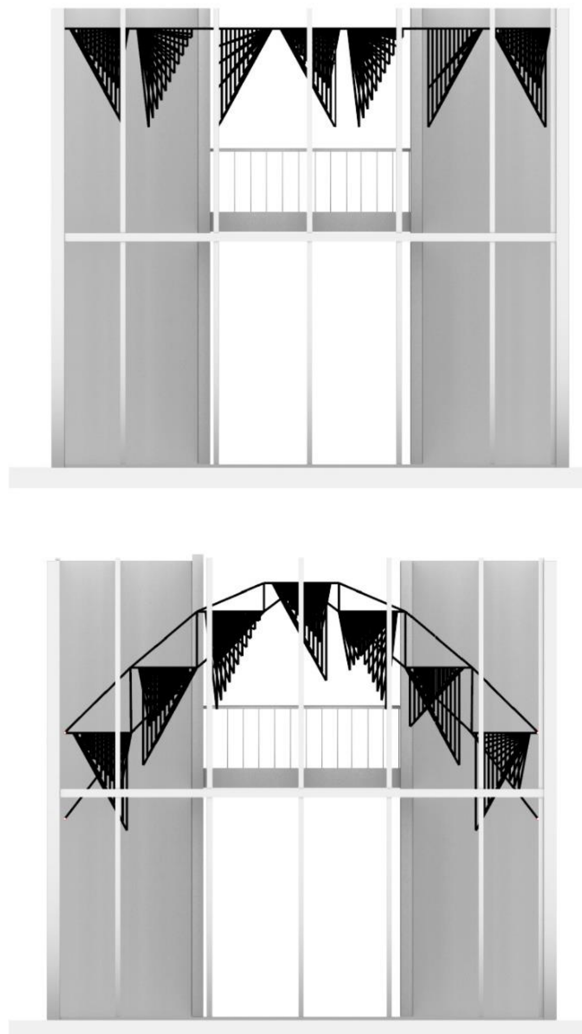

Fig. 5. Formal iterations that minimize the overall weight.

The *Quilt Forms* lab repositions structural analysis as a creative tool and emphasizes the reciprocal relationship between material behavior, spatial experience, and formal expression. Through Karamba3D, students develop proficiency in structural modeling, refining their ability to manipulate load paths, material stress, and support conditions as active design inputs. By deconstructing and reassembling quilt geometries into space frames, they cultivate an intuition for modular systems and geometric transformation, reinforcing the spatial and structural implications of form. The iterative process of structural analysis and material optimization

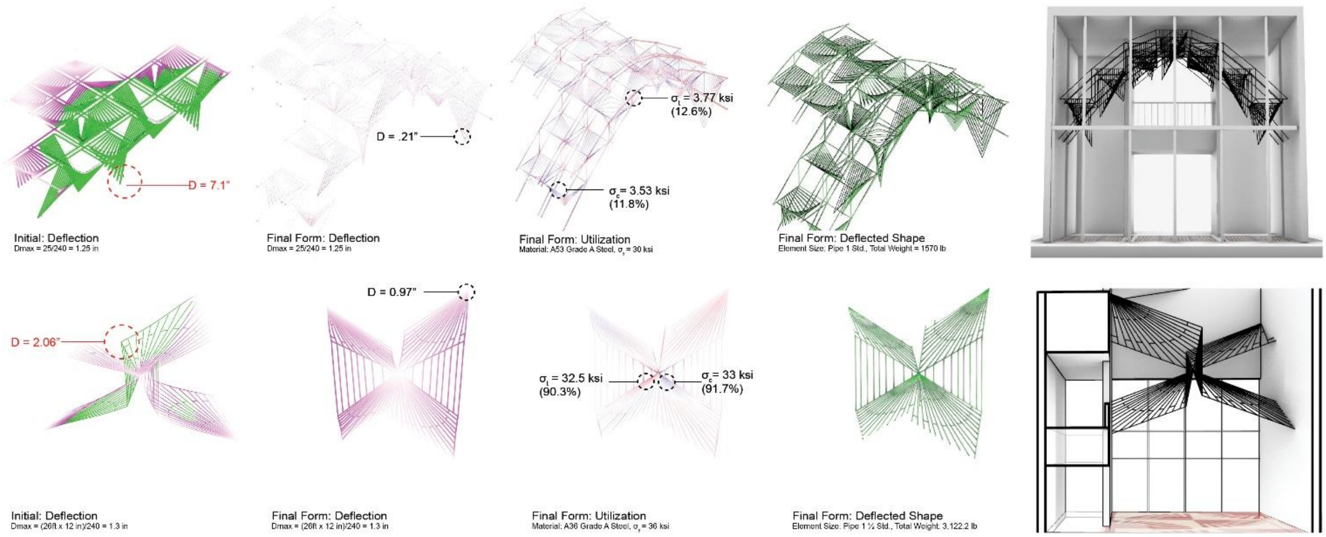

Fig. 6. Students use deflection and stress utilization to develop and refine a structural form.

challenges them to minimize material use while maintaining structural integrity, instilling an awareness of efficiency, fabrication, and sustainable design. Finally, by synthesizing technical documentation and structural analysis, students begin to develop the visual and textual fluency necessary for interdisciplinary collaboration with structural engineers.

Conclusions and Future Directions

The gray-boxing methodology introduced in *Structural Systems in Architecture II* has demonstrated its effectiveness in integrating structural analysis tools into architectural education, expanding on the need to engage students with structural, material, and spatial variables from conceptual ideation to design development.[14] The laboratory case studies reveal how the approach enables students to move from passive understanding to active application of structural principles in the context of design and optimization problems. By engaging with physical and digital systems, students develop a holistic view of structure as a medium for experimentation and innovation, ensuring that they develop material awareness and an embodied understanding of structural performance—a crucial competency for both sustainability and fabrication. In doing so, they not only develop skills in the technical aspects of structural analysis but also embrace its role as a generative force in architectural design.

While gray-boxing facilitates a performance-based engagement with structures in architectural education, its future applications extend beyond the foundational level. The methodology has significant potential for integration into advanced design studios and research initiatives, where its framework can be expanded to address more complex architectural and environmental challenges. In this context the investigations could incorporate dynamic analysis, environmental performance metrics, and user experience analytics, further embedding gray-boxing as a tool for performance-driven design. Expanding its reach into digital fabrication workflows, including composite material systems and circular construction strategies, would enhance its applicability to contemporary material research and fabrication methodologies.

Ultimately, gray-boxing represents a shift in how architectural education engages with structural thinking—moving away from prescriptive formulas toward a generative, iterative, and integrative approach. By positioning structure as an active force within the design process, this methodology prepares students to navigate the increasingly interdisciplinary and performance-driven landscape of contemporary architecture. Future research will continue to refine and expand these methods, ensuring that students are not only capable of working within existing paradigms but are prepared to push them forward, redefining how we teach, learn, and collaborate in the design of the built environment.

Notes:

1 Andrew Saint, *Architect and Engineer: A Study in Sibling Rivalry* (New Haven: Yale University Press, 2007), 10.

2 Fred N. Severud, "Structures: The Feel of Things," Journal of Architectural Education (1947-1974) 16, no. 2 (Summer 1961): 19.

3 Mario Salvadori, "Teaching Structures to Architects," Journal of Architectural Education (1947-1974) 13, no. 1 (Spring 1958): 6.

4 Andrew Saint, *The Architect and Engineer: A Study in Sibling Rivalry* (New Haven, CT: Yale University Press, 2008), 4.

5 J.J. Castellón González, *Constructing Equilibrium: A Methodological Approach to Teach Structural Design in Architecture*, presented at the IV International Conference on Structural Engineering Education: Structural Engineering Education Without Borders, June 20–22, 2018, Madrid, Spain, 2.

6 Mario Salvadori, "Teaching Structures to Architects," Journal of Architectural Education (1947-1974) 13, no. 1 (Spring 1958): 6.

7 Fred N. Severud, "Structures: The Feel of Things," Journal of Architectural Education (1947-1974) 16, no. 2 (Summer 1961): 19.

8 Mamoru Kawaguchi, "Physical Models as Powerful Weapons in Structural Design," in *Proceedings of the IASS Symposium: Shell and Spatial Structures from Models to Realization*, Montpellier, September 2004, 1.

9 Sinéad C. Mac Namara, "Bringing Engineering into the Studio: Design Assignments for Teaching Structures to Architects," in *Proceedings of the 119th ASEE Annual Conference and Exposition*, American Society for Engineering Education, 2012, 1.

10 J.J. Castellón González, "Structural Models in Architectural Education: Experimental Explorations Between the Physical and the Digital Realms," in *Structures and Architecture: A Viable Urban Perspective?*, ed. Paulo J.S. Cruz (Boca Raton, FL: CRC Press, 2022), 208

11 Synthetic thinking, open-ended questions, and heuristic methods.

12 National Institute of Standards and Technology (NIST), "Gray Box Testing," *Computer Security Resource Center*, accessed November 14, 2024, https://csrc.nist.gov/glossary/term/gray_box_testing.

13 American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures* (ASCE/SEI 7-10) (Reston, VA: American Society of Civil Engineers, 2010).

14 J.J. Castellón González, *Constructing Equilibrium: A Methodological Approach to Teach Structural Design in Architecture*, presented at the IV International Conference on Structural Engineering Education: Structural Engineering Education Without Borders, June 20–22, 2018, Madrid, Spain, 2.